Impacts of Climate Change on Water Resources in Southern Africa: A Review

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Abstract

The Intergovernmental Panel on Climate Change concluded that there is consensus that the increase of atmospheric greenhouse gases will result in climate change which will cause the sea level to rise, increased frequency of extreme climatic events including intense storms, heavy rainfall events and droughts. This will increase the frequency of climate-related hazards, causing loss of life, social disruption and economic hardships. There is less consensus on the magnitude of change of climatic variables, but several studies have shown that climate change will impact on the availability and demand for water resources. In southern Africa, climate change is likely to affect nearly every aspect of human well-being, from agricultural productivity and energy use to flood control, municipal and industrial water supply to wildlife management, since the region is characterised by highly spatial and temporally variable rainfall and, in some cases, scarce water resources. Vulnerability is exacerbated by the region's low adaptive capacity, widespread poverty and low technology uptake. This paper reviews the potential impacts of climate change on water resources in southern Africa. The review begins by highlighting studies on detected climate changes particularly focusing on temperature and rainfall. The impacts of climate change are highlighted, and respective studies on hydrological responses to climate change are examined. Challenges in climate change impact analysis, which inevitably represents existing research and knowledge gaps are discussed. Finally the paper concludes by outlining possible research areas in the realm of climate change impacts on water resources, particularly knowledge gaps in uncertainty analysis for both climate change and hydrological modelling.

Keywords: Climate change, southern Africa, water resources, hydrological modelling, uncertainty.

Highlights

- Climate change in southern Africa will impact on the availability and use of water resources.
- Climate change impacts include increased frequency of extreme climatic events.
- Challenges in climate change impact analysis are outlined.
- Critical issues concerning uncertainties in hydrological modelling using outputs from climate models are highlighted.

1. Introduction

The African continent has been identified as particularly vulnerable to the changing climate due to its envisaged low adaptive capacity and vulnerability (Callaway, 2004). The southern African region is regarded as one of the most vulnerable regions in Africa (IPCC, 2007b). Within the climate change matrix, water resources are at the epicentre of projected climate change impacts. If the observed changes in climate in the last century (IPCC, 2007) persist into the future, the potential impacts on water resources are likely to increase in magnitude, diversity and severity. Given the already large spatial and temporal variability of climatic factors in southern Africa (Gallego-Ayala, 2011); cimate change impacts on water resources are likely to be more pronounced in the near future than previously foreseen (IPCC, 2007b). Climate change impacts on water resources will have both direct and indirect effects on the socio-economic and the biophysical environments (Arnell, 1999; Bates et al., 2008; Kundzewicz et al., 2008; Rutashobya, 2008; Schulze, 2005). Already, this is evident in several sectors, such as agriculture (Crane et al., 2011; Pielke et al., 2007; Vermeulen et al., 2012), health (Bunyavanich et al., 2003; Gage et al., 2008), ecosystems and biodiversity (Eriksen and Watson, 2009) and energy generation (Magadza, 1995, 2000; Yamba et al., 2011).

The assessments of the Intergovernmental Panel on Climate Change (IPCC, 2007) have demonstrated that, due to increasing greenhouse gases, the Earth’s climate is changing. Future experiences are likely to include higher sea levels, more intense storms and heavy rainfall events (McBean and Ajibade, 2009). Climate hazards are already occurring and impacting human settlements causing loss of life, social disruption and economic hardships (Desanker, 2002; Hulme, 1996; IPCC, 2001; McBean and Ajibade, 2009). Such hardships are already being heavily felt by the poor in most Southern African Development Community (SADC) countries as reported by Magadza (1996); Ngigi (2009) and Simms and Reid (2005).

While there are diverse views regarding the magnitude of change of climatic characteristics in southern Africa, and the possible impacts at the scale at which land and water resources are managed, several scholars have however noted that there is certainty, that, climate change will impact on the availability and use of water resources (see for example Desanker and Magadza, 2001; Matondo et al., 2005; Ngigi, 2009; Omari, 2010; Schulze, 1999, 2000, 2005; Yamba et al., 2011).

What is certain is that in southern Africa, our climate is changing. To date, however there are only few studies examining the hydrological responses of climate change in Africa (Boko et al., 2007) and southern Africa (Manase, 2010) in particular, upon which base generalisations about the future availability of water resources can be made for planning and management purposes. There are also a myriad of other supply and demand pressures such as land degradation, pollution and population and urban growth, affecting water resources (Arnell, 1999; McMullen, 2009; United Nations, 2011). Climate change has the potential to exacerbate these pressures in southern Africa. The region encompasses the following countries: Angola, Botswana, the Democratic Republic of Congo, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe. To our knowledge, there is no comprehensive review of studies assessing impacts of climate change on water resources. The objective of this paper is to review literature on detection of changes in climate and impacts of climate change on water in southern Africa, as well as identifying and highlighting research gaps and needs.

2. Detection of Climate Change

Long term trends analysis of atmospheric variables such as temperature, rainfall and evapotranspiration have been used extensively [e.g. rainfall by Warburton and Schulze, 2005; Dore, 2005, temperature by Kruger and Shongwe, 2004; New et al., 2006; Warburton et al., 2005, evaporation (and soil moisture) by Malisawa and Rautenbach, 2012], as proxies for detecting changes in climate. The increased frequency of occurrence of extreme events such as droughts, floods and cyclone activity in southern Africa has also been cited as evidence of a changing climate. Most scientists (e.g. Mirzaa, 2003; Rosenzweig et al., 2001; Reason and Keibel, 2004; Reason, 2007; Warburton et al., 2005) are of the view that the increased frequency of extreme events may be attributable to increasing greenhouse gas (GHG) emissions. The following section reviews some of the studies undertaken on climate change detection particularly on rainfall and temperature.

2.1 Temperature

Analyses of both remote sensing derived and observed temperature records in southern Africa agree that over the last decades the region has been experiencing a warming trend. Several scholars, including Kruger and Shongwe (2004), Hughes and Bally (1996), Warburton et al., 2005), Unganai (1996) and New at al., 2006) analysed observed temperature trends. The basic conclusion drawn from these studies is that temperatures are rising, with minimum temperatures rising faster than maximum temperatures. The overall result has thus been a warming trend.

An increase in temperature typically causes the intensification of the hydrological cycle, as a result of the increase in evaporation as well as rainfall (Warburton et al., 2005). That is, temperature changes may lead to changing patterns of rainfall, the spatial and temporal distribution of runoff, soil moisture, and groundwater reserves, as well as (increase) the frequency of occurrence of droughts and floods (Schulze, 2011). Consequently, temperature changes have a direct bearing on water resources availability within southern Africa.

Most studies analysing temperature changes were carried out in South Africa. For example, Kruger and Sekele (2012) concluded that warm extremes increased and cold extremes decreased for South Africa. Kruger and Shongwe (2004) conluded that 23 (of 26) stations analysed showed positive trends in annual mean maximum temperature, 13 statistically significant, with trends higher for central stations than those closer to the coast. Levy (1996) showed an upward trend of 10 % (+ 1.5"C) noted in the winter series. Jones (1994) showed a warming rate of 0.31°C per decade whilst Karl et al., (1993) concluded that an increase in both maximum temperatures and minimum temperatures was observed. Tshiala et al., (2011) in studying catchments in the Limpopo Province of South Africa showed an increase of 0.12°C/ decade in the mean annual temperature. However, Muhlenbruch (1992) concluded that the data were inconclusive as to whether South Africa was warming or cooling for the duration of his study.

On regional and country level studies, Collins (2011) concluded that significant increasing temperature trends were found in Southern Hemisphere of Africa. Morishima and Akasaka (2010) in his studies in southern Africa concluded that annual mean surface temperature showed an increasing trend across the whole region, with particularly large rates of increase in Namibia and Angola. New et al. (2006) analysed daily (maximum and minimum) temperature between 1961-2000 for the SADC region and concluded that temperature extremes show patterns consistent with warming over most of the region with diurnal temperature range (DTR) showing consistent increases in a zone across Namibia, Botswana, Zambia, and

Mozambique, coinciding with more rapid increases in maximum temperature than minimum temperature extremes. Hulme et al (2001) concluded that for southnern Africa temperatures during the 1990s were higher than they were earlier in the century and are currently between 0.2 and 0.3°C warmer than the 1961–90 average.

Overall, for southern Africa we can conclude that temperatures are rising, with minimum temperatures rising faster than maximum temperatures for the whole region. As a result there is also a notable decrease in cold extremes and an increase in warm extremes. From the temperature studies, apart from the general trend of increasing temperatures, still unresolved in the magnitude of change which is variable across the region.

2.2 Rainfall

Climate change detection studies on rainfall have been carried out using observed, interpolated and remote sensing derived rainfall. For Malawi, Ngongondo et al. (2011) using 42 rainfall stations showed that most stations revealed statistically non-significant decreasing rainfall trends for annual, seasonal, monthly and the individual months from March to December at the 5% significance level. For Zambia, Sichingabula (1998) showed an increasing 11-year coefficients of variation (CVs) for selected stations and decreasing rainfall trends observed in southern Zambia after 1975. For Zimbabwe, Mazvimavi (2010) concluded that rainfall in Zimbabwe has high inter-annual variability, and currently any change due to global warming is not yet statistically detectable.

Several studies in South Africa showed that rainfall in South Africa is characterised by high inter-annual variability. For example, Kane (2009) showed that annual rainfall had considerable year-to-year fluctuations (50% to 200% of the mean), while five-year running means showed long-term fluctuations (75% to 150% of the mean). However, running means over 21 years did not indicate linear trends, upwards or downwards. In the largest part of South Africa there was no real evidence of changes in rainfall over the past century Kruger (2006), there are, however, some identifiable areas where significant changes in certain characteristics of rainfall have occurred over the period 1910 to 2004.

Still other studies have looked at rainfall changes for the southern African region. For example, Shongwe et al. (2009) concluded that currently, rainfall trends are characterised by more severe droughts in the southwest of southern Africa and enhanced rainfall farther north in Zambia, Malawi, and northern Mozambique. However, Chamaillé-Jammes et al. (2007) and Joubert et al. (1996) concluded that rainfall in southern Africa showed no consistent or statistically significant trends across the region, with; however, a noted decrease of regionally-averaged total rainfall (but is not statistically significant). Nicholson (2000, 2001), found a shift from relatively wet conditions of the 1920s - 1950s to dry conditions from the 1970s onward. For the northernmost part of southern Africa, including Zimbabwe, an increase in rainfall in the 1970s of 6% followed by a reduction of 5% in the 1980s was shown by Nicholson (2001). Morishima and Akasaka (2010) analysed rainfall data for the 1979-2007 period for southern Africa and concluded that annual rainfall has decreased over the African continent from the equator to 20ºS, as well as in Madagascar resulting in a shorter and weaker rain season in southern Africa, with rainfall in Angola, Zambia, and Namibia tending to decrease from December to March. New et al. (2006) reported a spatially coherent increase in consecutive dry days over much of southern Africa in the last decades of the twentieth century. However, analysis of observed rainfall trends for Zimbabwe (1933 - 2000) by Mazvimavi (2010) showed that there was no statistically significant rainfall reduction in Zimbabwe. This contrasts sharply, however, with earlier results from Unganai (1996) who concluded that areal annual rainfall in Zimbabwe had declined by 10% between 1900 and 1994. Elsewhere, in South Africa, Hewitson and Crane (2005) using 50 years of data (1950-1999) reported rainfall increases in regions where orography plays a strong role, and also increases in late summer dry spell duration for much of the summer rainfall region. These studies and reports suggest that annual rainfall has not had a clear tendency in the last 20 or 30 years, but most concur that dry periods in southern Africa have become longer and more intense. The basic conclusion from the analysis of rainfall trends is that changes in rainfall are subject to considerable uncertainty, regarding the extent (spatial and temporal) and magnitude of change (Schulze et al., 2005; Mazvimavi, 2011). This is largely because rainfall is characterised by high inter-annual variability over southern Africa. The insufficient data records for southern Africa also make analysis challenging (Mazvimavi, 2011). These limitations render detection of rainfall changes due to climate change difficult. However, as pointed out by Warburton and Schulze (2005) changes in rainfall have important implications for the hydrological cycle and for water resources, as rainfall is the main driver of variability in the water balance, upon which humans and the environment depend.

3. Climate change impacts on hydrological response drivers

Manase (2010) reported that most climate change impact studies have been carried out in developed countries with few studies undertaken for developing countries, particularly from Africa. Sub-Saharan Africa is still lagging behind most regions of the world in general scientific research (Mouton et al., 2010) including climate change. This dearth of literature on climate change impacts for sub-Saharan Africa has been attributed to inadequate research financing (Yanda, 2011), poor research infrastructure (Manase, 2010), technological constrains (Chhetri et al., 2012), constrained information dissemination (Mazvimavi, 2011) and a myriad of other endogenous and exogenous factors. However, it is in sub-Saharan Africa that the impacts of climate change are likely to be severest due to the extreme poverty, hunger and malnutrition (Magadza, 2010) and low adaptive capacity (Arnell, 1999; Mazvimavi, 2011). Several studies in the region have, however, looked at the potential impacts of climate change on water resources, with a general consensus that, as mentioned earlier, climate change will affect both the quality and quantity of available water resources in the region (e.g. Mazvimavi, 2008; Schulze, 2000, 2005, 2010; Warburton, 2010). The following section reviews impacts of climate change on key climatic drivers of hydrological responses namely: temperature and rainfall in southern Africa.

3.1 Temperature

Changes in temperature and rainfall have a direct effect on the quantity of evapotranspiration and on both quality and quantity of the runoff. Consequently, the spatial and temporal availability of water resources, or in general the water balance, can be significantly altered with any changes in temperature.

Warming will increase the frequency and intensity of tropical storms in the Indian Ocean and consequently, that coastal areas may be subject to flooding due to rising sea levels (Nicholls et al., 2007; Rahmstorf, 2010). Most studies over southern Africa project a temperature increase of around 3^0C. For example, Mujere and Mazvimavi (2012) projected a 3^0C maximum temperature increase for Mazoe catchment in Zimbabwe; Beck and Bernauer (2011), a 2.9^0C maximum increase for the Zambezi Basin; Graham et al. (2011) a 3^0C maximum temperature increase for Thukela Catchment, South Africa; Hewitson and Tadross (2011) a 3^0C maximum temperature increase for South Africa, Swaziland and Lesotho. Other scholars projected temperature changes of between $2\text{-}5^0$C for different areas within southern Africa including

Losjö et al. (2007); Schulze et al. (2005); Tadross et al. (2005); Matondo et al. (2004); Arnell et al. (2003); Hudson and Jones (2002) and New (2002). All projections show a temperature increase for southern Africa. However, different regions are characterised by different ranges of temperature increases, with the wet tropical areas near the equator (parts of Zambia and DRC) having a lower temperature changes as compared to the dry regions of Botswana, Namibia and parts of Zimbabwe and South Africa. Projections have shown that, the arid and semi-arid areas are likely to get drier due to climate change than more humid areas in countries such as Tanzania or Zambia (IPCC, 2008). However, the different scholars used different global climate models in their projections. Moreso, others relied on use of a single GCM (e.g. Mujere and Mazvimavi, 2012). Additionally, only a few studies used RCM (e.g. Engelbrecht (2005); Schulze et al. (2005); Tadross et al. (2005)) despite these having a better spatial resolution for better teperature projections.

Most studies concluded that, based on future climate modelling results, southern Africa's climate will become hotter and drier. This warming will be greatest over the interior and semi-arid margins of southern Africa, the Sahel and central Africa. Projections show that temperature changes will not be uniform over the region: the central, southern land mass extending over Botswana, parts of north-western South Africa, Namibia and Zimbabwe are likely to experience the greatest warming of 0.2 - 0.5°C per decade (Christensen et al., 2007).

3.2 Rainfall

Rainfall trends have been extensively studied in assessing impacts of climate change on water resources. Most scholars concur that, even without climate change, rainfall exhibits extreme variability in time and space over southern Africa. While there is uncertainty on the magnitude of climate change impacts on rainfall in southern Africa (Christensen et al., 2007), the IPCC (2007) suggest that climate change will decrease rainfall. Many models project that by 2050 the interior of southern Africa will experience decreased rainfall during the growing season due to reductions in soil moisture and runoff. Additionally, many climate change models, predict a 5 to 15% decrease of growing season rainfall in southern Africa (IPCC, 2001). Hulme (1992) predicted a 5 – 10% reduction in rainfall and Mazvimavi (2011) projected a 3 - 23% decrease in rainfall under climate change in southern Africa. Several scholars share the same view (e.g. Hulme et al., 2001; Arnell et al., 2003) and have predicted that the region will be characterized by below-normal rainfalls and frequent droughts in future. Although most studies (e.g. Kenabatho et al., 2012; Mhlanga et al., 2012; Zhu and Ringler, 2010; Andersson et al., 2009; Engelbrecht et al., 2008; Christensen et al., 2007; Tadross et al., 2005; Matondo et al., 2004; Arnell et al., 2003; Hudson and Jones, 2002) indicate future reduction in rainfall of up to 50%, projected future changes in mean seasonal rainfall in southern Africa are less well defined (Manase, 2010; Schulze et al., 2012).

Scientific evidence points to an increased inter-annual variability, with extremely wet periods and more intense droughts in different countries in future. Besides volumes, rainfall patterns are also expected to change in intensity and frequency, resulting in more extreme events and longer periods between rainfalls (Christensen et al., 2007). At the same time, the demand for water in the region is increasing rapidly due to population growth and economic development (AWDR, 2006). Still, in the region, most livelihoods are dependent rain-fed agriculture, that which will be affected by reduction in rainfall under climate change (Thornton et al., 2009; Thornton et al., 2010).

Although most rainfall projections based on global circulation models show reduced rainfall for much of southern Africa (see for example Arnell, 2003, 2004; Nicholson, 2001;Mazvimavi, 1998; Hudson and Jones, 2002; Matondo et al., 2004; Graham et al., 2011; Zhu and Ringler, 2010), to date there has not been consensus on the magnitude of potential rainfall reductions due to (1) use of different climate models, (2) variations in climate change model outputs, (3) different responses to climate change due to differences in catchment physiographic characteristics, among other factors (Leavesley, 1994; Xu, 1999; Schulze, 2010). Some models, on the other hand, show that other areas will experience increased rainfall amounts. For example, Schulze et al. (2010) and Tadross et al. (2011) reported that the north eastern regions of South Africa will actually experience increased rainfall under different climate change scenarios.

4. Hydrological responses to climate change

Changes in climate, with resultant increasing temperatures and changing rainfall patterns may alter hydrological responses (Kundzewicz et al., 2007). Most assessments of climate change impacts have been primarily undertaken at macro and regional scales, masking the complex hydrological interactions at the local, catchment scale (Schulze, 2000). As a result reported streamflow responses to climate change are varied, both spatially and temporally.

Although most studies have been confined to modelling hydrological responses to climate only, Warburton et al. (2011) showed that land use and land cover plays a significant role in controlling hydrological responses. Additionally, streamflow is influenced not only by climate, but by numerous other human activities such as catchment land use changes, inter-basin water transfers, water abstractions, return flows or reservoir construction (Warburton and Schulze, 2005). These may conceal, obliterate, or reverse climate change induced trends. Ultimately, streamflow is the integration of several aspects of climate over both time and space, hence trends in one driver may be offset by opposite trends in other hydrological drivers such as catchment soils, geology or land use (Warburton et al., 2011; Arnell et al., 2003; Schulze et al., 2011).

Despite the above challenges, the hydrological responses to climate change in the southern Africa have been investigated using mostly rainfall – runoff hydrological models. According to Schulze (2005) rainfall runoff models are invaluable tools in simulating information for use in making decisions for water resources planning and management including evaluating impacts of climate change on water resources. The following section reviews some of the studies on hydrological responses to climate change undertaken in southern Africa.

4.1 Streamflow projections under climate change

Several runoff projections under climate change have been provided by different scholars for southern Africa. River runoff and water availability are projected to decrease by 10 to 30% in the dry tropics (IPCC, 2007). Arnell (1999) predicted a reduction in runoff of 26 to 40% in the Zambezi river system, as a result of reduced rainfall and increased evaporation. Evaporative increases of 40%, for example, could result in reduced outflows from reservoirs. Additionally, the projected increased frequency of droughts will most likely increase the frequency of low storage episodes (see e.g. Desanker and Magadza, 2001), which will inevitably affect for example, future hydro power generation from such dams as the Kariba and Cabora Bassa (Yamba et al., 2011). Cambula (1999) (cited in Desanker and Magadza, 2001) in his work on the Zambezi basin in Mozambique, for example, showed a decrease in surface and subsurface runoff of about 40% or more under climate change. Yamba et al., 2011) further showed that under climate change, the hydroelectric power generation potential for the Zambezi Basin will be gradually reduced for existing and proposed hydroelectric power schemes owing to increased frequency of droughts (reducing run-off and hence reservoir storage capacity).

The general conclusion from most studies is that streamflow is projected to decrease by 2050. For example, Matondo (2012) projected that for Swaziland streamflow will decrease by up to 40%; Beck and Bernauer (2011) projected a decrease of up to 20% for the Zambesi catchment; Andersson et al. (2010) (and Losjö et al., 2007), up to 75% decrease for the Pungwe catchment; Zhu and Ringler (2010), up to 35% decrease for the Limpopo catchment; Graham et al. (2011), up to 18% decrease for Thukela catchment, South Africa; Andersson et al. (2006), up to 20% decrease for the Okavango in Botswana; Arnell (1999), up to 45% decrease for the Zambezi, Limpopo, Ruvhuma and Orange catchments; Mazvimavi (1998), up to 50% decrease for the Gwayi, Odzi and Sebakwe catchments in Zimbabwe. However, some catchments were projected to experience increases in streamflow like parts of the Thukela catchment in South Africa (Graham et al., 2011; Andersson et al., 2009) of between 16 - 38%. Also some catchments in Swaziland were projected to have increased streamflow of between 5-34% as modelled by Matondo (2012); Mhlanga et al. (2012) and Matondo et al. (2004).

From the above studies, there is still no consens on the magnitude of decrease or increase of streamflow, although most studies conclude that streamflow will decrease. To reduce such uncertainity, more information can be derived from the use of downscaled GCMs and subsequently, distributed hydrological models especially on modelling streamflow changes under climate change. Additionally, use of an essemblege of climate models is likely to improve projected streamflow changes for southern Africa.

5. Discussion: Challenges in modelling climate change impacts on water resources

Many challenges encountered in climate change modelling are detailed in the literature. The following sections describe some of the possible challenges in modelling the impacts of climate change on water resources in southern Africa.

5.1 Use of emission scenarios in climate change modelling

Tadross et al. (2011) pointed out that although circulation models can reliably and skilfully project changes in temperature, these models are often less-skilled in translating that information into changes in rainfall (and other parameters) at the local scale. Rainfall is, however, the main driver for hydrological modelling (Hughes, 2004; Schulze, 1995; Jewitt and Schulze, 1999). This implies that hydrological models used for climate change impacts analysis also inherit the uncertainties from climate models. Other sources of uncertainty in climate change modelling include: choice of climate models, quality of historical data, methods of downscaling and boundary uncertainty (Hewitson and Tadross, 2011). Considering all the other possible sources of uncertainty, the output from climate models will therefore suffer from compounded uncertainty. For southern Africa, while it has always been recognized that uncertainty exists it has not been properly quantified, nor consistently included as part of the risk in decision making in water resources management.

5.2 Skills limitations

Mazvimavi (2011) also pointed out that southern Africa lacks skills, for developing and implementing effective responses to climate change, and for timely dissemination of relevant information to land and water users. Mouton et al. (2010) reported that scientific research is mainly confirmed to South Africa in southern Africa, with limited research and publication elsewhere.

5.3 Climate modelling and downscaling constraints

Global climate model projections are considered as the most advanced tools for projecting future climate change scenarios and have been extensively used in the study of climate change; however, they operate on a coarse spatial resolution. In response to this, downscaling methods have improved substantially, with regional downscaling having been undertaken for southern Africa.

According to Hulme et al. (2001) and Nikulin et al. (2012) downscaling of GCM outputs to finer spatial and temporal scales has, however, received relatively little attention in Africa, despite the widespread use of downscaled outputs in other parts of the world. The Coordinated Regional Downscaling Experiment (CORDEX) program, established by the World Climate Research Program (WCRP) was a direct response to the need of downscaled products in climate modelling (Jones et al., 2011). CORDEX-Africa is aimed at developing a coordinated framework for generating improved regional climate change projections, as well as to meet the growing demand for high-resolution downscaled projections to inform climate change impact and adaptation studies (Jones et al., 2011; Nikulin et al., 2012). Thus downscaling for southern Africa facilitates analysis of climate change at the scale at which water resources are managed since Regional Climate Models have achieved spatial resolution of 10km^2 to 50km^2(Tadross et al., 2011; Nikulin et al., 2012).

Although, the use of downscaled RCM reduces the spatial scale, Wilby et al. (1999) cautioned that different circulation schemes and downscaling methodologies yield noticeably different regional climate change scenarios, even when common sets of RCM outputs are used. For example Nikulin et al. (2012) noted that projections in precipitation have larger uncertainties compared to the temperature ones particularly for annual and diurnal cycles of precipitation. Consequently, impacts of climate change on water resources, particularly hydrological responses under such uncertainty are still to be evaluated for southern Africa.

5.4 Rainfall runoff modelling and climate change

Most of the basins in the southern Africa are classified as poorly gauged due to the rather low and unevenly distributed hydro-meteorological stations (Nikulin et al., 2012; Mazvimavi, 2003; Saunyama, 2008). Within this data scarce region, water resources planning and management decisions are frequently based on simulated information using hydrological models. The most widely used hydrological models are the (a) Pitman model, which is a conceptual, semi-distributed monthly time-step model (Hughes, 2004; Hughes et al., 2006), developed by Pitman in 1973, and (b) The ACRU model, developed by Schulze (and Smithers) (Schulze, 2005; Smithers and Schulze, 1995) which is a physical conceptual model capable of daily time step modelling.

Rainfall-runoff hydrological models have been used widely for estimating available water resources or assessing impacts of development needs or climate change. Still, as mentioned earlier, both hydrological models and regional climate models are simplified representations of reality which are frequently based on inadequate input data and uncertainties in parameter values and poor mathematical representation of processes. This makes both climate and hydrological models subject to predictive uncertainty. Renard et al. (2010) summarises the main sources of predictive uncertainty as: (a) data (e.g. spatial representation and measurements of input and output time-series), (b) model (e.g. process descriptions and mathematical implementation), and (c) the modelling approach (e.g. the method chosen for parameter estimation). An important science question that now arises is how predictive uncertainty can be acknowledged, quantified and ultimately reduced for climate change modelling as well as for hydrological modelling? Evaluation of uncertainty is necessitated by the need to give an accurate and/or optimum basis for decision making regarding future hydrological responses under climate change. To date compounded uncertainty from use of downscaled climate data and of hydrological models in climate change impact analysis has not been evaluated for southern Africa, despite the clear need to ascertain, acknowledge and quantify such uncertainty.

6. Conclusion

The potential wide ranging impacts of climate change on water resources (availability, accessibility and demand) as reviewed above make a compelling case for the need to strengthen integrated water resources management institutions in respective southern Africa countries since decisions for water resources planning and management (including aspects of climate change impacts) are made within such structures. At catchment level it is then possible to make maximum use of current and future advances in the fields of geographical information systems, remote sensing, information management, and computer science in evaluating climate change impacts on water resources.

Incorporation of climate change information should be done even at regional level through such structures as the SADC protocol on shared water courses, as the region has 12 shared river basins (namely: Zambezi, Limpopo, Orange, Pungwe, Inkomati, Okavango, Ruvuma, Buzi, Kunene, Save and Usutu basins). Given such linkages, the projected reduction in the stream flow for the Zambezi basin, for example, will inevitably affect all the eight SADC riparian states (home to over 40 million people) in terms of water availability (e.g. for irrigation or hydroelectric power generation), wetlands, agriculture (Thornton et al., 2009), and tourism (Beck and Bernauer, 2011). It thus become imperative to enable collaborative regional training and research that critically evaluates the potential impacts of climate change on water resources in different southern Africa hydro-climatic regions so as to inform policy and improve adaptation measures.

Whilst most of the studies reviewed above looked at the potential impacts of climate change on water resources, it is argued here that the focus of the studies were mostly sub-regional and country level, and relying mostly on use and interpretation of GCM projections and only until recently, few studies using downscaled RCMs. As such this makes for a compelling case for catchment level studies in southern Africa since water resources management decisions are undertaken at catchment level. Such research should therefore focus on the following: (a) improving use of downscaled climate change information for input into hydrological modelling, (b) refining use of earth observation and in situ data to increase understanding and improve prediction of climate change, (c) improving the utility of available model outputs by acknowledging and quantifying compounded predictive uncertainty.

Addressing the above research issues will ultimately help address problem areas related to a number of climate and hydrological modelling issues discussed above, including parameter estimation, temporal and spatial scale of application, validation, climate-scenario generation, data, and modelling tools. Solutions to these problems would significantly improve the capability of models to assess the effects of climate change on water resources in southern Africa; hence water resources evaluation and management under a changing climate.

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