Climate change impact on water availability in the Olifants catchment (South Africa) with potential adaptation strategies

Mary Funke Olabanji [1], Thando Ndarana[1], Nerhene Davis[1] and Emma Archer[2]

[1] Department of Geography, Geo-informatics and Meteorology, University of Pretoria, South Africa.

[2] Centre for Environmental Studies/Department of Geography, Geo-informatics and Meteorology, University of Pretoria, South Africa.

Correspondence: u18098267@tuks.co.za

Abstract

Increasing population and economic growth has intensified water supply pressure on the Olifants River Basin causing it to become water-stressed. Climate change is expected to aggravate existing water supply challenges in the basin if urgent interventions are not implemented. This study evaluates the impacts of climate change on water availability and demand in the Olifants River Basin of South Africa, and assesses to what extent a combination of management strategies can mitigate current and longer term impacts using the Water Evaluation and Planning (WEAP) model. The results demonstrated by the two projected climate change scenarios (RCP4.5 and RCP8.5) showed a rise in temperature of approximately 1℃ to 4℃, and a decrease in precipitation of 5% to 30%, as compared to the baseline climate of 1976-2005. Results also showed that pressure on water supply due to increased economic activities and a decline in streamflow will increase unmet water demand by 58% and 80% for the mid and end century periods respectively. Results further revealed that the combination of management measures proposed by decision makers is expected to decrease future unmet water demand from 1006MCM to 398MCM, 1205MCM to 872MCM and 1251MCM to 940MCM

for reference, RCP4.5 and RCP 8.5 scenario respectively. The study therefore concludes that the combination of management strategies provides a much better and more efficient solution to water scarcity issues in the basin, compared to a reliance on a single strategy.

1. Introduction

Population growth and modern industrialization are the main contributors to increased greenhouse gas (GHG) emission, which is considered to be the major cause of global climate change (Wu et al. 2019). The Intergovernmental Panel on Climate Change (IPCC) in 2018 projected an increase in global temperature of 1.5°C above pre-industrial levels because of increasing GHG emissions (First, 2018). This predicted increase is expected to result in detrimental climate related risks for both the natural and human systems. These risks depend, however, on the extent of warming, geographical setting, levels of development and vulnerability, as well as on the adoption and implementation of adaptation and mitigation choices (First, 2018). There is considerable evidence that climate change will negatively impact river basins and regions (IPCC 2007), particularly in Africa. According to Niang et al. (2014) the African region is most vulnerable to the impact of climate change due to its high exposure and poor adaptive capacity.

Changes in South Africa's climate will lead to variation in rainfall patterns, increased intensity of floods and drought, the alteration of hydrological cycles and challenges in crop production (Mantel, 2015; Serdeczny et al. 2017). According to Kusangaya et al. (2013) atmospheric variables such as rainfall and temperature are widely used to determine climate change. To detect climate change impacts on the hydrological cycle of catchments, a paired approach which combines the use of rainfall-runoff models, generalized likelihood uncertainty estimation methods and GLS regression change detection are used (Eslamian et al. 2010).

The magnitude of the threat posed by climate change are highly uncertain and can significantly alter the availability of water resources thus exacerbating existing water related stress that could end up restraining development (Kusangaya et al. 2013). South Africa is a water scarce country, characterised by the descending branch of the hardly cell (Mahlobo et al. 2019), which makes the country most vulnerable to the vagaries of climate risk. Projections for South Africa's climate shows a substantial increase in temperature and a reduction in precipitation (Mukheibir, 2008). Such changes are expected to lead to an increased intensity and frequency of droughts. In 2000, all of South Africa's Water Management Areas (WMA) which includes Olifants, Nkomati, Thukela, Movoti and Gouritz experienced severe water stress (ASSAf, 2017), with the Olifants River Basin identified as the most stressed basin in terms of water quantity and quality (WFF-SA, 2016).

The impacts of climate change on the availability of water in the Olifants catchment is therefore of particular concern. In tandem with the climate change related considerations, an increase in population and related economic activities will further intensify the water supply demands on the catchments which could result in severe water scarcity issues. The uncertainty in future water availability caused by climate change will ultimately be a significant threat to water and food security. It is therefore imperative to implement suitable and sustainable adaptation measures that will mitigate the impacts of climate change and improve the capability of the catchment to meet future water demands.

Several studies have been undertaken to assess the impact of climate change in the Olifants catchment. For instance, a study by Singh et al. (2014) focused on the hydrological impacts of climate change in gauged and ungauged stations in the catchment, confirming possible decreases in runoffs arising from increasing temperature and declining precipitation. Also, a study by Cullis et al. (2011), assessed the impacts of projected climate change on water resource planning. Other studies (McCartney and Arranz, 2007; Arranz and McCartney, 2007), evaluated water management strategies under different socio-economic conditions and its' related impacts on current and future water demand. Wagener et al. (2010), evaluated the credibility of hydrologic models in capturing the impacts of climate change in the Olifants catchment. Their findings suggest that these models are often unable to capture the full extent of hydrologic changes due to a lack of stream flow gauges. This results is inadequate for the calibration of watershed models which increases the uncertainty in model predictions (Wagener, et al. 2010). A study undertaken by Rasiuba (2007), evaluated rainwater harvesting as an adaptive measure to improve water use efficiency and increase agricultural production in the Olifants River Basin. Nkhonjera et al. (2020) used the Soil and Water Assessment (SWAT) model to investigate the variability of local precipitation in the upper middle Olifants River Basin and found a wide monthly and seasonal variability of precipitation. The results further present a decreasing trend in spatial precipitation. Another study by Talukder (2019) assessed the impact of climate change on the Olifants catchment, the result of this study showed an increase in temperature of 1℃ to 4.6℃ and a decrease in future precipitation.

To date, the studies undertaken in the Olifants catchment mostly tend to focus on the hydrological response of the catchment to climate change. Limited attention has been directed towards exploring adaptation strategies that could be deployed to mitigate climate change related impacts on the water resources. This paper therefore aims to assess the impact of climate change on water availability and demand as well as to evaluate the extent to which a range of adaptation strategies can be used to reduce the potential impacts in the Olifants catchment, using the Water Evaluation and Planning (WEAP) model. Assessing the impacts of different adaptation strategies on water availability in the context of a changing climate is essential to provide water managers with the right information on the most suitable adaptation measures to be adopted in order to sustain both current and future water availability. The specific objectives this paper seeks to address are; (1) to evaluate climate change impacts on the hydrological process of Olifants catchment (2) to assess current and future climate change impacts on water supply and demand and lastly (3) to simulate the behaviour of demand and supply under different plausible adaptation scenarios in the context of current and future climate change.

The results generated from this study are intended to guide policy makers and water managers towards the development of appropriate adaptation strategies that will minimize the risks associated with long-term changes in climate, and enhance the sustainability of water resources in the Olifants River Basin.

2. Materials and Methods

2.1 Study area and Data

The Olifants River Basin is a major tributary of the Limpopo River (Nkhonjera, 2017). It flows through the east of Johannesburg, in the province of Gauteng, to the province of Mpumalanga and Limpopo, before passing through Mozambique, and reaching the Indian Ocean (Figure 1). Rainfall in the catchment occurs during the summer months from October to April, with average annual rainfall ranging between 500 to 800mm in most parts of the Olifants catchment and surpasses 1,000mm along the escarpment (McCartney et al. 2004). Evaporation varies across the catchment with high values occurring in the north and west, and low values occurring in the south east. Elevations range from 300m to over 2300m above sea level - explaining the relatively cool winter and annual wide-range of temperature variation, which ranges from -4 to 45°C.

The basin has a total area of 54,475km^2 and a population size of approximately 3.2 million, with two-thirds of the population living in the rural communities (Magagula et al. 2006). The two major urban centres in the catchment are Emalahleni and Middleburg. Activities within the catchment such as mining, industry and agriculture are largely reliant on water resources, and contribute about six percent of South Africa's GDP (McCartney and Arranz, 2007). There are large imbalances in the domestic and industrial use of water resources in areas that were formerly branded as "homelands" by the apartheid regime, as compared to the rest of the catchment (Cullis and Van Koppen, 2007; Van Vuuren et al. 2003). Currently, efforts are being made to increase domestic water supply in many areas of the catchment by the Department of Water and Sanitation (McCartney et al. 2004).

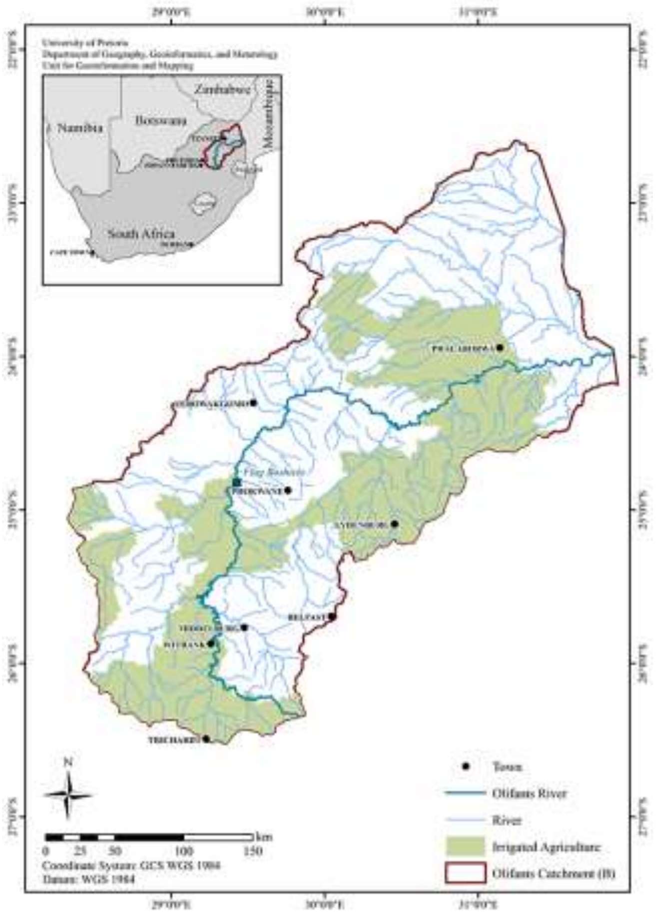


Figure 1. Map of the Olifants River Basin, showing the major rivers, and towns

For this study, a reconciliation strategy report published by the Department of Water Affairs were consulted to identify factors influencing water demand trends in the Olifants catchment (Comrie, 2011). The report indicated that an increase in domestic water use is expected in the next thirty years. This increase is anticipated due to an uninterrupted growth in population, improved standard of living and improvement in service delivery to rural communities. Agricultural water demand was anticipated to remain constant in the next thirty years, because a moratorium has been placed on the issuing of new irrigation licenses due to water stress in the catchment. Nevertheless, some growth in water demand in the catchment for mining use is expected, as a result of an increase in the price of platinum (Comrie, 2011). The authors of the reconciliation strategy report assume a population growth of 2.4% and an economic growth of 1.2% which was also the assumptions adopted for the analysis in this study.

To analyse climate change impact on water availability and demand in the Olifants catchment, observed streamflow data were obtained from the Department of Water and Sanitation (DWS) and used to calibrate and validate the WEAP model. Demographic data such as population and water demand for four sectors (urban, rural, irrigation and mining) were also obtained from DWS. Meteorological data were obtained from the South African Weather Service (SAWS) and from the Co-ordinated Regional Downscaling Experiment-Regional Climate Model (CORDEX-RCMs) website (https://esgf-index1.ceda.ac.uk/search/esgf-ceda). CORDEX data is dynamically downscaled from General Circulation Models (GCMs), which have coarse resolutions that are inadequate for regional impact studies. The downscaled CORDEX_RCMs operates over an equatorial domain with a quasi-uniform resolution of approximately 50km by 50km. Climate models simulate atmospheric variables at grid points, since the partial differential equations that describe the evolution of the climate system may only be solved using numerical methods. This necessitates the interpolation of the variables to the stations' points of interest, using inverse square distance from the immediate grid points surrounding the station serving as the weight (Ly et al. 2011).

Two Representative Concentration Pathways (RCP4.5) and (RCP 8.5) GHG scenarios for the period 2006-2100 were used. RCP 4.5 scenario assumes a stabilization of radioactive forcing by 2100, without surpassing 4.5W/m2 (~650ppm CO_2) – which constitutes a high mitigation scenario (Amin et al. 2018). Whilst the RCP 8.5 scenario assumes a high concentration of GHG emission in the absence of any climate change policies, thereby increasing radioactive forcing pathway of 8.5W/m2 (~1370ppm CO_2) by 2100 (Riahi et al. 2007).

Interpolated monthly climate variables from six GCMs-driven RCM (Table 1) were bias corrected with the observed climate data obtained from SAWS using the linear scaling bias correction method.

It was necessary to bias correct the ensemble GCMs driven RCM data, as they may contain biases that prevent an appropriate reproduction of the observed hydrological conditions from the simulations (Wood et al. 2004). The linear scaling bias correction is based on the average difference between monthly observed time series data. These differences were then applied to the simulated climate data to obtain bias corrected variables (Shrestha, 2015). The bias corrected climate data were then inputted into the WEAP hydrological model to evaluate water availability, demand and adaptation strategies.

Table 1. Global Climate Models (GCMs) used to drive the Regional Climate Models (RCMs) in the CORDEX Africa.

Model	**Short Name**	**Institution**	**Reference**
CCCma CanESM2	CanESM2	Canadian Centre for Climate Modeling and Analysis	Arora et al. (2011)
CNRM CERFACS CNRM-CMS	CNRM-CMS	Centre National de Recherches Meteorologiques, France	Voldoire et al. (2013)
CSIRO QCCCE Mk3.6.0	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial	Jeffrey et al. (2013)
IPSL-CM5A-MR	IPSL-CM5A	Institut Pierre-Simon Laplace, France	Hourdin et al. (2013)
MIROCv5	MIROC5	University of Tokyo, Japan	Watanabe et al. (2010)
MPI MPI-ESM-LR	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)	Giorgetta et al. (2013)

2.2 Description of WEAP Hydrological Model

In order to achieve the stated objectives of this study, a number of hydrological models that has been applied to study hydrological response to climate change in other catchments of South

Africa was assessed to determine their suitability in this study. Models such as the Soil and water assessment tool (SWAT), Pitman hydrological model and SPATSM was ruled out as unsuitable, partly because a multi-disciplinary approach was needed to achieve the stated objectives of this study. The WEAP hydrological model allows the integration of municipal, industrial and agricultural water use whilst taking into consideration demand priorities, supply preference and socio-economic issues of the Olifants river system and linking them to the natural and hydrological process of the catchment. The WEAP hydrological model developed by the Stockholm Environment Institute (SEI) was therefore considered to be the most suitable hydrological model for this study. The applications of WEAP hydrological model globally (Rochdane et al. 2012; Leong and Lai, 2017) and in South Africa (Arranz 2006; Arranz and McCartney, 2007; Hajj, 2011) also presented us with some level of confidence about its validity.

The water evaluation and planning (WEAP) model was used in this study to integrate climate change scenarios and hydrological process alongside other factors such as population growth, economic expansion and policies on current and future water availability and demand in the Olifants catchment. The model operates on the basic principle of water balance, and it is capable of addressing a wide range of problems' arising from sectoral demand analyses, water rights and allocation priorities, reservoir operations, water conservation, streamflow simulations, ecosystem requirements, and project cost-benefit analyses (Sieber and Purkey, 2011). For analytic purposes, the modelling system is represented by its various sources of supply such as rivers, groundwater, reservoirs, withdrawal, transmission and wastewater treatment facilities, ecosystem requirements and water demands. The model also provides a graphic representation or digital visualisation of the physical features in the catchment for simulation.

The development and application of WEAP model involve the following steps. The *study definition* which sets up the time frame, spatial boundary, system components and configuration of the problem. The *Current Accounts tool*, provide a snapshot of actual water demand, pollution load, resources and supplies for the system for the current or a baseline year. S*cenarios* are built on the *Current Accounts* to allow the exploration of the impact of alternative assumptions or policies on future water availability and use, and are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables (SEI, 2005).

The model was calibrated and validated using observed streamflow data obtained from the Olifants River gauge stations. The period 1996 to 2002 was used for the calibration process, while 2003-2005 was selected for validation. Calibration involves changing the parameters of the model to provide a better simulation of the projected scenarios. This was done by altering demand priorities to increase the fit between observed and simulated flows. The WEAP does not calibrate the hydrological model automatically, therefore, calibration and validation were done manually.

The efficiency of the model performance was determined by comparing the observed against the simulated flow using three verification statistics such as Coefficient of Determination (R^2), Nash-Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS).

The *Coefficient of Determination* (denoted by R^2 or r^2) measures the degree of collinearity between measured and simulated data (Leong and Lai, 2017). Values of R^2 ranges from 0 to 1, with higher values signifying lesser error variance. The formula for calculating R^2 is expressed below:

$$R^2 = \frac{\sum_{i=1}^{n}\left(Y_i^{sim} - \overline{Y}^{sim}\right)\left(Y_i^{obs} - \overline{Y}^{obs}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - \overline{Y}^{sim}\right)^2} \sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)^2} \quad (1)$$

Where, Y_i^{sim} is the simulated streamflow, Y_i^{obs} is the observed streamflow, $\overline{Y}^{sim}$ is the mean of simulated streamflow, and $\overline{Y}^{obs}$ is the mean of observed streamflow.

The *Nash-Sutcliffe Efficiency (NSE)* is used to evaluate the hydrological models predictive capability. NSE value ranges between −∞ and 1.0 (1 inclusive), where NSE = 1 indicate a perfect match of simulated flow to the observed flow (Nash and Sutcliffe, 1970). An efficiency of 0 (NSE =0) shows that the model predictions are as accurate as the mean of the observed data, an efficiency less than zero (NSE<0) shows that the observed mean is a better predictor than the model (Nash and Sutcliffe, 1970). NSE is computed as shown below:

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)^2} \qquad (2)$$

Where Y_i^{sim}: is the simulated streamflow, Y_i^{obs}: is the observed streamflow and $\overline{Y}^{obs}$: is the mean of observed streamflow

Percent Bias (PBIAS) measures the tendency of the simulated data to either be greater or lesser than their observed counterparts (Gupta et al., 1999). The ideal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation, while Positive values indicates model underestimation bias, and negative values indicates model overestimation bias (Gupta et al. 1999). PBIAS is calculated as shown below:

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * (100)}{\sum_{i=1}^{n} Y_i^{obs}} \qquad (3)$$

Where Y_i^{sim}: is the simulated streamflow and Y_i^{obs}: is the observed streamflow

2.3 Experimental Design

Three experiments were conducted to evaluate climate change impact on water availability and demand in the Olifants Basin (Figure 2).

These experiments were:

Experiment 1, which is the control experiment (Reference scenario), assumes that the present condition of climate will continue into the future, hence present climate conditions are projected to remain constant into the future.

Experiment 2, which is the RCP4.5 scenario, describes climate with moderate concentration of greenhouse gas emissions.

Experiment 3, presents the RCP8.5 scenario, which describes climate with high concentration of greenhouse gas emissions.

The RCP4.5 and RCP8.5 climate change scenario results were then compared against the current climate condition (reference scenario). After evaluating the impact of this change on water availability and demand, as a result of the changing GHG concentrations, we assessed different adaptation strategies under each experiment to determine the extent to which a range of intervention measures can mitigate the impact of the current and projected climate change.

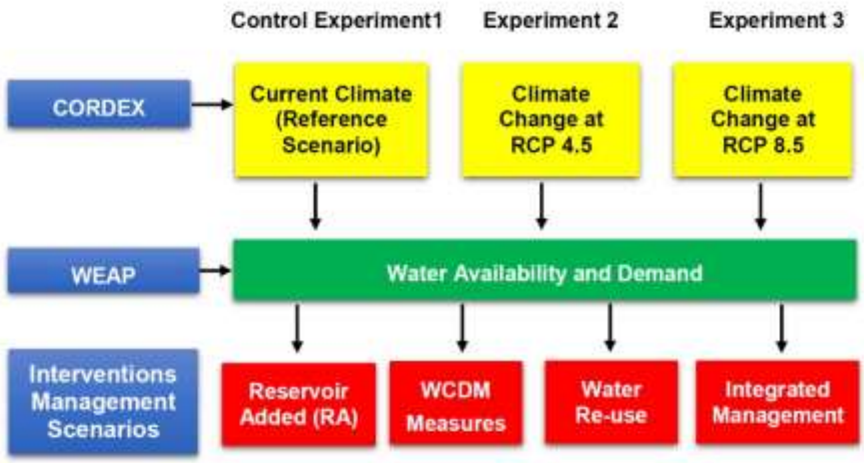


Figure 2. A workflow of WEAP model setup

The management strategies proposed in the reconciliation strategy report for the Olifants River Basin (Comrie, 2011) were used to inform this part of the analysis. More specifically, this study evaluated three management strategies obtained from the reconciliation report. The three proposed intervention strategies evaluated in this study included:

Construction of a new reservoir: This strategy assumes the construction of an additional reservoir with a storage capacity of 159 Million Cubic Meter (MCM) to augment existing water supply.

Water Conservation and Demand Management Strategy (WCDM): The implementation of water saving strategies by 2030 was assumed in this strategy, with 15% saving expected from agriculture, 10% from urban use, 5% from rural and 5% from the mining sector. This saving was assumed to be achievable by using water efficiency devices, improved conveyances (i.e. Reducing canals/pipe leaks) and improved management through metering and billing.

Water re-use Strategy: This strategy requires the reclamation of treated Acid Mine Decant (AMD) as well as the re-use of treated wastewater for domestic use. In terms of this approach, 40% of the water use is expected to be reused by 2035 which will then reduce the pressure on the water supply system.

A fourth scenario was also anticipated which involved the integration of all three adaptation strategies: The fourth scenario thus took into account conditions where the reservoir was added in tandem with water conservation and demand management; and water re-use strategies.

However, before integrating the climate data into the WEAP model to assess water availability, demand and management strategies, seasonal and annual rainfall and temperature for the projected climate change of RCP4.5 and RCP8.5 for the period of 2010-2039 (Early-century), 2040-2069 (Mid-century) and 2070-2099 (End-of-the-century) were analysed from the baseline 1976-2005.

3. Results

3.1 Analysis of climate change

The result obtained from the analysis of projected climate change in this study is similar to predictions made in the Fifth Assessment Report of IPCC 2013 (Hartmann et al. 2013). Using the data sourced from CODEX, our calculation of future climate anomalies for 2010-2039, 2040-3069, 2070-2099 relative to current climate 1976-2005 for both temperature and precipitation showed an increase in temperature and a reduction in precipitation. With respect to the increase in mean temperature, model predictions show it may reach 1℃, 2℃, and 4℃ during 2010-2039, 2040-2069 and 2070-2099 respectively in the Olifants catchment as presented in Figure 3.

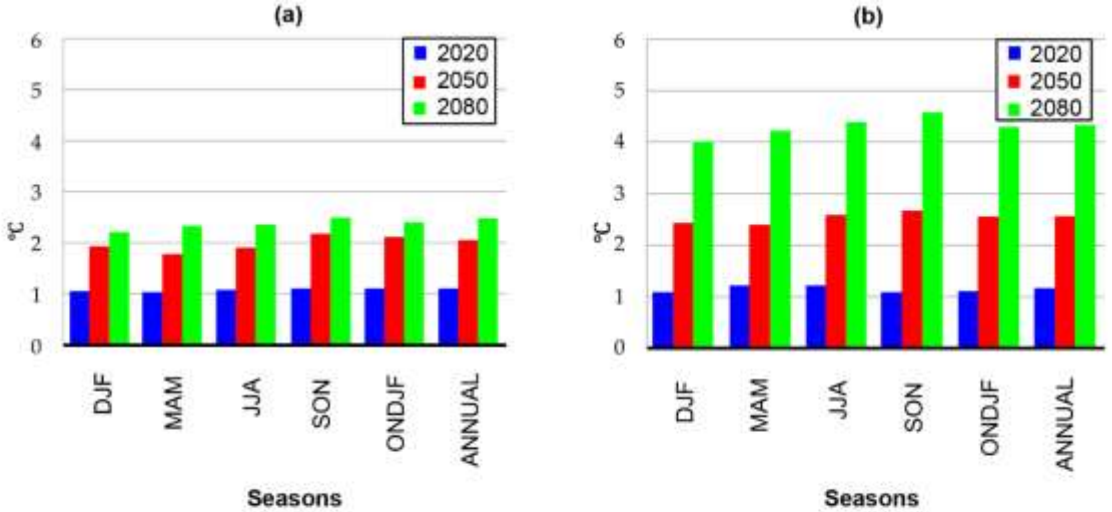


Figure 3. Seasonal and annual mean temperature (℃) anomalies for the three future time slabs 2020, 2050 and 2080 relative to baseline climate 1976-2005 for: (a) RCP4.5 (b) RCP8.5 emission scenarios in the Olifants catchment

Precipitation is projected to decrease by 5-10% during 2010-2039, 10-20% during 2040-2099 and by 20-30% at the end century (i.e. 2070-2099). A progressive decrease in seasonal and annual precipitation is observed in RCP8.5, while RCP4.5 revealed a more prominent decrease in precipitation during the mid-century followed by a slight increase in precipitation towards the end of the century as shown in Figure 4. Importantly, both RCP 4.5 and RCP 8.5 scenarios anticipates a decline in precipitation for the already water-stressed catchment area, thus necessitating early adaptation and intervention.

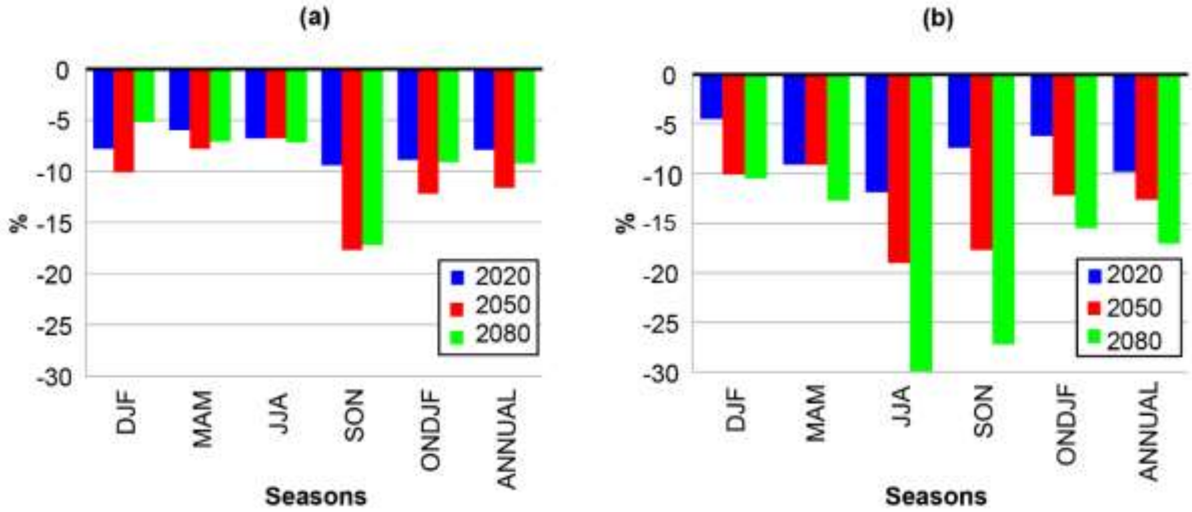


Figure 4. Percentage change in the level of cumulative seasonal and annual rainfall for the three future time slab 2020. 2050 and 2080 relative to baseline climate 1976-2005 for: (a) RCP4.5 (b) RCP8.5 emission scenarios in the Olifants catchment

3.2 WEAP Model performance

The WEAP hydrological model was calibrated and validated with historical streamflow data in order to assess the model performance against observations. Details about the procedure and the statistical equation used for the calibration and validation of the WEAP model has already been discussed in the section above. The monthly streamflow recorded at the gauge stations located on the Olifants River were compared with simulated values obtained from the model for the period 1996-2002 for calibration, and 2003-2005 for validation. The result presented in Figure 5, shows that the simulated flows matches very closely with the observed values, with a NSE of 0.98 and Coefficient of determination R^2 =1.0 during calibration, NSE=0.81 and R^2=1.0 during validation.

The PBIAS was estimated as 11.7% during calibration and 13.2% during validation. The qualitative and quantitative agreement between the simulated and observed streamflow indicates that the Olifants River Basin hydrology is represented accurately by the model, thus supporting the contention that future streamflow prediction may be accurately projected based on future climate change.

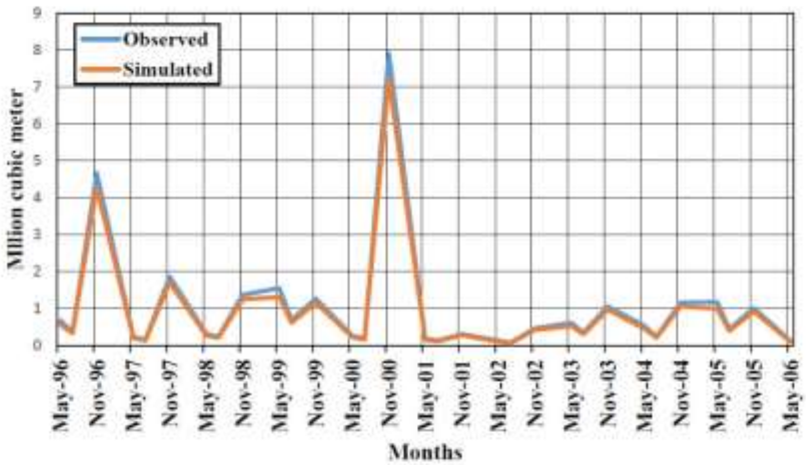


Figure 5. Calibration and validation of observed monthly streamflow along with simulated values for the Olifants River Basin

3.3 Hydrological Impact

The comparison of simulated annual streamflow for RCP4.5 and RCP8.5 scenarios relative to the Reference scenario of current climate (assumed to be constant) is presented in Figure 6. The results from the analysis shows that both RCP4.5 and RCP8.5 climate change scenarios led to decreased streamflow, with RCP8.5 showing a stronger decrease towards the end-of-the century. However, under RCP4.5, average annual streamflow declined by 8 percent (1712MCM) in 2020, 12 percent (1643MCM) in 2050 and 9 percent (1688MCM) in 2080. In the RCP8.5 scenario, average annual streamflow declines by 7 percent (1736MCM) in 2020, 13 percent (1625MCM) in 2050 and 17 percent (1542MCM) in 2080 against 1859MCM of reference scenario (current climate). The decrease in streamflow for the two climate change scenarios is therefore consistent with the reduction in precipitation as seen with these scenarios. The result obtained from this study is also similar to a recent study undertaken by Udall (2018), which shows that flow in the Olifants River will likely reduce due to the reduction in rainfall as the 21st century warms up. Thus, leading to a decrease in the amount of water available in the system.

\

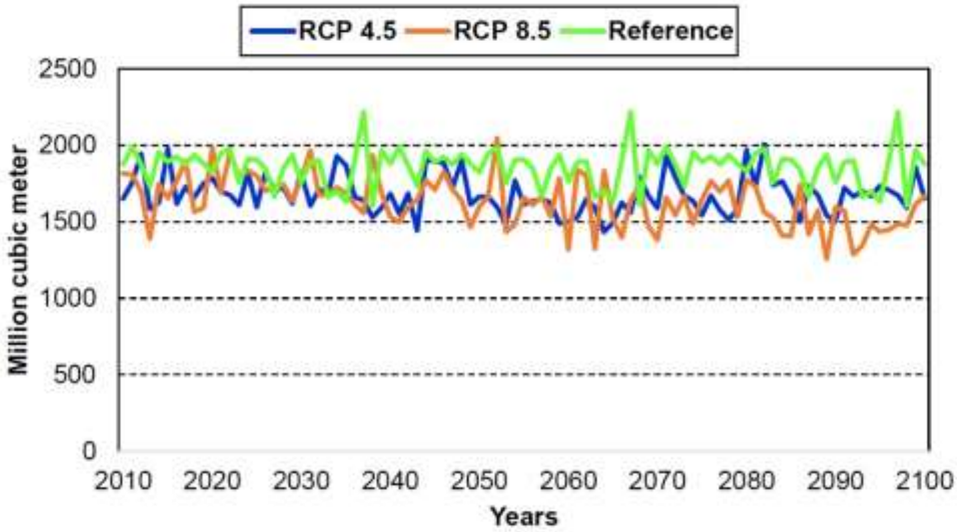
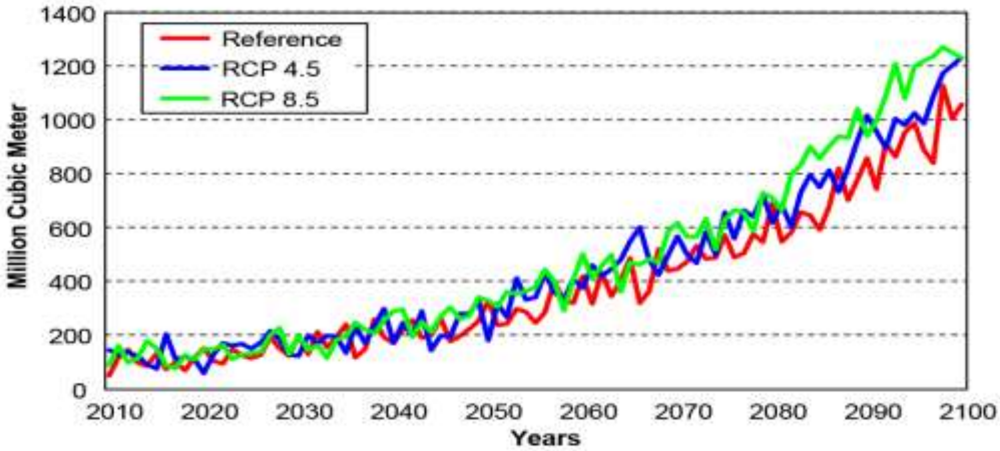


Figure 6. Comparison of average annual streamflow for RCP4.5 and RCP8.5 scenarios relative to the Reference (Current climate) scenario in the Olifants catchment

3.4 Analysis in the absence of Adaptation

We evaluated climate change impact on water supply and demand based on the assumption of increased population and economic growth without management strategies or interventions implemented. An increase in water demand was observed for the three climate change scenarios. The total annual unmet water demand for all the demand sites modelled in WEAP without adaptation strategies implemented, increased by 54%, and 80% for both mid-century (2050), and end-of-the century (2080), all calculated relative to the early term (2020). Comparing the total annual unmet water demand for both RCP 4.5 and RCP 8.5 climate change scenarios to the reference scenario (current climate) shows an increase of 12% and 18% of the total water demand, with RCP 8.5 exhibiting a more pronounced increase, as shown in Figure 7.



\

Figure 7. Annual unmet water demand for all demand sites in the Olifants catchment under the Reference, RCP4.5 and RCP8.5 scenarios without adaptation strategy

The agricultural sector consumes the largest amount of water in the basin, and will be the most significantly affected by the impact of climate change, as about 480 MCM (62% of the total water demand) was required for irrigation, 178 MCM (23%) for city water use, 86 MCM (11%) for mining and 29 MCM (4%) for rural water use, as illustrated in Figure 8.

The non-implementation of appropriate adaptation strategies will thus intensify the pressure on existing water resources, and significantly impact livelihoods security in the catchment.

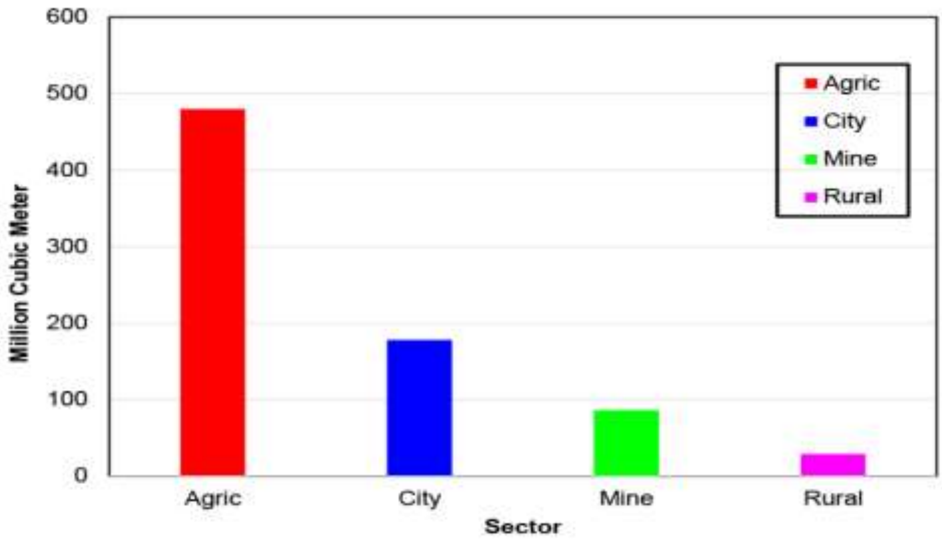


Figure 8. Water demand for all demand sites under 2005 baseline year

3.5 Analysis with Adaptation Strategies

The previous section showed that the reduction in rainfall as a result of climate change exacerbates unmet water demand. We now consider the ability of the water resources system to satisfy future water demand, given the changing climate as a constraint by evaluating water management strategies in terms of mitigating the anticipated impact of climate change. As mentioned earlier, four management strategies were considered separately, namely reservoir added, WCDM, water re-use strategy and the integration of the three adaptation strategies.

The result presented in Figure 9 shows that the average annual unmet water demand for reference scenario decreased from 1006 MCM to 847 MCM, 765 MCM, 723 MCM and 398 MCM. RCP4.5 scenario decreased from 1205 MCM to 1046 MCM, 927 MCM, 872 MCM and 497 MCM. While RCP8.5 scenario decreased from 1251 MCM to 1092 MCM, 940 MCM, 887 MCM, and 551 MCM by 2099.

A maximum water savings of 31,392 MCM was achieved with the adoption of the integrated management strategies from 2006-2100. The offset in water demand with the adoption of the three management strategies was greatest in the reference scenario of current climate as compared to the two projected climate change scenarios.

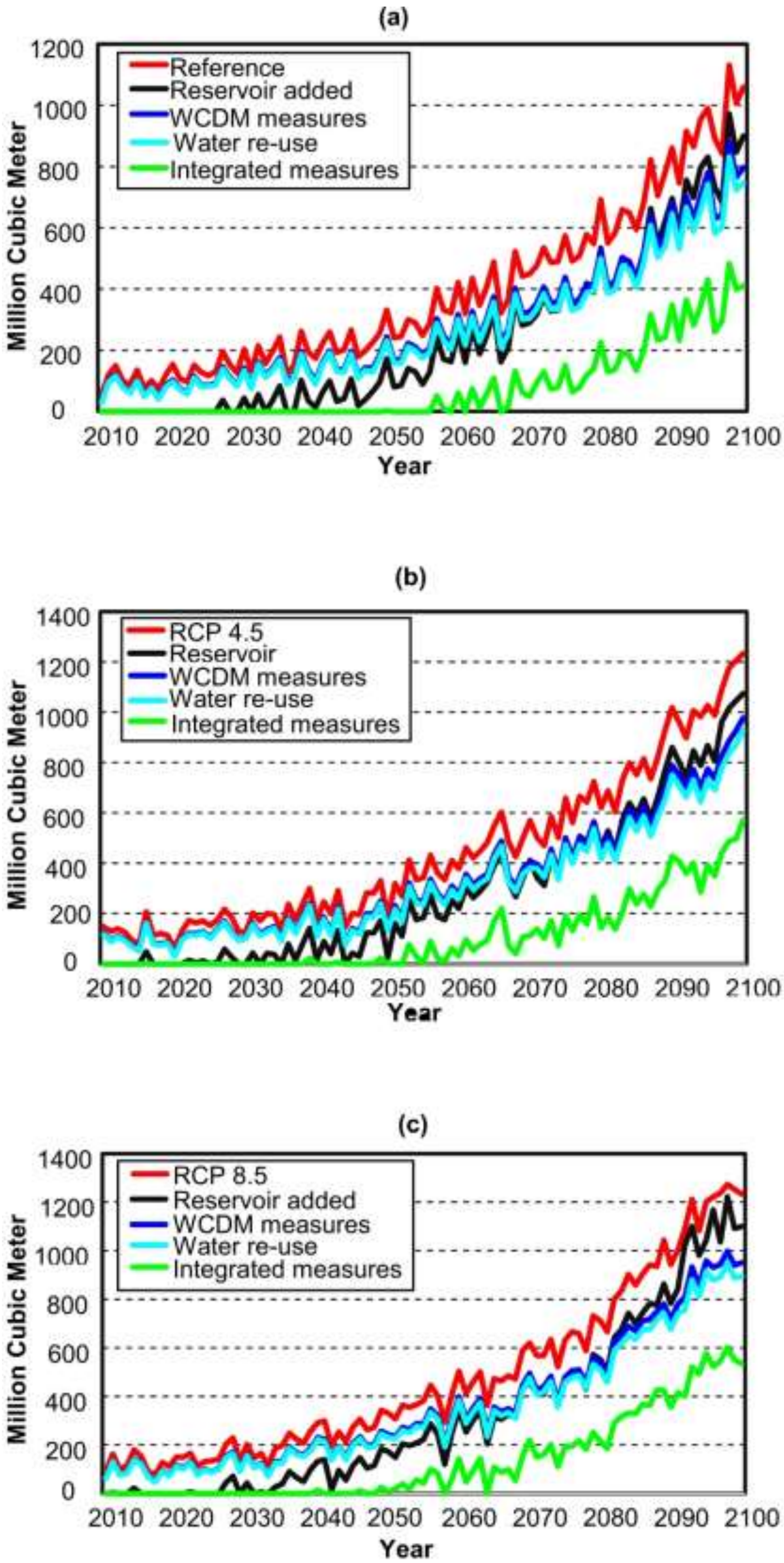


Figure 9. Changes in unmet water demand for all demand sites in the Olifants catchment under the: (a) Reference (b) RCP4.5 (c) RCP8.5 scenarios associated with adaptation strategies

The combination of the three adaptation strategies shows that the Olifants River Basin water supply will be able to satisfy water demand up until 2055, 2049 and 2040 for Reference, RCP4.5 and RCP8.5 Scenarios respectively, as shown in Figures 10. Thereafter, a steady increase in the unmet water demand was observed in the last decade of the study period - due to increased population and economic growth, as well as decreased inflow into the catchment resulting from climate change.

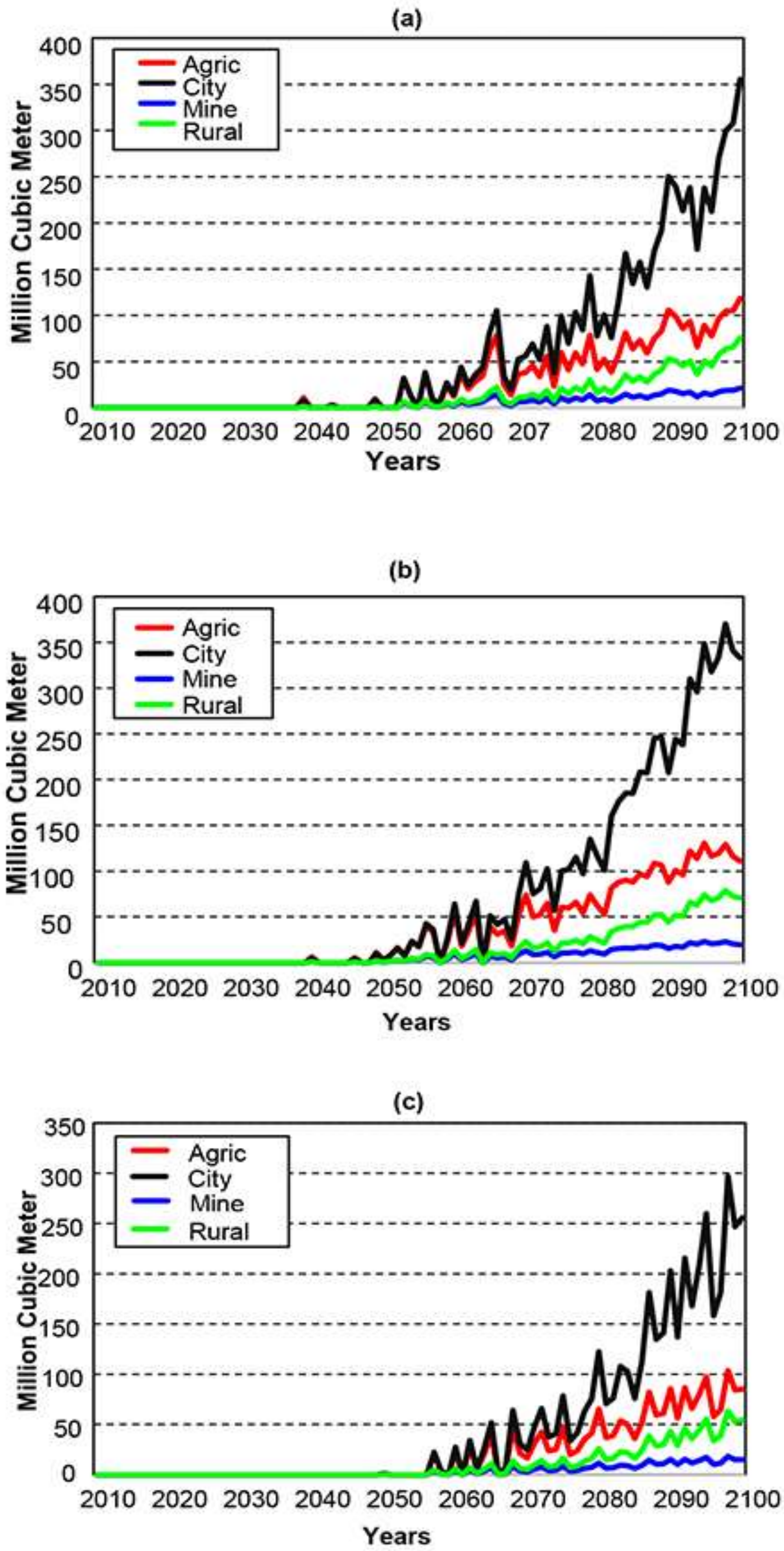


Figure 10. Unmet water demand under the integration of the three proposed adaptation strategies for: (a) Reference (b) RCP4.5 and (c) RCP8.5 scenario in the Olifants catchment

4. Discussion

This study assessed the impact of climate change on water availability, demand and supply in the Olifants catchment. The findings in this study reveals that climate change amongst other existing stressors such as population growth, economic expansion and policies issues will affect the availability of water in the catchment. In line with Arranz and McCartney's (2007) suggestion, we therefore propose that immediate action alongside adequate measures be taken in order to ensure the sustainability of existing and future water availability in the catchment.

The initial step in this study analysed the impact of climate change in the Olifants catchment, the result from the analysis showed that an increase in temperature trend of about 1-4℃ is anticipated for both RCP4.5 and RCP 8.5, and precipitation is expected to decline by 5-30% for both climate change scenarios. The results from this study aligns with the predictions of Cullis et al. (2011) and Hartmann et al. (2013) who also observed that changes in temperature and rainfall influences the availability of water in the catchment that will consequently affect the catchment's ability to meet water demand.

The study then further assessed the impact of climate change on water availability and demand, the results showed that water supply will not be able to meet future demands, as a result of decreased precipitation, coupled with increasing population and economic growth. An earlier study conducted by McCartney and Arranz (2007) found a similar trends comparing the linkages between these variables, thus supporting the findings in this study.

We also evaluated a range of management strategies to meet future water demand in the Olifants catchment taking different socio-economic factors and climate change scenarios into account.

The addition of reservoirs in the catchment proposed by decision makers to help reconcile water demand and resources was assessed, the result illustrated by this strategy shows that water supply will be sufficient to satisfy the demand in the catchment until the mid-century, while a shortfall in supply to all demand sites towards the end of the century will be experienced. This finding aligns with Arranz's (2006) study, which suggested that the construction of new reservoirs will sustain water demand in the catchment under current growth rate, and similar to our projection the findings from this study also predicts a shortfall in supply under medium and high growth rate.

The study then moved on to consider the feasibility of other management strategies that was proposed for the catchment. The implementation of water conservation and demand management (WCDM) strategies was found to be a promising approach, especially for an already water stressed catchment, as the strategy requires reducing water demand through the efficient use of water resources. Unmet water demand decreased by 16%, 13% and 12% for reference, RCP4.5 and RCP8.5 respectively. Similar findings was also noted in Leon and Lai (2017) study.

The adoption of water-reuse strategies will help in reducing over exploitation of freshwater in the system, and therefore increase the sustainability of existing water resources, though a shortfall exist towards satisfying future water demand as observed in the results.

The combination of the three proposed management strategies based on the outcome of our analysis provides a better and more efficient solution to water scarcity issues under the short-term climate change impact than the implementation of a single strategy. However, combining these management strategies does not provide a lasting solution to water crisis issues under the impacts of long-term climate change driven by socio-economic development. A steady increase in unmet water demand was observed towards the mid-century under the combination of management strategies. This finding of our study agrees with the 2011 reconciliation strategy projections which shows that water shortages will be experienced towards the mid-century in the Olifants catchment (Comrie 2011). The shortages in water supply aggravated by climate change will pose serious challenge for the agricultural sector, as irrigation consumes the largest amount of water in the catchment. More so, farmers who depend largely on rain-fed agriculture are considered most vulnerable to the impact of climate change, as decrease in precipitation coupled with a rise in temperature will reduce crop yield and consequently affect food security. We therefore suggest that government should provide farmers with clear information about projected changes based on up to date scientific evidences and possible impacts on their current agricultural practices, management strategies should also include effort to provide farmers with essential tools on how to make decision regarding their present and future practices, as well as organising trainings to educate farmers on the best approaches to be applied in curbing the impact of climate change.

5. Conclusion

This study investigated the impacts of climate change on water availability to satisfy current and future water demand in the Olifants catchment. The study went further to evaluate a range of adaptation strategies proposed by decision makers to offset anticipated impact of climate change on water resources. The WEAP hydrological model which was calibrated and validated by historical data, was used to simulate current and future climatic conditions from the dynamically downscaled CORDEX-RCM under two emission scenarios (RCP4.5 and RCP8.5). The results from the analysis showed that average annual unmet water demand in the region will increase dramatically in the coming decades, due to socio-economic development alongside changes in climatic condition. The evaluation of individual adaptation strategies did not yield a single concise solution. However, the model predicts that a combination of these strategies in the basin would provide decision makers with scope to reduce water scarcity implications due to climate change, in the short-term. With regard to longer terms predictions which includes growing pressure as a result of increasing economic activities and population, the model however reveals water demand and supply challenges in terms of longer term climate change impacts. Therefore, to ensure a balance between water supply and demand under long term climate change impacts coupled with pressures arising from socio-economic development, this study recommend the need for additional intervention measures to increase water supply and reduce current water use.

The application of WEAP hydrological model in this study have shown that the model is capable of characterizing water resources management under the impact of socio-economic development and climate change. A few limitations in relation to the use of the model is acknowledged. In this regard the calibration of catchment hydrology was conducted manually as the WEAP model could not perform the task automatically, since there are no optimization routine installed in the model. The major challenge associated with this technique is that, it takes a lot of time, during the configuration of each model run. It is therefore recommended that the developers of the WEAP model takes this limitation into consideration by providing a more suitable and time efficient approach to calibrating the model, in order to reduce the amount of time spent during configuration of more than one models. Finally, in terms of management of water resources in the Olifants catchment, the study concludes that a combination of adaptive strategies such as those evaluated in this study as well as other strategies which include the use of grey water, the installation of rainwater harvest tanks and integrated watershed management should be deployed in response to various climate change scenarios to ensure long term sustainability of the catchment and its ability to cope with current/predicted water demands.

Funding: This research was fully funded by the National Research foundation-The World Academy of Science (NRF-TWAS) Grant NO 110268.

Acknowledgement: Authors would like to acknowledge the South African weather service for the observed climate data provided in this study.

Conflict of Interest: Authors declares no conflict of interest.

References

Academy of Science of South Africa (ASSAf). 2017. First Biennial Report to Cabinet on the State of Climate Change: Science and Technology in South Africa. https://doi.org/10.17159/assaf.2016/0015.

Amin, A., Iqbal, J., Asghar, A., & Ribbe, L. 2018. Analysis of current and future water demands in the Upper Indus Basin under IPCC climate and socio-economic scenarios using a hydro-economic WEAP model. *Water*, 10(5), 537. https://doi.org/10.3390/w10050537

Arora, V. K., Scinocca, J. F., Boer, G. J., Christian, J. R., Denman, K. L., Flato, G. M., Merryfield, W. J. 2011. Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases. *Geophysical Research Letters,* 38(5). https://doi.org/10.1029/2010GL046270

Arranz, R. 2006. Future water demands and resources in the Olifants catchment, South Africa: A scenario analysis approach using the WEAP model. Masters of Science, Colorado State University, USA.

Arranz, R., & McCartney, M. P. 2007. Application of the Water Evaluation and Planning (WEAP) model to assess future water demands and resources in the Olifants Catchment, South Africa (Vol. 116). IWMI. http://www.iwmi.cgiar.org/Publications/Working_Papers/working/WOR116.pdf

Comrie, w. P. 2011. Development of a reconciliation strategy for the Olifants River water supply system. P wma 04/b50/00/8310/12. Accessed on 26 September 2018.

Cullis, J., Strzepek, K., Tadross, M., Sami, K., Havenga, B., Gildenhuys, B., & Smith, J. 2011. Incorporating climate change into water resources planning for the town of Polokwane, South Africa. *Climatic Change,* 108(3), 437-456.https://doi.org/10.1007/s10584-010-9891-9.

Cullis, J., & Van Koppen, B. 2007. Applying the Gini Coefficient to measure inequality of water use in the Olifants river water management area. South Africa, 1- 25.

Eslamian, S. S., Gilroy, K. L., & McCuen, R. H. 2011. Climate change detection and modelling in hydrology. Climate Change Research and Technology for Adaptation and Mitigation, 87-100.

First, P. J. 2018. Global warming of 1.5 °C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Water field (eds.). World Meteorological Organization, Geneva, Switzerland, 32 pp.

Giorgetta, M. A., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., & Glushak, K. 2013. Climate and carbon cycle changes from 1850 to 2100 in MPI- ESM simulations for the Coupled Model Intercomparison Project phase 5. Journal ofAdvances in Modelling Earth Systems, 5(3), 572-597. https://doi.org/10.1002/jame.2003

Gupta, H.V., Sorooshian, S. and Yapo, P.O. 1999. Status of Automatic Calibration for Hydrologic Models: Comparison with Multilevel Expert Calibration. Journal of Hydrologic Engineering 4 135-143.

Hajj, H. T. 2011. Impact of Climate Change on Surface Water Availability in the Upper Vaal River Basin. Master dissertation, Tshwane University of Technology, South Africa.

Hartmann, D. L., Tank, A. M. K., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y. A. R., & Soden, B. J. (2013). Observations: atmosphere and surface. In Climate change 2013 the physical science basis: Working group I contribution to the fifth assessment report of the intergovernmental panel on climate change (pp. 159-254). Cambridge University Press.

Hourdin, F., Foujols, M. A., Codron, F., Guemas, V., Dufresne, J. L., Bony, S., & Braconnot, P. 2013. Impact of the LMDZ atmospheric grid configuration on the climate and sensitivity of the IPSL-CM5A coupled model. Climate Dynamics, 40(9- 10), 2167-2192. https://doi.org/10.1007/s00382-012-1411-3

IPCC. 2007. Fourth Assessment Report, Climate Change, Cambridge: Cambridge University Press.

Jeffrey, S., Rotstayn, L., Collier, M., Dravitzki, S., Hamalainen, C., Moeseneder, C., & Syktus, J. 2013. Australia's CMIP5 submission using the CSIRO Mk3. 6 model. Aust. Meteor. Oceanogr. J, 63, 1-13. https://doi.org/10.22499/2.6301.001

Kusangaya, S., Warburton, M. L., Van Garderen, E. A., & Jewitt, G. P. 2013. Impacts of climate change on water resources in southern Africa: A review. Physics and Chemistry of the Earth, Parts A/B/C, 67, 47-54. https://doi.org/10.1016/j.pce.2013.09.014.

Leong, W. K., & Lai, S. H. 2017. Application of Water Evaluation and Planning Model for Integrated Water Resources Management: Case Study of Langat River Basin, Malaysia. In IOP Conference Series: Materials Science and Engineering. IOP Publishing. (Vol. 210, No. 1, p.012024). https://doi.org/10.1088/1757-899X/210/1/012024

Ly, S., Charles, C., & Degre, A. 2011. Geostatistical interpolation of daily rainfall at catchment scale: the use of several variogram models in the Ourthe and Ambleve catchments, Belgium. Hydrology and Earth System Sciences, 15(7), 2259-2274. https://doi.org/:10.5194/hess-15-2259

Magagula, T. F., van Koppen, B., & Sally, H. 2006. Water access and poverty in the Olifants Basin: A spatial Analysis of population distribution, poverty prevalence and trends. In 7th Water Net/WARFSA/GWP Annual Symposium (pp. 1-3).

Mahlobo, D. D., Ndarana, T., Grab, S., & Engelbrecht, F. 2019. Integrated climatology and trends in the subtropical Hadley cell, sunshine duration and cloud cover over South Africa. International Journal of Climatology, 39(4), 1805-1821. https://doi.org/10.1002/joc.5917

Mantel, S., Hughes, D. & Slaughter, A. 2015. Water resources management in the context of future climate and development changes: a South African case study. Journal of Water and Climate Change, 6 (4), 772–786. https://doi.org/10.2166/wcc.2015.098

McCartney, M. P., & Arranz, R. 2007. Evaluation of historic, current and future water demand in the Olifants River Catchment. South Africa. Colombo, Sri Lanka: International Water Management Institute. 2007, 48p. (IWMI Research Report 118) http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB118/RR18.pdf

McCartney, M. P., Yawson, D. K., Magagula, T. F., & Seshoka, J. 2004. Hydrology and water resources Development in the Olifants River Catchment (Vol. 76). IWMI.

Mukheibir, P. 2008. Water resources management strategies for adaptation to climate- induced impacts in South Africa. Water Resources Management, 22(9), 1259-1276. https://doi.org/10.1007/s11269-007-9224-6.

Nash, J. E., & Sutcliffe, J. V. 1970. River flow forecasting through conceptual models part I– A discussion of Principles. Journal of hydrology, 10(3), 282-290. https://doi.org/10.1016/0022-1694(70)90255-6

Niang, I., Ruppel, O., Abdrabo, M., Essel, A., Lennard, C., Padgham, J., and Urquhart, P. 2014. Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nkhonjera, G. K. 2017. Understanding the impact of climate change on the dwindling water resources of South Africa, focusing mainly on Olifants River basin: A review. Environmental Science & Policy, 71, 19-29. https://doi.org/10.1016/j.envsci.2017.02.004

Nkhonjera, G. K., Dinka, M. O., & Woyessa, Y. E. 2020. Assessment of localized seasonal precipitation variability in the upper middle catchment of the Olifants River basin. Journal of Water and Climate Change.

Rasiuba, T. 2007. Water budget water use efficiency in agriculture in Olifants Catchment. Masters Dissertation, University of the Witwatersrand, South Africa.

Riahi, K., Grübler, A., & Nakicenovic, N. 2007. Scenarios of long-term socio- economic and environmental Development under climate stabilization. Technological Forecasting and Social Change, 74(7), 887-935. https://doi.org/10.1016/j.techfore.2006.05.026

Rochdane, S., Reichert, B., Messouli, M., Babqiqi, A., & Khebiza, M. Y. 2012. Climate change impacts on water supply and demand in Rheraya Watershed (Morocco), with potential adaptation strategies. Water, 4(1), 28-44. https:// doi.org/:10.3390/w4010028

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., & Reinhardt, J. 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Regional Environmental Change, 17(6), 1585-1600. https://doi.org/10.1007/s10113-015-0910-2

Shrestha, M. 2015. Data analysis relied on linear scaling bias correction (V.1.0) Microsoft excel file. https://doi.org/10.13140/RG.2.1.3365.8967.

Sieber, J., & Purkey, D. 2011. WEAP: Water Evaluation and Planning System. User guide. Somerville, MA: Stockholm Environment Institute, US Center. http://weap21.org/downloads/WEAP_User_Guide.pdf.

Singh, R., van Werkhoven, K., & Wagener, T. 2014. Hydrological impacts of climate change in gauged and ungauged watersheds of the Olifants basin: a trading-space-for time approach. Hydrological Sciences Journal, 59(1), 29-55. https://doi.org/10.1080/02626667.2013.819431

Stockholm Environment Institute (SEI). 2005. WEAP: Water Evaluation and Planning System-User guide. Boston, USA.

Talukder, A. R. 2019. Impacts of Climate Change on the Hydrological Regime in the Olifants River, South Africa. Doctoral dissertation, University of Windsor, Canada..

Udall, B. 2018. 21st century climate change impacts on Olifants River flow South Africa. https://cer.org.za/wp content/uploads/2018/05/Udall-Olifants-River Analysis Final .pdf.

Van Vuuren, A., Jordaan, H., Van der Walt, E., & Van Jaarsveld, S. 2003. Olifants water management area, Water resources situation assessment. Department of Water Affairs and Forestry, South Africa.

Voldoire, A., Sanchez-Gomez, E., y Mélia, D. S., Decharme, B., Cassou, C., Sénési, S., & Déqué, M. 2013. The CNRM-CM5. 1 global climate model: description and basic evaluation. Climate Dynamics, 40(9-10), 2091-2121. https://doi.org/10.1007/s00382-011-1259y.

Wagener, T., van Werkhoven, K., & Singh, R. 2010. Credibility of Hydrologic Models in the Context of Climate Change Impact Studies-A Case Study in the Olifants Basin, South Africa. In EGU General Assembly Conference Abstracts (Vol. 12, p.7484).

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., & Takata, K. 2010. Improved Climate simulation by MIROC5: mean states, variability, and climate sensitivity. Journal of Climate, 23(23), 6312-6335. https://doi.org/10.1175/2010JCLI3679.1

Wood, A. W., Leung, L. R., Sridhar, V., & LetWtenmaier, D. P. 2004. Hydrologic implications of dynamical and Statistical approaches to downscaling climate model outputs. Climatic change, 62(1-3), 189-216. https://doi.org/10.1023/B:CLIM.0000013685.99609.9e

Wu, H., Chen, B., Snelgrove, K., & Lye, L. M. 2019. Quantification of uncertainty propagation effects during statistical downscaling of precipitation and temperature to hydrological modelling. Journal of Environmental Informatics, 34, 139-148. https://doi.org/10.3808/jei.201600347.

WFF-SA. 2016. Water: Facts and Futures-Rethinking South Africa's Water Future. https://slidelegend.com/water-facts-and-futures-wwf-south africa_59bfdb0d1723dd1242166361.pdf