Chapter Two: Literature Review

2.1 Introduction

Climate change is a natural cycle where climate changes to accommodate the energy received from the sun (Van Wageningen & du Plessis, 2008). Human activities such as fossil fuel burning, forestry and agricultural practices have become increasingly responsible for the gases that act as a greenhouse and raise the Earth's temperature (Burke *et al*., 2005). The gases, mainly carbon dioxide, scatter long-wave heat radiation from the Earth's surface, thereby increasing the temperature on Earth (Burke *et al*., 2005). Scientific observations indicate that the temperature of the Earth has increased by 0.3 to 0.7ºC during the past 100 years and by 0.2 to 0.4 ºC over the last 40 years (Schulze & Perks, 2000). The increase in temperature is expected to increase the demand on water resources (New, 2002). Some primary processes affected by global change include photosynthesis, respiration of plants, respiration of soil organisms, evapotranspiration and precipitation. The net effect includes an alteration of the carbon and the water balance (Niklaus, 2007). The water balance consists of an influx, outflow and storage of moisture on the Earth's surface. The influx is precipitation in the form of rain, snow and fog, while the outflow is evaporation and runoff. Runoff occurs when precipitation exceeds evapotranspiration (Schlesinger, 1997).

According to Hassan (2006), one of the most important impacts of climate change is on hydrology, which results in changes in river flows and regional water resources. Climate change is expected to intensify the global hydrological cycle resulting in major impacts on regional water resources. A change in the total amount, frequency and the intensity of precipitation will directly affect the amount and timing of runoff, and intensity of floods and droughts (Mukheibir, 2005). According to Ngongondo (2006), the global annual variation of precipitation change increased by 2% from 1900 to 1985. The increase in global mean temperatures has led to an increase in atmospheric water vapour resulting in an increase in the frequency of heavy precipitation events (Dunne *et al.*, 2008). Separate studies on rainfall variability over the long-term in England and India, revealed that short-term (year to year) variations were greater than long-term variations (Ngongondo, 2006). The continued global temperature and precipitation changes have major implications for long-term water resources. The impact of climate change on rainfall distribution within particular regions of countries may be variable (Weritty, 2002). For instance, the northwest of Scotland is expected to become wetter whilst the southeast is expected to become drier (Weritty, 2002). This implies that the impact of climate change on rainfall distribution is site specific. It is thus important to study regional rainfall patterns, preferably at the catchment scale, in order to determine the impact of rainfall on river flow. However, the GCM regional climate change output is dependant on the type of GCM and the downscaling method used. The downscaled solutions for South Africa are consistent between different GCMs and the spatial patterns agree but the magnitude of the projected changes differ (Hewitson & Crane, 2006).

2.2 Fluvial systems

Only 0.0002 % of the Earth's total moisture content flows through rivers, which are an important source of fresh water. In rivers, habitat conditions to support life such as fish, wildlife and birds are determined by river flow (Gordon, 2004). River flow may change both seasonally and inter-annually forcing river species to adapt to ever changing conditions (Gordon, 2004). Floods are important for creating favourable habitat conditions by redistributing sediment and shaping channels (Gordon, 2004). However, if the flow changes too rapidly, species dependant on rivers may not necessarily be able to adapt at an appropriate pace (Gordon, 2004). Although there are no known fish species that have become extinct in South Africa, evidence exists that some species have become extinct within specific fluvial systems and that 36% of freshwater fish are threatened. The increase in temperature due to global warming creates an environment that is more vulnerable to invasions by tropical alien species. Extreme weather events such as floods allow alien species to flourish in river ecosystems, and thereby compete with existing species for habitat and food (Driver *et al.*, 2005).

Rivers form the water link between inland and the coastal regions, thereby transporting nutrients to coastal fisheries. Rivers are an essential component in the continuous hydrological cycle which renews the supply of water (Postel & Richter, 2003). Increasing demands are placed on river ecosystems due to over abstraction of water (Driver *et al*., 2005). Abstraction and damming of water may lead to a reduction in river flow, thus exacerbating water shortages in downstream regions (Mukheibir, 2005). The total net abstraction of surface water in South Africa is 20% of the mean annual runoff per annum. Eight percent is lost through evaporation and 6% is lost via land-use activities (Mukheibir, 2005). Agriculture utilized as much as 62% of South Africa's water in the year 2000 (Mukheibir, 2005). In addition, the excessive extraction of water for forest and sugar cane plantations in the wetter areas of South Africa is known to reduce water supply to rivers (Mukheibir, 2005). Studies have also revealed that land use changes have a significant impact on water resources (Notter *et al.,* 2007).

The impact of climate change on water resources has been investigated using lake levels (e.g. Calder *et al.*, 1995), tree-ring growth rates (e.g. Lawford, 1988), ice core data (e.g. Lawford, 1988) and stream flow data (e.g. Pilon *et al*., 1991). Given that stream flow represents hydrological inputs that occur in the surrounding area, it is the most suitable method for determining the relative impact of climate change on river flow (Westmacott & Burn, 1997). Notably, long-term changes in water abstraction will also influence river flow, however the precise contribution of such abstraction to river flow changes is difficult to quantify as one would need to ensure that all abstraction sources are included (Mukheibir, 2005).

2.3 South African fluvial systems and global change

South Africa's southeastern coastal region receives high rainfall whilst the western and interior regions of the country are arid to semi arid. The quality and quantity of water in rivers changes due to seasonal and inter-annual rainfall changes (Mukheibir, 2003). The availability of water is limited through the dry season due to South African river flow being low for much of the year, with periodic high flows. In a global study examining the impact of climate change and population growth on global and regional water resources, it was argued that climate change increases water stresses by decreasing runoff in areas such as southern Africa, while runoff increased in other parts of the world (Arnell, 2004).

The African continent is expected to warm up to a greater extent compared to the global mean annual warming (Christensen *et al.*, 2007). South Africa is expected to become wetter in the east and drier in the west due to climate change (Hewitson & Crane, 2006) but Engelbrecht *et al.*, (2009) caution against this perception due to the uncertainties associated with the projections of climate change. The central and eastern region of South Africa is expected to experience increased summer rainfall, while little change is projected in the southwestern Cape (Hewitson & Crane, 2006). Reductions in runoff and/or stream flow of up to 10% are expected over the western parts of the country by 2015; the decline in such runoff will apparently gradually move from west to east (DWAF, 2004). The projected increase in evaporation as a result of higher temperatures, is expected to increase by 10 to 20%, resulting in increased evaporation losses from dams and increased irrigation demands for drier soils (Hewitson & Crane, 2006). Increasing temperatures implies an increase in water requirements for plants, placing higher demands on irrigation (DWAF, 2004). In addition to a decrease in water availability, there is an expected decrease in water quality (DWAF, 2004). Future rainfall is expected to increase in certain parts of the country and decrease in other areas resulting in lower or higher stress on water resources respectively (Mukheibir, 2003).

Factors governing rainfall variability over Africa include the ENSO, sea surface temperatures and land atmosphere feedbacks. The sea surface temperature is considered to be the primary influence over African rainfall (Nicholson, 2000). ENSO cycles play a vital role in inter-annual rainfall variability (Ngongondo, 2006). During pacific warm episodes, rainfall is usually below normal, whilst during La Niña or Pacific cold episodes it is above normal (Ngongondo, 2006). Rainfall is usually abnormally high over Africa during La Niña events, and particularly influences rainfall over western South Africa (Nicholson & Selato, 2000). Klopper *et al.* (1998) found an association between ENSO and seasonal mean maximum temperature over the eastern half of South Africa. Rainfall changes were also observed in other parts of the world (Ngongondo, 2006) such as in Ireland where substantial rainfall reductions have been recorded from 1975 to 2006 (Dunne *et al.,* 2008). A study of rainfall variability and trends in a river catchment in Malawi, using the non-parametric Mann-Whitney Pettit and Mann-Whitney-Wilcoxon statistics, found that the precipitation pattern followed the ENSO and La Nina episodes (Ngongondo, 2006). Rainfall variability is more detectable at catchment level than on larger scales (Ngongondo, 2006). A further study, examining the impact of the 1950 to 1990 warm ENSO events on river flow variability in nine southern Africa countries, using 260 river flow stations, found a general decline in annual runoff after the mid 1970s (Alemaw & Chaoka, 2006). An earlier study by the same authors (Alemaw & Chaoka, 2002a) examined 502 river flow stations, of which 260 stations were located in South Africa, over the period early 1950s to late 1990s. The study found that 137 rivers had a statistically significant decreasing trend, 9 with a statistically significant increasing trend and 269 with no trend (Alemaw & Chaoka, 2002a). Although the studies undertaken by Alemaw & Chaoka (2006, 2002b) provide a map of the distribution of river flow stations across South Africa, the exact location and stations used are unclear, and therefore cannot be used for comparison in the present study. In addition, these previous studies used a relatively short temporal scale (40 years) and the length of available data was insufficient to draw definite conclusions about the temporal variability of flow (Alemaw & Chaoka, 2002a).

The Department of Water Affairs and Forestry (DWAF) is the custodian of water resources in South Africa. DWAF uses the National Water Policy 1997, the National Water Act No. 36 of 1998 (NWA), and the Water Services Act No. 108 of 1997 to control water abstraction (Mukheibir, 2005). DWAF initiated the Rivers Health Programme (RHP), which monitors the ecological state of rivers in South Africa. River flow is monitored at 1 200 flow-gauging stations while evaporation and rainfall is monitored at 360 stations across South Africa (DWAF, 2008). Water resources are managed in South Africa by dividing the country into 19 water management areas, which are linked through inter-catchment transfers, transferring water from catchments with large quantities of water to regions that are more water scarce or have a high water demand (DWAF, 2004). South Africa does not have particularly large rivers, and the combined flow of all the rivers in the country is 49 000 million cubic metres per year, which is less than half that of the Zambezi River (DWAF, 2004). The *Department of Environmental Affairs and Tourism* (DEAT, 1999) is responsible for the "State of the Environment" reports, which serves as a framework to explain the factors responsible for environmental change.

This study examines river flow in the Orange, Tugela, Mgeni and Breede Rivers of South Africa. The Orange River catchment is 973 000 km^2, covering 77% of the land in South Africa. The Orange River is the longest river in South Africa, rising in the Lesotho Drakensburg (Sene *et al.*,

1998) and flowing westward draining into the Atlantic Ocean (DEAT, 1999). All the rivers and streams of Lesotho flow across Lesotho's southwestern border, contributing to approximately half the flow for the Orange River. Lesotho receives 80% of its average annual rainfall during summer, between October and March, with a mean annual rainfall of 780 mm, but varying from 500mm in the southwest of the country to 1600 mm in the northeast (Sene *et al.*, 1998). A study examining the relationship between rainfall and river flow and associated changes over time found a link between annual rainfall and flow but no statistical cyclical trend for the period of study (Sene *et al.*, 1998). The Orange River's largest tributary is the Vaal, which is responsible for supplying water to 37% of South Africa's economic sectors. The agricultural sector is the largest user of water in South Africa whilst the mining, industrial, urban and domestic sectors use smaller quantities of water (DEAT, 1999).

The Tugela River located on the eastern side of South Africa, is one of the largest rivers in the country and hosts seven large dams providing water via interbasin transfer to the Vaal, Mhlathuze and Mgeni Rivers. The Tugela River is experiencing reductions in flow and is predicted to be fully utilized by 2025 (DEAT, 1999). The Mgeni River catchment also located in the eastern part of South Africa, in KwaZulu Natal receives a mean annual rainfall (MAR) of 740 million cubic metres per annum and hosts Midmar, Albert Falls, Nagel and Inanda Dams. Water is transferred to the Mgeni River from the Mooi River in the Tugela River Basin by interbasin transfer (DEAT, 1999), which is critical for the economy of the area. The future mean annual runoff is expected to be reduced to a greater extent in the western regions of the catchment as opposed to the eastern portion. The use of water by forests and sugar cane plantations in the relatively wetter part of the country reduces the amount of rainfall that reaches the rivers (Mukheibir, 2005). In addition, population growth reduces water resources (Arnell, 2004). KwaZulu-Natal produces a quarter of the river flow of South Africa and double the quantity of runoff per unit rainfall than the entire of South Africa (Nel, 2008). The Breede River located in the Western Cape of South Africa has only the Brandvlei Dam on its 337 km length. The region's climate is variable and rainfall occurs during winter (DWAF, 2004), ranging from a mean annual rainfall of 1500mm in mountain catchments to 200mm in the southeast. The high evaporation during the dry summer ranges from 1300mm per annum at the coast to 1650mm in the Ceres River Basin (DWAF, 2001). Water is transferred into the Waterskloof Dam in the Breede River water management area from the Berg River water management, where it is seasonally stored and transferred back to the Berg River water management during the dry season, with additional water from the Breede River water management area (DWAF, 2001).

2.4 Rainfall trends in South Africa

South Africa is a water stressed country with an average rainfall that is considerably lower than the global average of 850 mm per annum (Mukheibir, 2005). No conclusive evidence exists for the claims that South Africa is drying up (Dyer, 1975). Analyses of rainfall data for 157 stations across South Africa for the period between 1880 and 1972 showed quasi oscillations of between 16 and 20 years and between 10 and 12 years (Tyson *et al.,* 1975). Of the 157 stations across South Africa, only 24 stations showed a decreasing trend, whilst 2 stations showed a positive trend (Dyer, 1975). A 20 year oscillation of rainfall trends was observed for the northeastern parts of South Africa over the period 1910 to 1972 (Dyer & Tyson, 1977). A quasi 18 year oscillation of inter-annual rainfall for 60 and 80 year data sets was found for the subcontinent including South Africa, Mozambique, Namibia, Botswana, Zambia and Swaziland using spectral analysis, with the majority of 18 year spectral peaks being statistically significant at the 95% level (Dube, 1999). An examination of climate variability over southern Africa using wavelet analysis for a 3500 year period revealed a 1500 year oscillation in rainfall variability (Tyson *et al.* 2002).

A significant increase in extreme rainfall events between 1931 and 1960, and between 1961 and 1990 was found for over 70% of South Africa (Mason *et al.,* 1999). Different rainfall patterns were noted in different regions of Africa as well as a change in the seasonality of rainfall over Africa from year to year. Rainfall trends over southern Africa ranged from dry conditions in the 1910s, 1940s and the 1980s to wetter conditions in the 1950s (Nicholson, 2000). An investigation of the annual and seasonal rainfall trends in the Drakensburg of KwaZulu-Natal between 1955 and 2000 found a strong correlation between summer rainfall and ENSO events (Nel, 2008).

The Special Report of the Intergovernmental Panel on Climate Change (IPCC, 1995) requested an increase in historical trend studies for a clear indication of the climate changes that have occurred, thus prompting historical climate trend studies (e.g. Kruger, 2006). A study of rainfall trends for 138 stations in South Africa between 1910 and 2004 concluded that no change in precipitation occurred over the majority of South Africa (Kruger, 2006). However, some areas (i.e., northern Limpopo, northeastern Free State, western KwaZulu-Natal and the southeastern regions of the Eastern Cape) experienced significant decreases in annual precipitation, whilst other areas (i.e., northern Northwest Province and an area over Northern Cape Province, Western Cape Province and Eastern Cape Province) recorded significant precipitation increases during the wet season (Kruger, 2006). Kruger (2006) expanded on the study by New *et al.,* (2006) by using a longer data set and a larger number of rainfall stations which enabled the identification of significant precipitation trends on a regional scale.

An examination of temperature and precipitation trends over the period 1956 to 2000 for centres in southern and western Africa, including Cape Town, Emerald Dale, Glen College, Langgewens, Port Elizabeth and Pretoria in South Africa, found a small number of statistically significant trends for rainfall (New *et al.,* 2006). However, no trends were identified in the mean annual rainfalls over southern Africa between 1900 and 1970 (Nicholson, 1986, 1989), or between the periods 1931 and 1960 and between 1961 and 1990 (Hulme, 1992). Similar conclusions were reached using 30 southern African station records dating back to the 1880s (Tyson, 1986). Whilst an examination of 42 years of existing historical rainfall data from Cape Town, found a decreasing rainfall trend, intensity of rainfall over the Western Cape has generally increased (Van Wageningen & du Plessis, 2007).

It would appear that whilst historical trends in precipitation over southern Africa have been extensively studied to some detail, the correlation of rainfall trends with river flow data has been limited. In a previous study, a direct relationship could not be established between the rainfall and runoff relationship in the upper Orange River catchment due to the wide range of mean annual rainfall in the area (Carter, 1967). However, a study of the daily, monthly and annual rainfall trends at four stations in and around the Bell river catchment in the Eastern Cape Drakensburg of South Africa, showed a high correlation between flow records and rainfall data in this catchment (Dollar & Rowntree, 1995). Annual and seasonal rainfall was found to peak every 16 to 19 years (Dollar & Rowntree, 1995). Studies conducted north of Lesotho found no rainfall trends between 1920 and 1970 (Onesta and Verhoef, 1976), whilst a more recent study confirmed no significant change in annual rainfall between 1930 and 1992 (Mason, 1996).

To expand on the previous studies undertaken in southern Africa, the present study focuses on the correlation of rainfall and river flow trends in strategically chosen catchments across South Africa.

2.5 Strategies to evaluate the impact of climate change on hydrology

Two main strategies have been developed to evaluate the impact of climate change on hydrology, which includes the analysis of precipitation and runoff over an appropriate time (Werritty, 2002). The availability and quality of long-term records is essential for the successful use of data, together with trend analysis for short-term water planning. Historical trend studies can be used to provide information on how the climate has changed and can also be used to verify climate models in order to improve model prediction (Kruger, 2006). The second strategy entails the use of estimates of future trends in global population, and economic and technological developments to generate climate scenarios in combination with General Circulation Models (GCMs) and the downscaling of temperature and precipitation to region or catchment levels (Werritty, 2002). Downscaling was specifically designed to obtain more detailed temporal and spatial information from GCMs (Hewitson & Crane, 1996). The rainfall-runoff models provide runoff estimates using climate scenarios for medium and long-term water planning. Due to the uncertainty of accurate and reliable GCMs outputs, downscaling to catchment level and calibration of rainfall-runoff models, the runoff estimates produced are subject to substantial errors (Werritty, 2002) such as amplified runoff changes in response to small precipitation changes and spatial and temporal scale mismatches (Perks *et al.*, 2000).

The majority of studies investigating the impact of climate change on hydrology have used GCMs. Models are "physical laws and empirical observations written in mathematical terminology to produce a set of results such as the runoff using inputs such as the rainfall" (Schulze & Perks, 2000, p4). Even though models are useful tools, it must be noted that predicted changes do not take into account natural climatic variability, thus often resulting in the generation of different values under different climate scenarios. However, Werritty (2002) found that the predictions of the GCMs were consistent with precipitation and runoff trends in Scotland. An assessment of the impact of climate change and land use on water resources on Mt

Kenya was conducted using the NRM3 stream flow model (Notter *et al.,* 2007), whilst the Soil and Water Assessment Tool (SWAT) model was used to determine the impact of climate change and land cover on river flow in the Poyang Lake basin, China (Guo *et al.,* 2008). The study by Guo *et al.* (2008) found that whilst climate affects annual stream flow, land-cover changes influenced seasonal stream flow.

In southern Africa, the modified *ACRU* agrohydrological modeling system has been used to determine the impact of climate change on water resources at Quaternary Catchment level (Schulze & Perks, 2000). The model uses total evaporation which is separated into soil water evaporation and transpiration, thereby accommodating carbon dioxide increases. The generation of runoff takes into account land use, induced changes in infiltration and soil water redistributions. Climate change also impacts on groundwater, also a source of water in South Africa and must be recharged. The *ACRU* model measures this recharge index to determine the impact of climate change in different regions of South Africa (Schulze & Perks, 2000).

The Hadley (1998) GCM, excluding sulphates, produced results showing that rainfall during the summer months in the Eastern Cape and the western part of the country decreased by more than 25%. The northern regions displayed a reduction in summer rainfall of 5%, whilst a 50% increase was indicated for the Western Cape (Schulze & Perks, 2000). This increase is unlikely to impact water resources since it occurs in the arid region of South Africa (Schulze & Perks, 2000). However, different models show different results, with the Climate System Model (CSM) indicating a 10% increase or 10% decrease of summer rainfall over southern Africa, whilst the Genesis GCM displayed increases across South Africa, with the exception of a decrease in rainfall over the Western Cape (Schulze & Perks, 2000). The Genesis and CSM models showed varying results for winter rainfall in the Western Cape (Schulze & Perks, 2000), with the CSM model indicating a 25% reduction in rainfall whilst the Genesis GCM reflected an overall increase in winter rainfall (Schulze & Perks, 2000). The models used by Hewitson & Crane (2006), based on a study of daily precipitation data over South Africa, also found inconsistent results between models, with the HadAM3 indicating a slight increase in rainfall over the Western Cape, whilst the ECHam4.5 indicated a decrease in rainfall over the same region. Empirical downscaling techniques, based on self organizing maps, was applied on daily precipitation data over South Africa, which indicated that summer rainfall increased in the interior and eastern regions but decreased in the western region of the country over the period 1979 to 2002 (Hewitson & Crane, 2006).

Climate change studies have also focussed on the Orange River and Mgeni River catchments using the Hadley (1998) GCM to simulate mean annual rainfall (Schulze & Perks, 2000). For the Mgeni River catchment, the model indicated a 0-12% decrease in mean annual runoff over the eastern half and 12-25% reduction over the western half of the catchment. The mean annual runoff for the majority of quaternary catchments in the Orange River Catchment seems to be decreasing in association with a decrease in precipitation, with the greatest reduction found in the eastern part of the catchment over northern Lesotho (Schulze & Perks, 2000). Since the location of the Orange River flow station in the present study is very close to the Lesotho border, the study by Schulze & Perks (2000) is important for comparison.

Trend detection in hydrological data has become increasingly popular in connection with climate change (Hamed, 2008). Trend analysis has been widely used to evaluate the potential impacts of climate change in hydrologic time series throughout the world, including the US, Western Europe, Canada and western Britain (Hamed, 2008). Analysis of historical annual stream flow records in Minnesota using the Mann-Kendal non parametric test reflected that the stream flow trends are different for different basins (Novtny & Stefan, 2006). The Mann-Kendall trend test was used in conjunction with a regionalization procedure to quantify the climate effect in the Churchill-Nelson River basin in Canada (Westmacott & Burn, 1997). Since climate variability in hydrologic data can adversely affect trend test results, the scaling hypothesis was proposed for modelling climate change (Hamed, 2008). Such a procedure would help in avoiding contradictions found in trend analysis, such as local or regional inconsistency (Hamed, 2008). According to Kundzewicz (2000), recent studies have established that river flow trends increase or decrease in different regions. In addition, the impact of climate change on stream flow varies regionally and with different scenarios. Climate change also causes trends not previously experienced or detected, which provide new challenges. Given that comparisons between rainfall trend and associated river flow studies have been limited in South Africa, this study will provide valuable insight into historical rainfall and river flow trends.