Integrated assessment of the influence of climate change on current and future intra-annual water availability in the Vaal River catchment

Akanbi T. Remilekun[1,*], Ndarana Thando[1], Davis Nerhene[1, 2] and Emma Archer[1, 2]

[1]Department of Geography,Geoinformatics and Meteorology, University of Pretoria, Private bag X20, Hatfield 0028,South Africa

[2]Centre for Environmental Studies, Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Private bag X20, Hatfield 0028, South Africa

*Correspondence to: remiafrica1@mweb.co.za

Abstract

Increasing water demand due to population growth, economic expansion and the need for development puts a strain on the supply capacity of the Vaal River catchment in South Africa. Climate change presents additional challenges in the catchment which supports the country's economic hub, more than 30% of its population and over 70% of its maize production. This study evaluates the influence of climate change on current and future intra-annual water availability and demand using a multi-tiered approach where climate scenarios, hydrological modelling and socio-economic considerations were applied. Results shows exacerbated water supply challenges for the future. Temperature increases of between 0.07 and 5 °C and precipitation reductions ranging from 0.4 to 30% for Representative Concentration Pathways (RCPs) 4.5 and 8.5, respectively, are also predicted by the end of the century. The highest monthly average streamflow reductions (8–10%) are predicted for the summer months beyond 2040. Water Evaluation and Planning (WEAP) simulations project an increase in future water requirements, gaps in future water assurance and highlight limitations in existing management strategies. The study recommends a combination of adaptation plans, climatic/non-climatic stressor monitoring, wastewater-reuse, conservation, demand management and inter-basin transfers to reduce future uncertainty in monthly water sustainability.

Keywords: climate change, intra-annual water availability, South Africa, Vaal river basin, WEAP

INTRODUCTION

Climate change is already becoming evident, partly through observed increasing temperatures and changes in precipitation patterns around the world (De Jong *et al.* 2019). According to Niang *et al.* (2014), the impacts of climate change will be significantly felt in Africa due to an assumed lower level of adaptive capacity compared to other continents.

Changes in South Africa's climate will likely lead to variations in rainfall patterns, intensity of storms, drought, flood extremes, changes in runoff, water availability, ecosystem imbalance, changes in biodiversity and will also present challenges to crop production (Grecksch 2015; Mantel *et al.* 2015; Engelbrecht & Engelbrecht 2016; Serdeczny *et al.* 2017). Kusangaya *et al.* (2014) indicated that short- and long-term trend analysis of atmospheric variables such as rainfall and temperature have been used extensively as proxies for detecting changes in climate. However, rainfall and spatial assessment of hydrological cycles are the main drivers of predictions of the variation in water balance which may result in extreme events such as floods, which are among the most destructive natural disasters (Mosavi *et al.* 2018). The magnitude of the threats posed by these changes are uncertain and can significantly alter the spatial and temporal availability of water, thereby aggravating existing water related stresses, and negatively impacting developmental needs (Kusangaya *et al.* 2014; Nyoni *et al.* 2019).

South Africa is a water scarce country as it lies within one of the regions of the world that is most vulnerable to climate change (Niang *et al.* 2014; Engelbrecht & Engelbrecht 2016), as characterised by the descending branch of the Hadley circulation (Mahlobo *et al.* 2019). Moreover, South Africa is in a negative runoff zone, where annual evaporation exceeds its rainfall (Jury 2016). The South African National Water Resources Strategy (Department of Water Affairs (DWA) 2013) suggests that water is the primary medium through which the impacts of climate change are being felt in South Africa. About 66% of the country's surface water comes from surface runoff, which is partly contained in its dams with a total storage capacity of $32.4 \times 10^6 m^3$and a total yield of more than $10,240 \times 10^6 m^3$ (Adewunmi *et al.* 2010; Statistics South Africa 2010).

While South Africa has a well-developed water resource infrastructure, it is fast approaching the full utilization of its surface water yields in certain areas; and in others, yields have already been exceeded, with suitable sites for new dams increasingly unfeasible (DWA 2013). It is anticipated that the intensification in climate variability and increasing water demand will result in water and food insecurities (Niang *et al.* 2014; Serdeczny *et al.* 2017).

It is expected that water resources will be fully depleted and unable to meet the needs of people and industry by the year 2030 (Oberholster & Ashton 2008). With the influence of climate change, South Africa is expected to see the strongest decrease in precipitation in sub-Saharan Africa with concurrent risks of drought (Serdeczny *et al.* 2017). Studies on the impact of climate change in South Africa have therefore largely focussed on its influence on agriculture, environmental stress, precipitation variation and temperature inconsistency (Walker & Schulze 2008; Engelbrecht & Engelbrecht 2016; Nyoni *et al.* 2019). The influence of climate change on hydrological cycles in South Africa and its water management areas has also received considerable attention in the last three decades (Kusangaya *et al.* 2014; Jury 2016). The general consensus is that climate change influences water availability at catchment scales in South Africa. It has been found by a limited number of studies (e.g. Jury (2016) and Kusangaya *et al.* (2014)) that climate change has important implications for the hydrological cycle and water resources as rainfall is the main driver of variability in the water balance.

South Africa has 19 Water Management Areas (WMAs). As part of its water management strategy these were merged into nine Catchment Management Agencies (CMA) for ease of water resource management, enabling water management authorities to regulate the abstraction and use of water within their boundaries. The Vaal WMA is perceived to be one of the most important WMAs in South Africa because it houses the highest concentration of urban, industrial, agricultural, mining and power generation developments in South Africa (Department of Water & Sanitation 2015). The water management area in its entirety (upper, middle and lower Vaal) contributes approximately 24% to the country's gross domestic product (GDP), indicating its importance in the country's economy. The strategic importance of the catchment is accentuated by the fact that it is also a hub for several inter-basin transfers (Department of Water & Sanitation 2015).

Water demand, however, significantly exceeds the available yield in the Vaal catchment (Ilunga 2017). The catchment is overburdened and requires seasonal augmentation through transboundary inter-basin transfers as its natural yield is insufficient to meet its supply requirements (Jury 2016). Changes in the intra-annual water availability in the catchment are expected to significantly impact the various sectoral water users such as agriculture, municipal water users, mining and industry, menacing food security and economic expansion. Monthly water requirements and availability is not homogenous; water demand by the different sectors peaks during different months based on socioeconomic and climatic factors. Hence, there is a need to identify current or future intra-annual water challenges.

Previous studies have been conducted to assess the impact of climate change in the Vaal catchment. For example, a study conducted by Jury (2016) focused on the influence of current climatic trends on the seasonal flow of the Vaal river, confirming possible hydro-climatic variations resulting from increases in temperature and precipitation reduction. Otieno *et al.* (2009) evaluated the effect of climate change on water availability, demand and quality at different segments of the Vaal catchment. The hydro-climatic study, however, only covered the upper Vaal for the near-term (until 2030). Their study highlighted the need for strategic national planning to protect precious water resources and ensure future sustainability. Current trends and conditions demonstrate that impacts of climate change are manifesting in the Vaal river catchment, with implications for food production and economic expansion (Otieno *et al.* 2009; Engelbrecht & Engelbrecht 2016; Jury 2016). Walker & Schulze (2008) accentuate the effects of climate change in the Vaal catchment on cereal production. These studies highlight the significance of changes in climate in one of South Africa's key food producing regions, where more than 70% of South Africa's cereal crops and over 80% of the commercially grown maize is cultivated.

Despite the strategic importance of the Vaal Catchment, the studies outlined to date have failed to explore the effect of climate change on current and future intra-annual hydrological processes in the entire catchment; nor have the implications of these on water demand and supply been considered in an integrated manner. The effects and impacts of climate change on the intra-annual variability in the water available in the entire catchment, i.e. hydrological processes in the catchment, is therefore a key consideration in this paper as we seek to draw particular attention to the linkages between these variables and anticipated implications.

In order to meet the stated aim of this study a number of existing hydrological models that have been applied in other catchments in South Africa were evaluated to gauge their suitability for this study. Models such as the Pitman hydrological model (www.wrc.org.za/wp-content/uploads/mdocs/TT%20686%20web.pdf) and Soil and Water Assessment Tool (SWAT) (https://swat.tamu.edu/), were ruled out as unsuitable approaches because a multidisciplinary and integrated approach was required to achieve the study's objectives. Given that the Water Evaluation and Planning (WEAP) model allows for the integration of municipal, agricultural, mining and industrial water uses, while taking into account the complex Vaal river transboundary systems, supply priorities, governance and socioeconomic issues and relating them to the natural and hydrological processes in the catchment, it was deemed as the most suitable hydrological tool for this study. The model also presented us with a level of assurance about its validity as it has been successfully applied both globally and in the South African context (Otieno *et al.* 2009; Mantel *et al.* 2015). This study integrates climate change scenarios and hydrological modelling using WEAP to assess the impacts of climate change alongside other prevailing stressors such as population growth, economic expansion and governance on current and future intra-annual water availability and demand in the Vaal catchment.

MATERIALS AND METHODS

Study area and data

The Vaal River is a key tributary of the Orange River, found at 26–28°S, 25–29.5°E. The catchment occupies the central northeastern part of South Africa (Otieno *et al.* 2009), with the source in Ermelo, in the Mpumalanga Province, west of Swaziland. It flows westward through Gauteng, the Free State, the Northwest Provinces and towards Kuruman (Northern Cape). It then joins the Orange River, which flows into the Atlantic Ocean (Department of Water & Sanitation (DWS) 2016). In the northwestern part of the WMA it borders Botswana, and the Crocodile (West) and Olifants Catchments. Johannesburg, an important economic hub in South Africa, is located on the northern boundary of the WMA, while Lesotho is on its southeast boundary (DWS 2016) (Figure 1).

The catchment's climate is sub-tropical dry savanna, with the mean annual evaporation at ∼1,300 mm, far exceeding the rainfall of ∼600 mm (Jury 2016). Precipitation has spatial variability and ranges from 800 to 1,000 mm in the east, to about 300 mm in the west (DWS 2015), and a mean annual temperature of 15 °C (DWS 2015).

The Vaal River catchment covers an area of about 196,000 km^2, with a length of about 1,300 km (Wepener *et al.* 2011). The Vaal river system provides water resource services to about 60% of the national economy and provides water to more than 45% of South Africa's population – approximately 20 million people (Department of Water Affairs 2013). Land use in the catchment is predominantly for agricultural use and, as a result, the catchment has the largest irrigation scheme in South Africa, referred to as the Vaalhart irrigation scheme (DWS 2015). The foremost water uses in the Vaal water management area include industrial, mining, power generation, agriculture, nature conservation, as well as urban and rural human uses. The major dams in the catchment include the Grootdraai, Vaal, Vaal Barrage, Bloemhof, Vaalharts, and Douglas Weir, with the Vaalharts and Douglas Weir used predominantly for irrigation. The water management area transfers water out to the

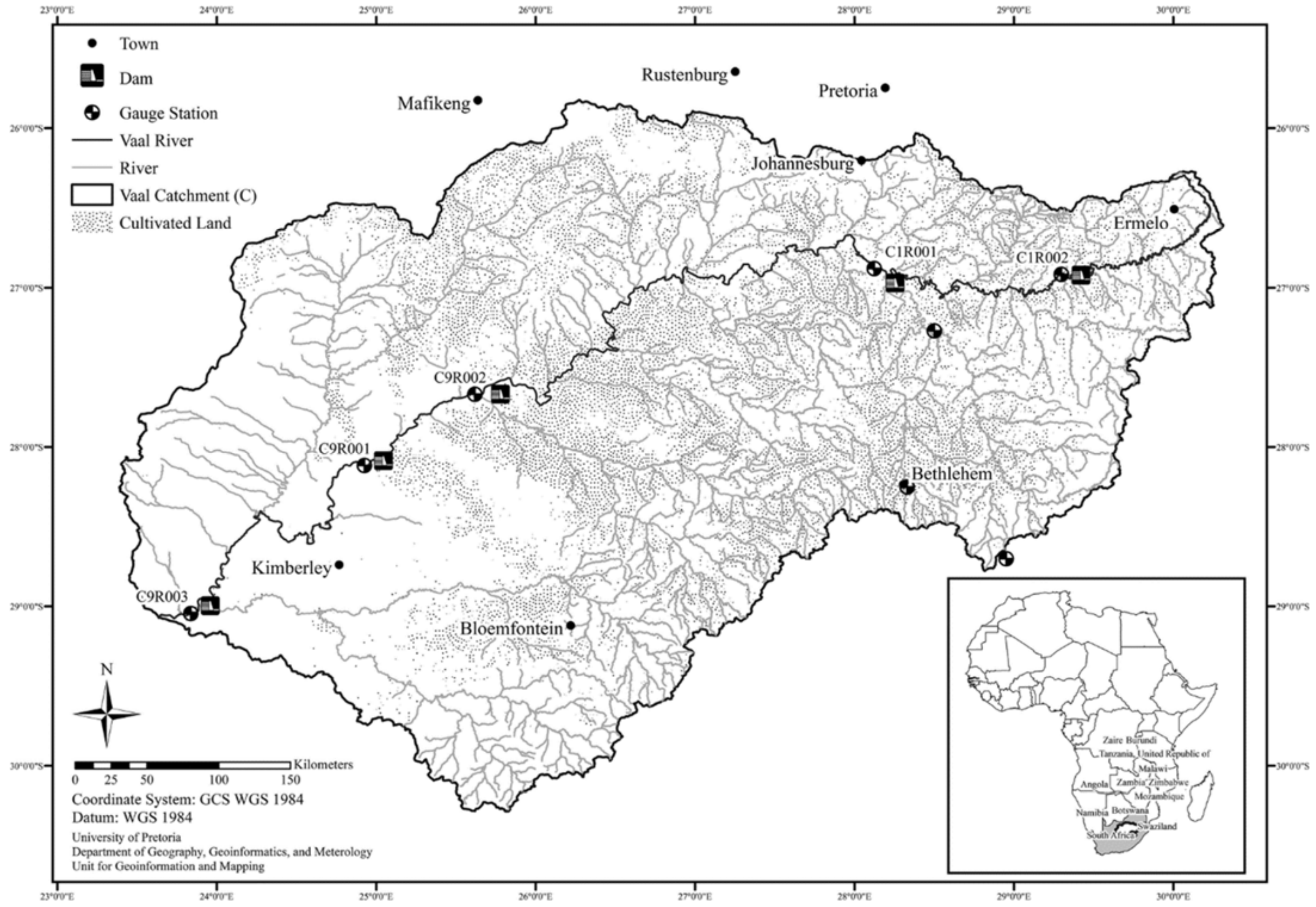

Figure 1. Diagram showing the location of the study area, the Vaal catchment. Presenting the Vaal river, some of its main reserviors, land area cultivated and reserviors and major cities.

Crocodile, Marico and Olifants management areas, and transfers water in from the Thukela, Usutu & Mhlatuze Management areas, well as from Lesotho (DWS 2016).

Dataset used

To achieve the study objectives, a variety of datasets were required, including hydrological data; i.e. monthly streamflow, reservoir operations details, groundwater details, land use, and other catchment specific details to characterize the model. Hydrological data were obtained from the South African Department of Water Affairs and Sanitation Hydrological Services online database (http://www.dwa.gov.za/Hydrology/).

Observed maximum and minimum temperatures, as well as precipitation data, for the catchment were obtained from the South African Weather Services (SAWS) for the period 1976–2018. Water demand and supply data for the major water users in the catchment was obtained from the 'Vaal River System: Large Bulk Water Supply Reconciliation Strategy Study' (Department of Water Affairs and Forestry (DWAF) 2009) (www.dwa.gov.za/Vaal/documents/LargeBulkWater/05_Water%20Resource%20Analysis_Final.pdf). Catchment demographic data such as population, as well as numbers of mining and industrial entities in the catchment, was obtained from the Statistics South Africa's 2010 Water Management Areas in South Africa discussion document (www.statssa.gov.za/publications/D04058/D04058.pdf) and the DWAF 2009 report and the 2009 reconciliation study mentioned above. Information about the water use rate, water consumption and land use were attained from a range of catchment publications, reports and strategies.

This study was carried out using output from the Coordinated Regional Climate Downscaling Experiment (CORDEX) (www.csag.uct.ac.za/cordex-africa/). To minimize climate model uncertainty, caused by large differences in physical parameterization schemes in the climate models, six general circulation models (GCMs) were used in the study (Table 1). High resolution RCM (regional climate models) nested within GCMs were applied. The downscaling of the GCM to RCM provides a better resolution output of the GCM, these are better suited for local and regional climate studies for policy making purposes (Homsi *et al.* 2020). Rather than downscaling a single GCM for climate projection, the downscaling of a number of models is suggested to limit variation in their performance, and common practice is to ensemble the GCM models (Homsi *et al.* 2020). The climatic models were therefore ensembled to prevent the over- or under-estimation of climate parameters limitations presented by using single GCMs. The averages of the output from the six selected GCMs were then applied in the study. The historical and predicted climate time series data that were obtained from the regional climate outputs of the CORDEX-Africa database were monthly precipitation and temperature (maximum, minimum and average) for the periods 1976–2100 for two emission representative pathways, RCP 4.5 and RCP 8.5, for the purpose of climate change scenario analysis and as inputs into the hydrological model. The choice of the emission representative concentration pathway was based on the need to compare the impact of RCP 4.5 which is an intermediate pathway around the stabilization level with RCP 8.5 which is the worst-case scenario pathway with no mitigation. The resolution of the RCM was 0.44° in longitude and latitude, and the description of the climate models is detailed in Dosio (2017).

Table 1. Data description and sources used in population of the water evaluation and planning (WEAP) model

Data	Description	Sources
Historical hydrological data	Stream flow gauge stations, dam data; 1976–2005	South African Department of Water Affairs and Sanitation Hydrological Services website[a]
Water demand data		Vaal River System: Large Bulk Water Supply Reconciliation Strategy Study' conducted by the Department of Water Affair and Forestry in 2009 (DWAF 2009) [b]
Population	Urban Rural	Statistics South Africa's 2010, Water Management Areas in South Africa discussion document[c] Vaal River System: Large Bulk Water Supply Reconciliation Strategy Study' conducted by the Department of Water Affair and Forestry in 2009 (DWAF 2009) [d]
Historical climate data	Temperature Precipitation	African Weather Services (SAWS) for the period 1976–2005
Climate data	Model	Institution
	CCCma CanESM2	Canadian Centre for Climate Modelling and Analysis
	IPSL IPSL-CM5A-MR	Institut Pierre Simon Laplace, France
	CNRM CERFACS	Centre National de Recherches Météorologiques, France
	MIROC MIROC V5	Model for Interdisplinary Reseacrch On Climate, Japan
	MPI MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
	CSIRO QCCCE Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation, Australia

[a] www.dwa.gov.za/Hydrology/.

[b] www6.dwa.gov.za/Vaal/documents/LargeBulkWater/05_Water%20Resource%20Analysis_Final.pdf.

[c] www.statssa.gov.za/publications/D04058/D04058.pdf.

[d] www6.dwa.gov.za/Vaal/documents/LargeBulkWater/05_Water%20Resource%20Analysis_Final.pdf.

The data from the RCPs were bias corrected to prevent over- or under-estimation, and to ensure a realistic representation of the future climate. Several bias correction techniques have emerged over the years, such as quantile mapping (QM), general quantile mapping (GQM) power transformation (PT), and linear scaling (LS) (Homsi *et al.* 2020). According to Homsi *et al.* (2020), linear scaling showed better efficiency in bias correcting the ensemble GCM. The linear scaling (LS) bias correction method described by Shrestha (2015) was used in this study to appropriately adjust the climate model's average value to observations. The performance of the ensemble data was therefore substantiated with observed SAWS gauge station data from 1976 to 2005 to improve data confidence.

To inform the WEAP scenario development, socioeconomic data on farmers' perception of future water requirements from an ongoing exploratory study in the Vaal catchment looking at the perception of climate change by maize producers was utilized. The respondents' use of irrigation as an adaptation strategy in response to climate change showed the projected increase in irrigation water requirements. Most of the surveyed farms were rain fed (more than 85%) and farmers identify irrigation as one of the adaptation tools that could improve their resilience. A total of 105 maize farming households across the catchment were surveyed.

METHODS

Experimental design

Although the study objective was to determine the combined impact of climate change and other existing water stressors on intra-annual water availability and demand in the Vaal catchment, there was a need to initiate the study with an assessment of the climatic changes that have occurred in the catchment, and the projection of future catchment climate. The study therefore consists of three approaches. The first was to determine catchment current climate and estimate future climatic changes predicted for the catchment by comparing the mean historical climate with three future periods under two emission pathways. This was followed by the evaluation of the impact of these climatic changes on water availability and the understanding of current water demand and supply status in the catchment using the WEAP model. The final approach was to force WEAP with downscaled climate data to evaluate future scenarios of intra-annual water demand, supply and identify possible gaps in future water assurance. The use of these multiple approaches in achieving the study objective is expected to facilitate a broader understanding of the hydro-climatic interactions in the catchment.

Climate change scenarios

Intra-annual temperature and precipitation analysis were carried out using six CORDEX GCMs nested RCM described above for all the months to evaluate monthly variation in catchment climate for the study periods. Agriculture is the predominant type of land use in the study area as the Vaal river system supplies water to South Africa's main maize production areas. Attention was therefore given to the maize planting months in the catchment, which are September to February (Greyling & Pardey 2019), to assess possible climate change impacts on water availability for crop production and other competing water uses during those months and other times of the year. An assessment of a 30-year average current climate of the Vaal was conducted for the period 1989–2018 to determine what the monthly average temperature and precipitation in the catchment was for ease of comparison with future changes in climate and to understand the intra-annual variation in the catchment's climate.

A baseline period of 30 years (1976–2005) was selected to establish baseline time series of the Vaal climate data, and three future periods, 2011–2040, 2041–2070 and 2071–2100, for the purpose of climate change scenario analysis and input into the hydrological model. Changes were assessed as deviation of the future time slices from the historical period for all the months. Changes in future intra-annual water availability for those periods were assessed and compared for the two climate change scenarios. RCP 4.5, which represents a scenario where stringent emission mitigation measures would be imposed, and RCP 8.5, represent a scenario where no mitigation policy to anthropogenic emissions is applied.

WEAP application to the Vaal catchment

The WEAP21 model was developed by the Stockholm Environment Institute (SEI) (SEI 2015) and may be used to address water demand or supply side problems, water conservation, water rights, allocation, streamflow and reservoir simulations (SEI 2015). Water is allocated to the demand side based on predefined priorities. Scenarios may then be developed to answer what-if situations relating to water demand and supply, such as water demand projection, hydrological infrastructure development, and water conservation (SEI 2015).

The various competing water user's demand and allocation for the current account year were used to characterize the model. The current account is the first year of the model simulation, where data for the surface water availability (supply) and water allocation (demand) are available. In this study, 2009 was used as the current account year, as the most recent Vaal catchment full reconciliation strategy was published for that year. The current account was characterized with the water abstraction details, land use, water use rate, water supply and inter catchment transfers details to simulate the catchment's water resources.

The land, water use, and estimated abstraction data were aggregated where necessary. The WEAP water year method described below was chosen for this study. The method allows the integration of climate data as part of the characterisation of the model. The method represents variations in annual climate data such as precipitation in different water year regimes based on the extent of their deviation from the normal water year. They are classified as either dry, very dry, normal, wet or very wet. The current account year 2009 was classified as a normal year.

The model configuration process included the creation of supply and demand nodes, representing the aggregated demand and supply details of the catchment with relevant linkages to the river system. Four demand nodes were created for municipal, agricultural, industrial/mining and wetland/river losses. The demand for the four nodes was recorded as $1.67 \times 10^6 m^3$, $1.09 \times 10^6 m^3$, $0.5 \times 10^6 m^3$ and $0.3 \times 10^6 m^3$, respectively, for the 2009 current account year (DWAF 2009). The municipal population for the current account year was recorded as 9.9 million, 146,773 ha of irrigated areas, 18 major mines and industry. For the Vaal catchment, nodes were combined to fall under the following major demand municipal nodes which service the urban and rural requirements, agricultural (irrigation water use), mining/industrial and wetland and river uses. WEAP was used to estimate the baseline scenario of the current account year of 2009. The model then simulates the actual hydrological dynamics of the Vaal river system for that year. WEAP compares future catchment development with the snapshot of actual water demand and supply, as provided by the study's current account year (SEI 2015). All other scenarios are built on the data from the current account year. The reference scenario, also referred to as the business-as-usual scenario, builds on the current account and the future scenario builds from the reference scenario. The reference scenario allows for the comparison of future scenarios with current account model data.

WEAP model calibration and validation

Model calibration and validation were aimed at adjusting parameters necessary for the generation of runoff from climate inputs, by measuring the fit between simulated model discharge and observations. Manual model calibration and validation was carried out using historical streamflow. The calibration of the model requires several steps including study time frame definition and setup, Vaal catchment spatial boundary characterization and representation, and model system configuration for problem evaluation. Following the calibration of the hydrological model for the period 1980–1990, the climate model was applied for the period 1991–1999 under the current climate to validate the system. To verify the model's ability to simulate observations, output from the model is compared with observations. Commonly used model performance measures are the Nash–Sutcliffe model efficiency, coefficient of determination, root mean square error (RMSE), and percent bias (PBIAS). The Nash–Sutcliffe model efficiency and coefficient of determination are the most frequently used due to their sensitivity. To measure the goodness of fit between the simulated and observed data, the coefficient of determination (R^2) and Nash–Sutcliffe efficiency, as described by Leong & Lai (2017), was utilized. Coefficient of determination (R^2) measures the degree of collinearity between simulated and measured data. It ranges from 0 to 1. Higher values indicate less error variance. Where Y_i^{sim} is the ith simulated streamflow, Y_i^{obs} is the ith observed streamflow, $\bar{Y}^{\mathrm{sim}}$ is the mean of simulated streamflow and $\bar{Y}^{\mathrm{obs}}$ is the mean of observed streamflow (Leong & Lai 2017).

$$\mathrm{R}^2 = \left[\frac{\sum_{i=1}^{n}(Y_i^{sim}-\bar{Y}^{sim})(Y_i^{obs}-\bar{Y}^{obs})}{\sqrt{\left(\sum_{i=1}^{n}(Y_i^{sim}-\bar{Y}^{sim}\right)^2\sum_{i=1}^{n}(Y_i^{obs}-\bar{Y}^{obs})^2}}\right] \tag{1}$$

The Nash–Sutcliffe model efficiency coefficient (NSE) is used to assess the predictive power of hydrological models. It is defined as:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_0^t)^2}{\sum_{t=1}^{T}(Q_0^t - \overline{Q_0})^2} \tag{2}$$

where $\overline{Q_0}$ is the mean of observed discharges, and Q_m is modelled discharge. Q_o^t is observed discharge at time t (Leong & Lai 2017). NSE efficiency ranges from −∞ to 1, with higher efficiency indicating a good match between the simulated and observed variables.

Current and future water availability in the catchment

The monthly variation in water availability in the Vaal catchment was estimated using changes in streamflow based on the projected precipitation inputs through the water-year method. The monthly variation in streamflow in the near-term (2011–2040), the mid-term (2041–2070), and the far-term (2071–2100) departure from the simulated historical flow (1976–2005) were evaluated and used to quantify the changes in water yield of the catchment under the climate change representative pathways of RCP 4.5 and RCP 8.5.

Impact of climate change on plausible future water use and supply in the Vaal catchment

The WEAP model allows for the development of 'what-if' scenarios that can be compared to the reference scenario (Table 2). These 'what-if' scenarios are alternative assumptions based on different factors that could affect water demand such as impact of climate change, demographics, socioeconomics and water conservation policies. For this study, the reference scenario and five plausible future scenarios were proposed. These scenarios were based on Vaal water planning scenarios as detailed in the 2009 reconciliation strategy. In the planning scenarios, Water Conservation/Water Demand Management (WC/WDM) strategies to reduce water loss, reduce urban water use and improve water efficiency by 15%, and another to reduce unlawful irrigation water use by 15%, were proposed. To assess the impact of climate change on plausible future water demand and supply in the Vaal catchment, the five scenario options listed below were evaluated under two future climate representative pathways RCP 4.5 and RCP 8.5, to identify potential additional challenges that could be presented as a result of changes in climate, in addition to the original limitations identified during the Vaal scenario planning stages. The development of the scenarios was informed by the Vaal 2009 reconciliation strategy (which is the most recent **strategy for the catchment).**

Table 2. WEAP scenarios of possible future water demand from the Vaal basin, assessed under RCP 4.5 and RCP 8.5

Scenarios	Description
Scenario 1	High population growth rate of 1.82%, as a result of economic expansion, infastructure development, better employment and other socioeconomic factors that attract people to the catchment area. Leading to population increase. Other assumptions for this scenario are increasing irrigation, no intervention
Scenario 2	High population growth rate, 15% redution in irrigation water use due to the achievement of the strategy to remove unlawful water use
Scenario 3	High population growth rate, Vaal Water conservation/water demand management (WC/WDM) incorporated, leading to a 15% reduction in municipal water use as a result of reduction in urban water use, loss reduction and water use efficiency
Scenario 4	Low population growth rate of 1.66%, 15% reduction in municipal water use
Scenario 5	High population growth rate, achievement of the WC/WDM (15%) reduction in municipal water use and, removal of unlawful water use (15%) resulting in a total of 30% reduction in water use.

Reference scenario

Assume that development and improvement programs will be insignificant, and growth will be at the normal rate of 1.66% (this assumption is based on the normal Vaal catchment growth rate provided in the 2009 reconciliation strategy (DWAF 2009)).

Scenario 1: Assumes population growth based on catchment higher growth rate projection of 1.82% (DWAF 2009), increasing irrigation based on farmers' perception of irrigation as an adaptation tool. Under this scenario, irrigation water use increased until it reached the maximum allowable irrigation limit of 1,375 × $10^6 m^3$ (DWAF 2009). This scenario is assuming that the proposed unlawful irrigation water use strategy of the catchment is not achieved. The assumption is based on the fact that the catchment may be unable to police and enforce the strategy to eradicate the unlawful irrigation water use strategy. Mining and industrial water use was capped for this scenario, as the Vaal Water Management Authority no longer issue new licenses for mining water use. Industrial water use increases were also capped as it is assumed that water use by the decommissioned industries will negate the water use by the emerging industries.

Scenario 2: Assumes higher population growth rate, no increase in irrigation, constant industrial and mining water use, due to the cancelling effect of the decommissioning of some of the mines and reinstatement of some of the power plants to accommodate population expansion and power shortages. Under this scenario eradication of unlawful irrigation water use strategy was achieved, leading to a 15% reduction in irrigation water use. Water loss reduction through conservation and demand management was not achieved under this scenario.

Scenario 3: Assumes a high population growth rate, no irrigation increase, mining/industrial growth remains constant and water loss reduction through conservation and demand management achieved. Municipal water use under this scenario was reduced by 15%. Unlawful irrigation water use was not achieved for this scenario.

Scenario 4: Assumes a scenario of lower population growth rate, which could be due to saturation in water availability, resulting in poor water assurance and emigration. This scenario also assumes that factors such as the HIV/AIDS (human immunodeficiency virus/acquired immunodeficiency syndrome) pandemic in South Africa, if not managed sustainably, may result in a decline in population. Current focus on disease management through the increase of life expectancy and not prevention could lead to new and more cases of infection, consequently the inability to sustain the management programs could lead to a population decline. The scenario assumes that water loss and WC/WDM was achieved resulting in a 15% reduction in municipal water use.

Scenario 5: Assumes a high population growth rate, no increase in irrigation, constant mining and industrial water use, removal of unlawful irrigation water use, achievement of the WC/WDM reduction in water loss, reduction of urban water uses and the application of water efficiency programs. Based on the achievement of all these interventions, municipal water use was reduced by 15% and irrigation water use reduced by 15%, resulting in a total of 30% reduction in water requirement.

Water demand for agriculture (irrigation) and mining/industry sectors were assumed to remain constant in most scenarios, except scenario one, as new licenses are no longer issued to these sectors by the Vaal Water Management Authorities (DWAF 2009). This is part of the catchment's strategy to reduce irrigation water use, there are however licenses that have already been issued but water is not abstracted due to lack of irrigation infrastructures, hence the increase in water demand under scenario 1 to the allowable maximum limit. The total registered water use for irrigation in the Vaal River System is estimated to be 1,375 million m^3/annum (DWAF 2009) and the DWAF reconciliation of irrigation water use in 2009 puts irrigation at 970 million m^3/annum.

The outputs from the scenarios were then assessed to determine the various possible scenarios of the future water situation in the Vaal catchment in the context of climate change. The effectiveness of the current strategies to satisfy current, mid- and far-term intra-annual water demands in the catchment was analysed to inform future intra-annual water management planning.

RESULTS

Climate model validation

The performance of the RCM in the current climate was assessed by comparing it with average catchment observed temperature and precipitation data from 1976 to 2005, to determine the ability of the atmospheric models to simulate the observed climate. Such an approach helps to build confidence in the model data for future climate change projections. The outcomes of these assessments are shown in Figure 2(a), where the observed historical RCM after bias correction mostly agrees with catchment observed precipitation. Figure 2(b) demonstrates that ensemble historical average monthly temperature from the RCM has good agreement with observed catchment average monthly temperature.

Catchment's current climate

The observed SAWS climate was analysed as shown in Figure 3 to express the observed average monthly temperature and precipitation pattern in the catchment for the period 1989–2018. This is to indicate the current observed monthly climate pattern in the Vaal catchment. Temperature peaks in the summer months from November to January and drops to sub-zero temperatures in the winter months. The catchment falls within the summer rain region of South Africa with rainfall peaking in January.

Climate change scenarios

Using average climate ensemble in this study was an attempt to reduce the uncertainties in temperature and precipitation projections. For both temperature and precipitation, climate change scenarios are presented as differences between the current climate (baseline period) 1976–2005 climatology and climate for three future periods of: near-term (2011–2040), mid-term (2041–2070), and far-term (2071–2100) for RCP4.5 and RCP 8.5. These were calculated for each month to evaluate the intra-annual changes, presented in Figure 4.

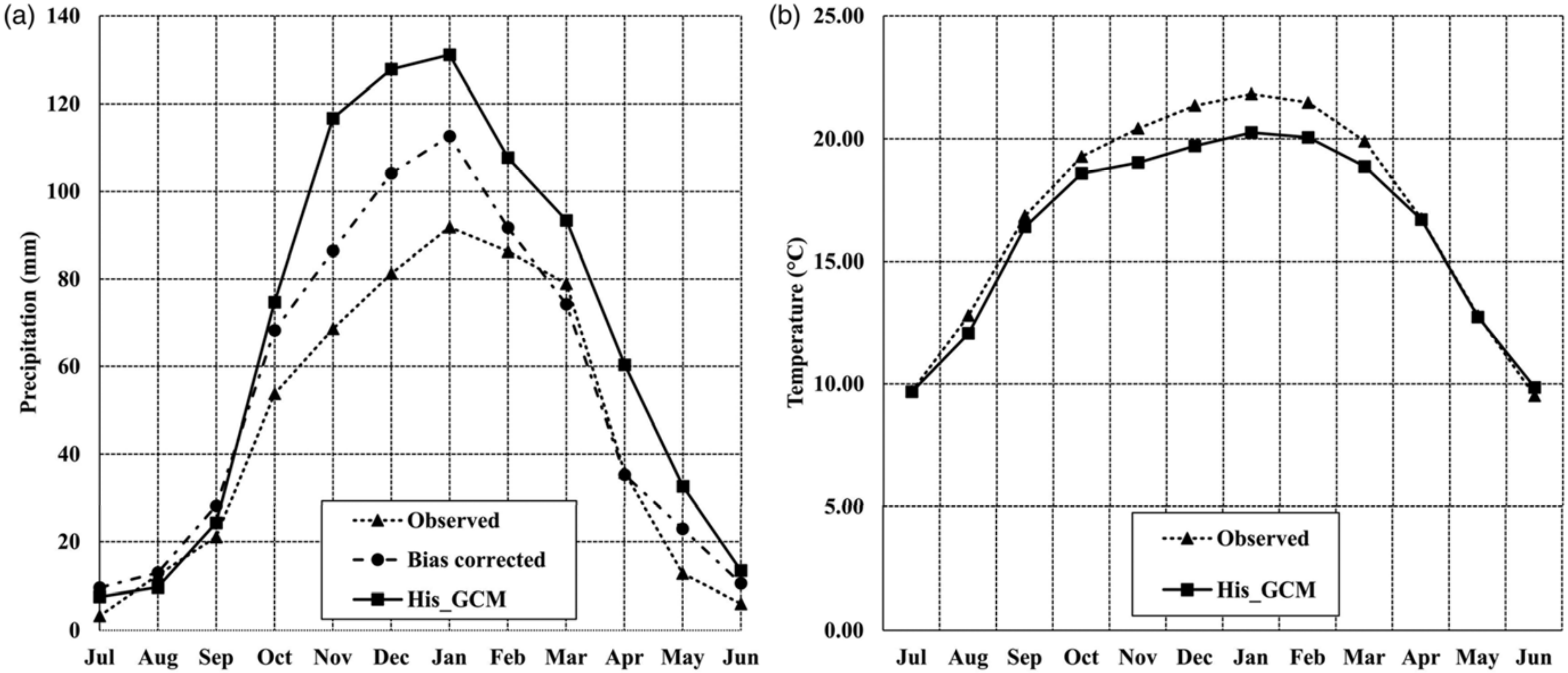

Figure 2. Vaal catchment current monthly climate: (a) showing the observed monthly SAWS precipitation, 1976–2005, plotted against the uncorrected historical ensembled precipitation from the RCM and the bias corrected ensembled RCM nested GCM; (b) ensembled historical average monthly temperature mirroring observed SAWS average monthly temperature.

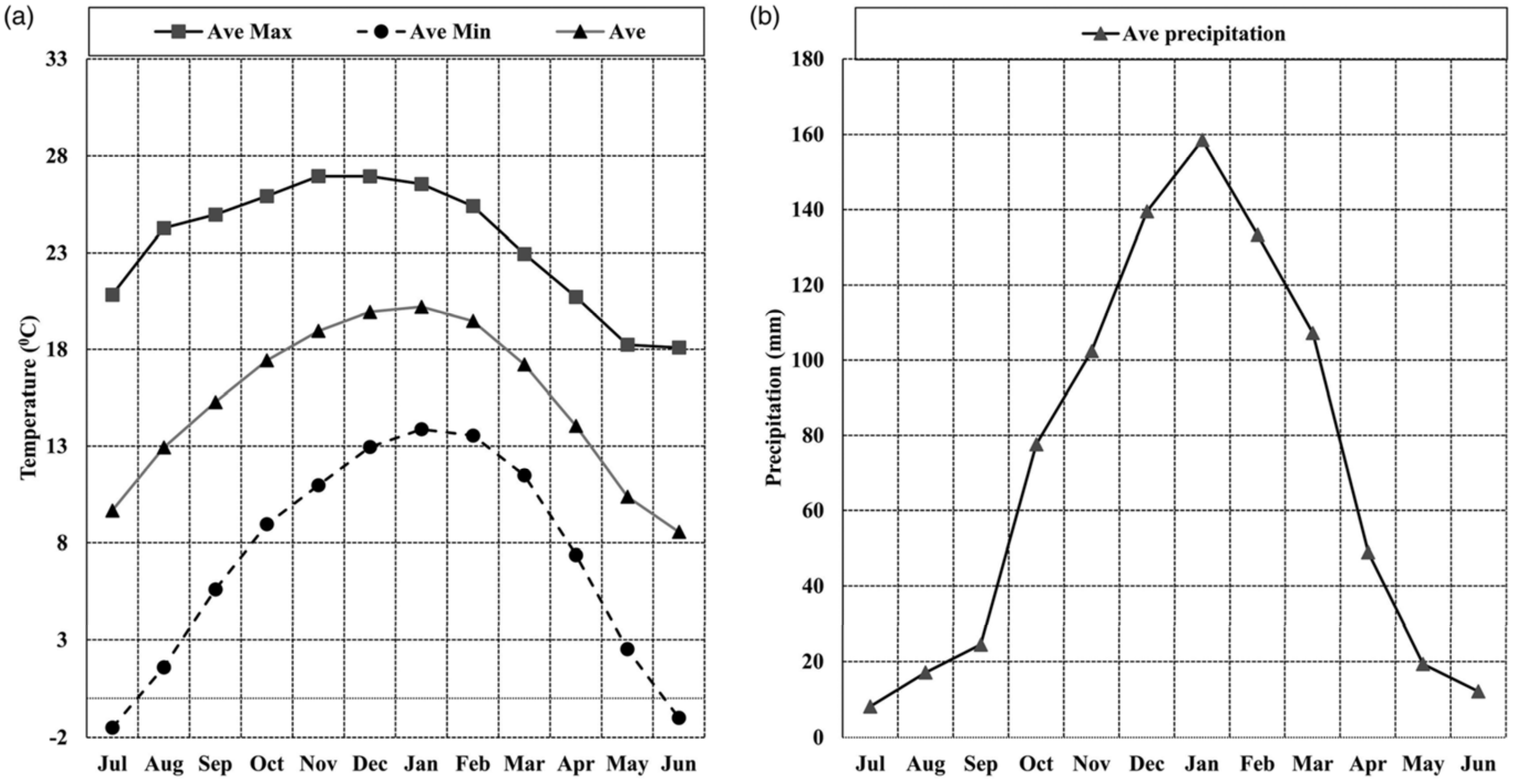

Figure 3. Showing the 30 years average catchment observed climate: (a) shows the monthly temperature pattern; and (b) precipitation.

Temperature

Changes in the intra-annual temperature pattern for the Vaal catchment during the period 2011–2100 are presented in Figure 4. The average monthly variation in temperature shows a general increasing trend for both RCPs for some of the months of the year. During the early term of 2011–2040, a slight decrease in temperature of between –0.31 and 0.71 °C is predicted for the summer months and increases of between 0.1 and 0.9 °C for the winter and spring months. For the mid-term (2041–2070) all the months show an increasing trend ranging from 0.3 to 1.8 °C. The far-term (2071–2100) has the highest increases, peaking at 2.4 °C in May for RCP 4.5 (Figure 4(a)). However, these are lower than those projected for RCP 8.5 (Figure 4(b)). Under RCP 4.5, winter months are projected to have the highest increases, and the summer months have the lowest increases in temperature. The highest increases under RCP 4.5 will be experienced during the period 2071–2100. Minimum projected temperature ranges from 2.8 to 14.47 °C for RCP 4.5, while maximum temperatures show an increasing trend of between 16.64 and 30.75 °C under RCP 4.5.

Temperatures under the RCP 8.5 are expected to show a slight decrease in the early term and increases in the mid- and far-terms. An increase of between 0.1 (lowest increase) to 5 °C (highest increase), with the highest monthly increases projected for the winter and spring months, were projected. Highest monthly increases are expected in the period 2071–2100 for RCP 8.5 as well. Average temperatures for both RCPs increased steadily from the onset of the projections in 2011 to the end of the century. Increases greater than 1.6 °C are predicted for both scenarios (Jury 2016). Minimum temperatures range between 3.3 and 17.4 °C for RCP 8.5. Maximum temperature increases are higher for RCP 8.5 compared to RCP 4.5 – ranging between 17.2 and 33.35 °C. Suitable adaptation measures are required for the vulnerable sectors in the catchment to mitigate impacts.

Rainfall

The outcome of the analysis of the variations in intra-annual predicted precipitation for the Vaal catchment for RCP 4.5 and RCP 8.5 are presented in Figure 4(c) and 4(d), respectively. As shown in Figure 4(c), an increase in precipitation for the RCP 4.5 scenario is expected in the early term summer months, and a decrease in the winter and spring months. This is followed by a dry mid-term for most of the months, and a drier far-term. Declines in precipitation of between 0.4 and 14% are projected for RCP 4.5 for the catchment. The mid-term (2041–2070) is the driest period under RCP 4.5.

The RCP 8.5 scenario shows a decreasing trend in most of the months in the early and mid-term. A slight increase is, however, predicted for the summer months in the far-term. The far-term (2071–2100) is the driest period for RCP 8.5. Decreases of between 1.5 and 30.2% are predicted for RCP 8.5, with the spring months experiencing the highest decreases in precipitation. The key implication of these projections for crop production (maize) in the catchment is that precipitation will be reduced predominantly during the maize planting season, when water is most required (Greyling & Pardey 2019).

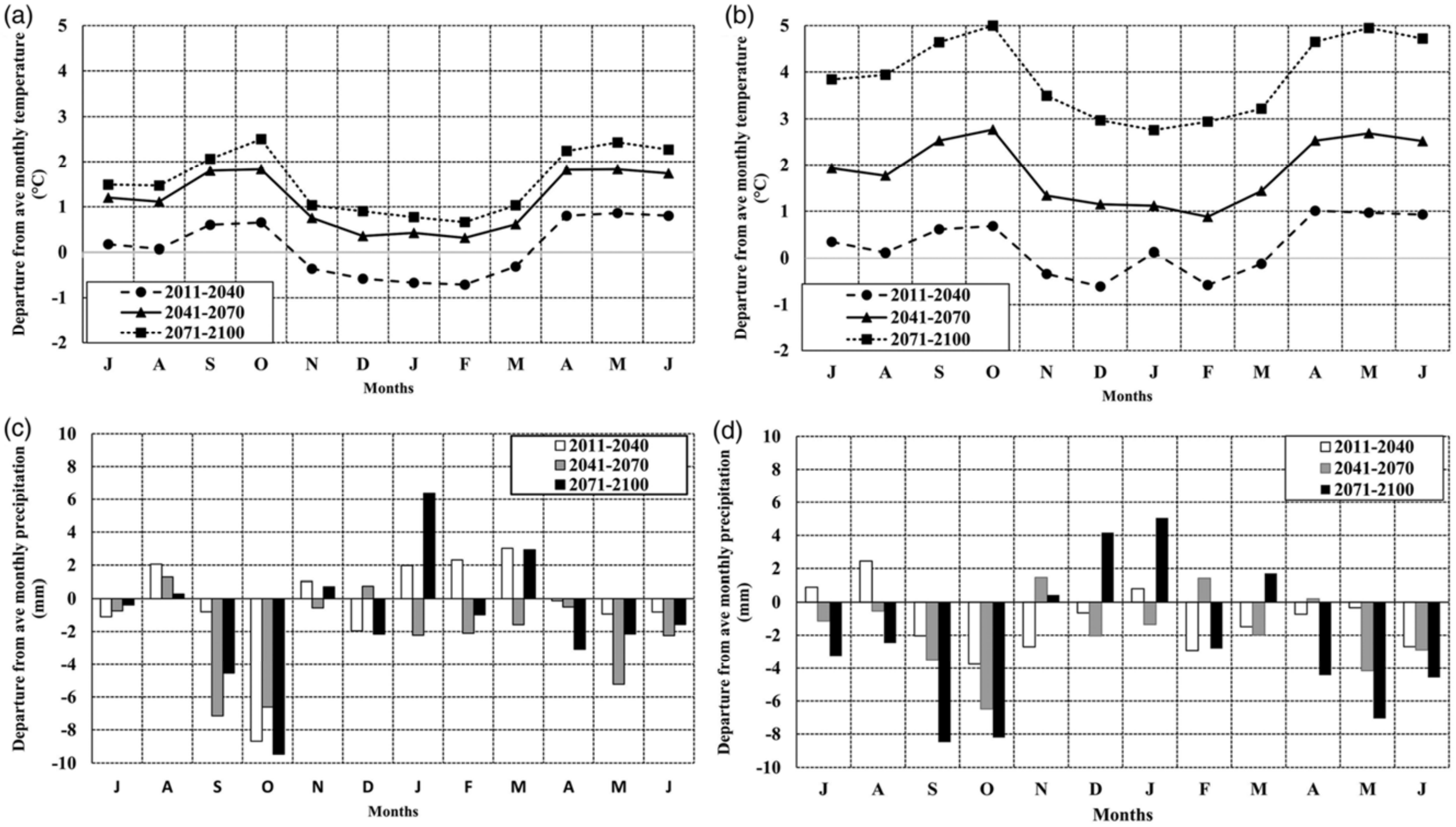

Figure 4. Vaal catchment future monthly climate departure from observed pattern: (a) 30 years temperature anomaly time slices for RCP 4.5 and (b) RCP 8.5; (c) and (d) showing 30 years precipitation anomaly time slices for RCP 4.5 and RCP 8.5 respectively.

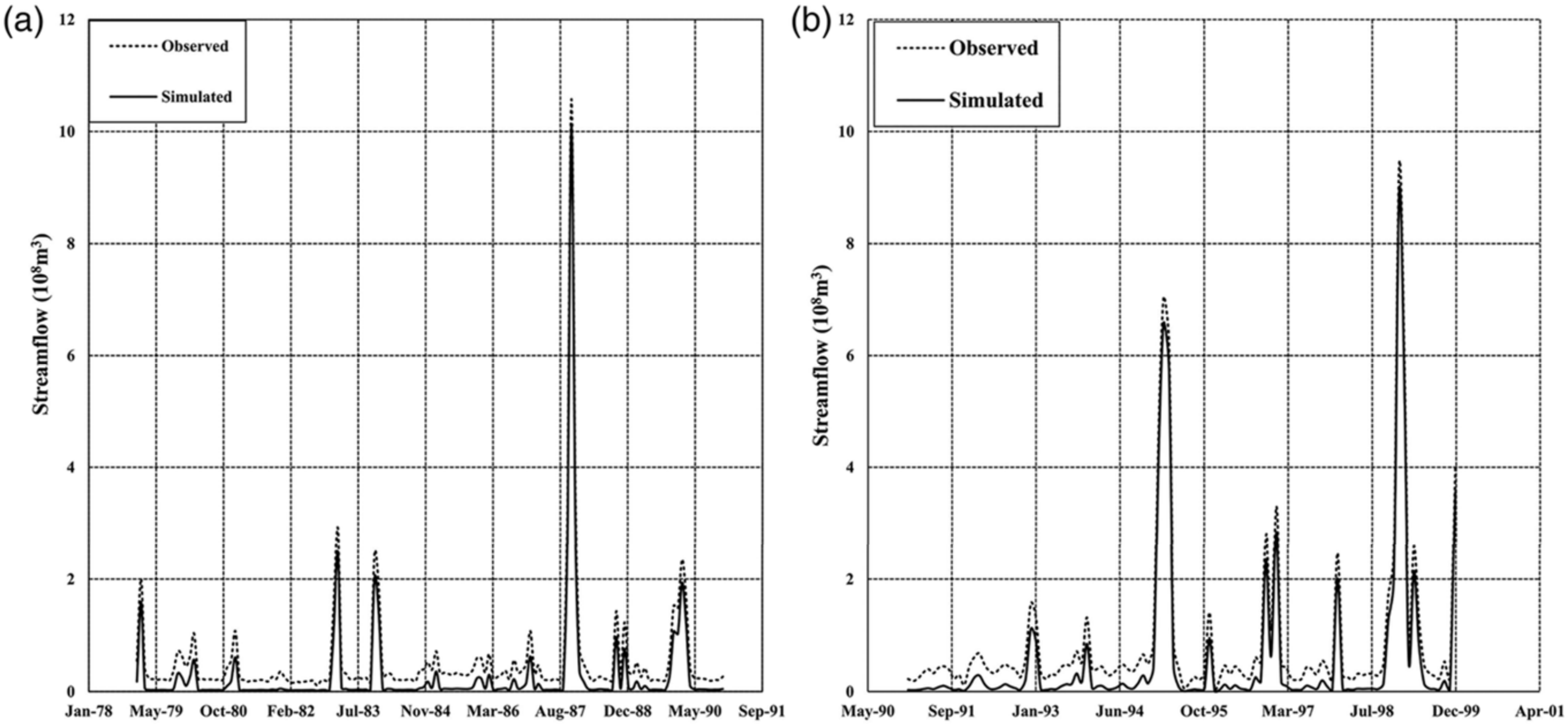

Figure 5. WEAP model calibration and validation using monthly simulated and observed streamflow from the gauge station at the outlet of the upper Vaal: (a) model calibration; (b) model validation.

Assessment of current and future water situation in the Vaal basin using WEAP

Model calibration and validation

The model is calibrated to adjust the model parameters to improve the fit between observations and simulated outputs from the model. The model was calibrated with streamflow from the gauge station located at the outlet of the Upper Vaal. The historical observed stream flow from 1979 to 1990 was used for calibration, while the model validation was for the period 1991–1999, as shown in Figure 5(a) and 5(b). The sensitivity of the model performance was checked with statistical performance indicators of coefficient of determination (R^2) of 0.993 and 0.995, Nash–Sutcliffe efficiency of 0.927 and 0.925, respectively. These correlations indicate that there is a good agreement between the modelled discharge and observed streamflow. This confirms the ability of the model to reproduce future streamflow trends.

Water availability

To assess the impact of climate change on current and future water availability in the catchment, projected climate data was used to force the WEAP model to simulate the effect of precipitation variation on streamflow. Two WEAP scenarios were developed for this purpose, i.e. the WEAP RCP 4.5 scenario assumes a more optimistic climate outlook, and the WEAP RCP 8.5 scenario assumes a more pessimistic climate outlook. Streamflow outputs from WEAP for the two scenarios were assessed to identify the difference in monthly patterns of streamflow and how they have deviated from the observed historical streamflow pattern.

The comparison of the simulated streamflow for the near- (2011–2040), mid- (2041–2070) and far- (2071–2100) terms for the two RCPs shows streamflow increasing by about 2% for the time slice 2011–2040 compared to the reference during the spring and summer months for RCP 4.5. The highest flow increase of 7% relative to the reference is predicted for February. The lowest streamflow output for RCP 4.5 was observed in June in the mid-term followed by a slight increase in the far-term. Minor increases are predicted for RCP 8.5 in the early term and a cumulative decrease for the time slice of about 7%. The decrease in streamflow for the period 2041–2070 was 8% for RCP 4.5 and 5% for RCP 8.5, predicting that RCP 4.5 is drier than RCP 8.5 in the Vaal catchment for that period. A peak decrease in monthly flow of up to 10% is anticipated for the month of January in the far-term. Drier summer months during the mid-term are predicted for RCP 4.5 and the far-term for RCP 8.5.

A maximum monthly streamflow reduction of up to 8% may be anticipated for RCP 4.5 in the mid-term and 10% for RCP 8.5 in the spring/summer months of the far-term. This corresponds to the onset of maize planting in the catchment. The November–March months are predicted to have the highest reduction in streamflow of all the months (Figure 6).

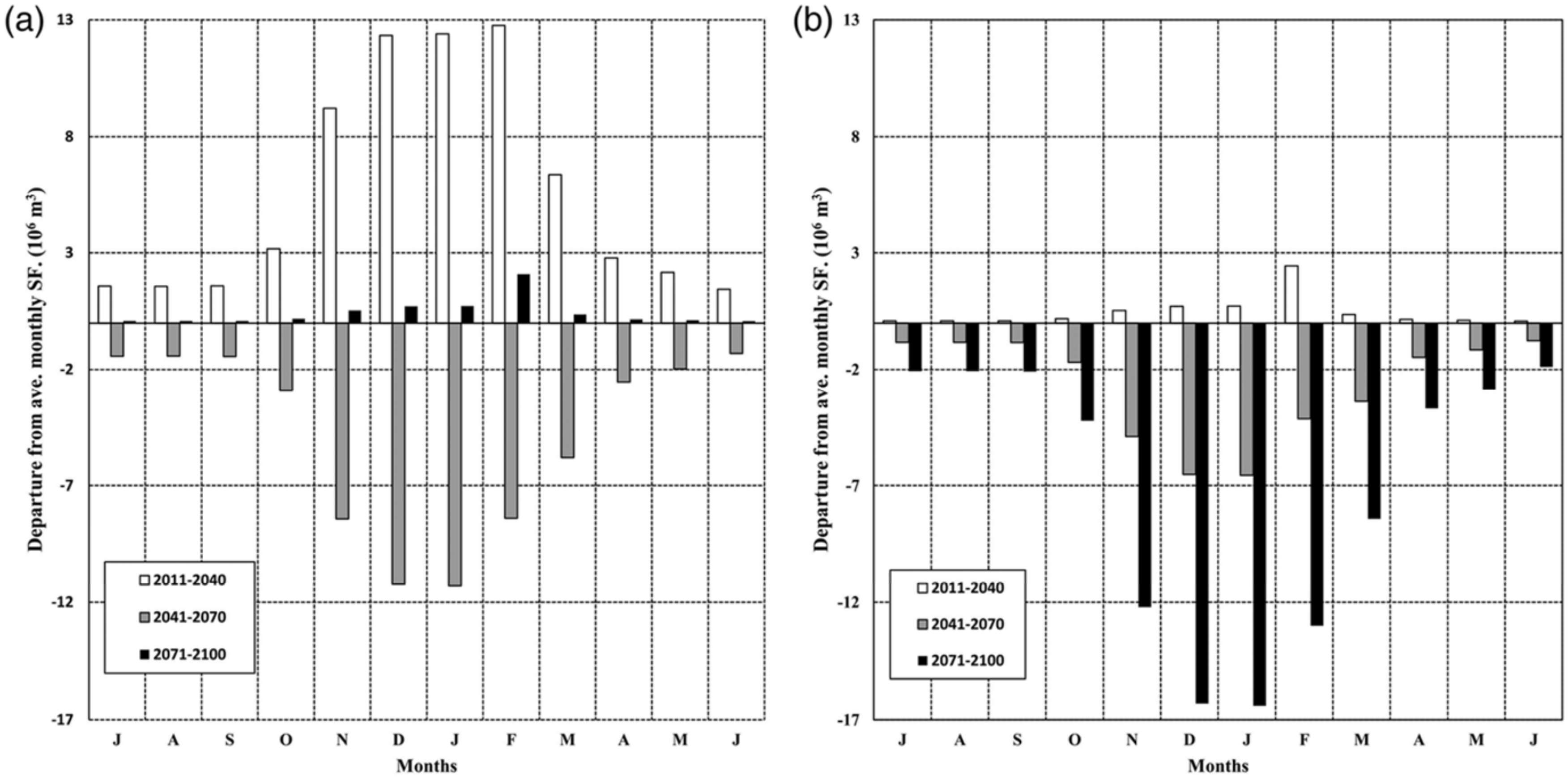

Figure 6. Impact of climate change on Vaal catchment intra-annual streamfllow variation, shown by (a) RCP 4.5 and (b) RCP 8.5. Predicted intra-annual streamflow depature from observed as influence by RCP 4.5 and RCP 8.5.

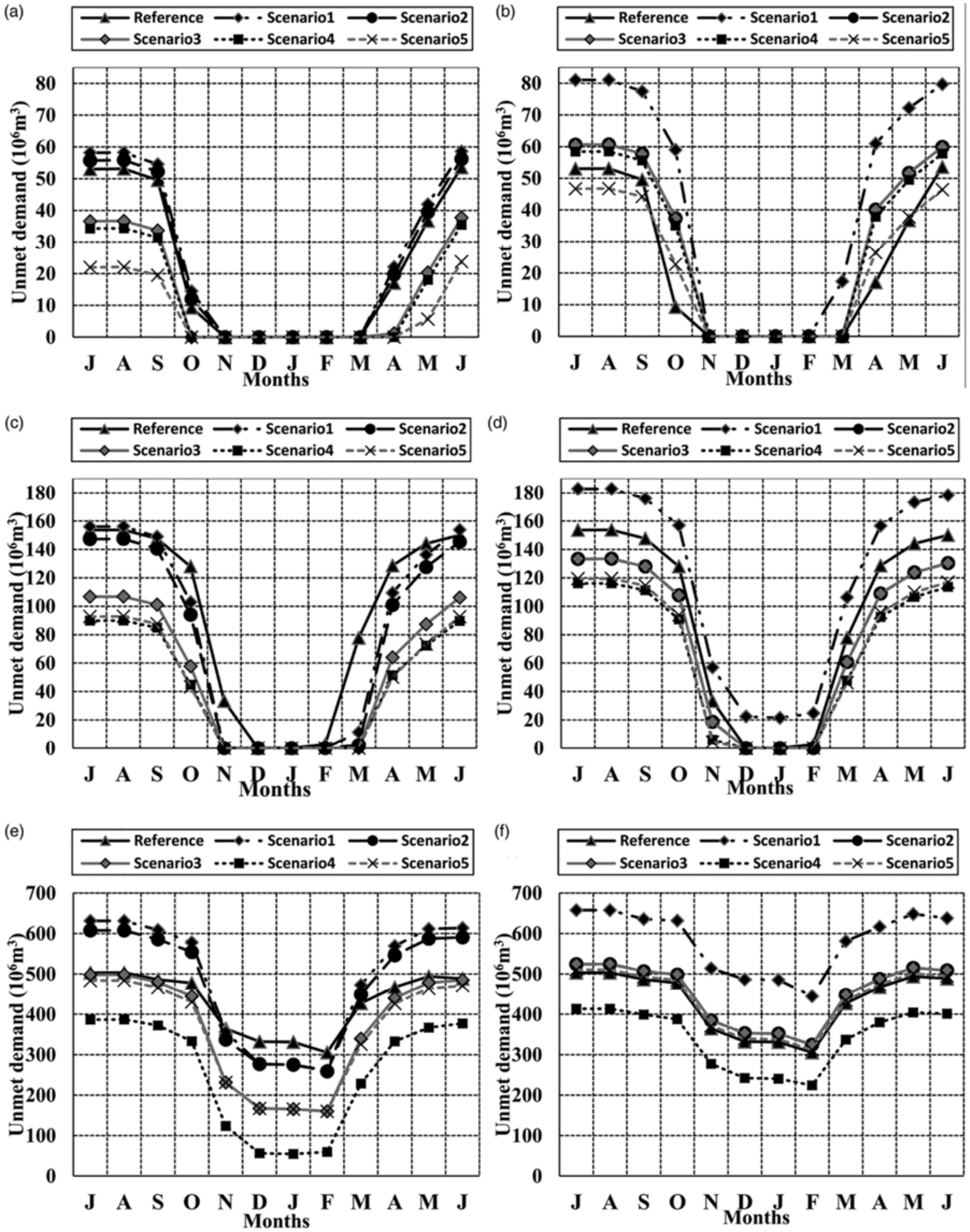

Figure 7. Unmet demand in the Vaal catchment based on the reference and five future WEAP scenarios. The plot presents the future projection of unmet water demand in the near-, mid- and far-terms under RCP 4.5 ((a), (c) and (e)), and RCP 8.5 ((b), (d) and (f)).

Possible future water demand and supply scenarios in the Vaal basin

The water requirement to meet the various demand nodes requirements in the catchment was totalled by the model to be 3.6 × $10^6$$m^3$ in 2009. The estimation of the inter annual water demand for the catchment indicated that the total water demand increased from 3.627 × 10^6 m^3 in the near-term to 4.913 × 10^6 m^3 in the mid-term, and 9.03 × 10^6 m^3 in the far-term. The monthly water demand peaks in the winter months and the lowest demand is experienced between January and March, which correlates with months of high precipitation. The monthly water flow in the catchment increased during the summer months.

The results of the analysis of alternative scenarios of changes in water demand and management option are presented below using the reference scenario and five future water demand and supply allocation scenarios to simulate the influence of future climate change on the ability of the Vaal basin to meet its future monthly water supply obligations. Figure 7 shows the different scenarios of water demand and supply in the Vaal catchment for three time slices and two emission scenarios.

WEAP Reference Scenario: A linear increase in water demand under this scenario was assumed to rise at the normal growth rate of 1.66% for the municipal water use. The results for this scenario show water demand being met in most of the spring and summer months. Under this scenario unmet demand is projected to be at the highest in July.

WEAP Scenario 1: With this scenario, population was assumed to be growing for the municipal water use at 0.22% higher than the normal growth rate of 1.6%. The assumption is based on the growth rate published in the 2009 Vaal Bulk Reconcillation strategy. The irrigation water use also grew from 1,092 × 10^6 m^3 at the onset of the projections in 2011 to 1,370 × 10^6 m^3 at the end of the century. The mining and industry sector were assumed to have minimal increases as new water licenses are no longer issued to those sectors in the catchment. The results under this scenario saw a projected average monthly water demand increase of about 3.2% grow to 17% by 2100, relative to the reference scenario at the start of the projection in 2011. Total unmet demand under this scenario increased from 16% for RCP 4.5 and 21% for RCP 8.5 in near-term, to 38% (RCP 4.5) and 41% (RCP 8.5) compared to the reference scenario in the far-term. For this scenario, demands were met in most of the spring, summer and autumn months for RCP 4.5 in the near-term but only in the summer months for RCP 8.5 in the near-term. Demands were, however, not met in the winter months for both RCPs in all the time slices, nor for any of the months in the mid- and far-term for RCP 8.5.

WEAP Scenario 2: For this scenario, assumption of a high population growth rate was applied. Mining and industrial water use was assumed to be constant. For the current account year of 2009, the area under irrigation in the basin was 146,342 ha, consuming 7,440 × 10^6 m^3 per hectare. Irrigation water use is assumed to remain constant under this scenario as it is assumed that the unlawful irrigation water use strategy was achieved, resulting in a 15% reduction in irrigation water use. Demand is assured under this scenario in the months of November to March in the period 2011–2040 for RCP 4.5 and 8.5. During the period 2041–2070, demands were only met from November to March for RCP 4.5 and

December to February for RCP 8.5. Demands are not met in any of the months in the period 2071–2100. Unmet demand was 10.5% (RCP 4.5) and 6.3% (RCP 8.5) less, relative to reference in the near-term, this increased to 27% (RCP 4.5) and 30% (RCP 8.5) in the period 2071–2100. The highest unmet demand will be experienced in the winter/early spring months of May to September while demands were met in the summer months.

WEAP Scenario 3: Assumes a high population growth, irrigation and mining water requirements remain constant. The intervention to reduce water loss strategy was assumed to have been achieved under this scenario, reducing municipal water use by 15%. The result shows that for this scenario demand could be met from October to April during the period 2011–2040 under RCP 4.5, and November to March for RCP 8.5 during the same period. Highest unmet demand will be experienced during the period 2070–2100 between May and August for RCP 8.5, with the July and August unmet demand dropping to 15% lower than reference. Demands for this scenario were mostly met in the summer months of the near-term; this steadly changes in the mid-term months, and by the end of the century, demands were not met in any of the months.

WEAP Scenario 4: This scenario adopts a lower population growth rate of 1.66% compared to scenarios 1–3. It assumes that socioeconomic factors highlighted in the scenario description resulted in a population and water requirement reduction in this scenario. Water conservation and demand management led to a 15% reduction in municipal water use in this scenario. There was no growth in the irrigation, mining and industrial sectors under this scenario. The results show water demand growing at the same rate as the reference. Unmet demand under this scenario was lower than the reference for both RCP 4.5 and 8.5 in the near-term, a decrease of –19% for RCP 4.5 and an increase of 11% for RCP 8.5. Demands were met in the summer months for both RCPs. Unmet demand peaked in the winter months for both RCPs in the period 2071–2100.

WEAP Scenario 5: This scenario assumes high population growth, expansion in irrrigation, and mining and industrial water demand kept constant. Water conservation and demand management, as well as a reduction in water loss and removal of unlawful water use, were expected to be achieved, ensuring a total of 30% reduction in water demand requirement under this scenario. The results predict water assurance between October and April in the near-term for RCP 4.5 and November–March for RCP 8.5. The 30% reduction in water demand for this scenario could result in up to a 65% reduction in unmet water demand compared to the reference scenario in the period 2011–2040 for RCP 4.5. Unmet demand for RCP 4.5 and 8.5 in the mid- and far-term were more pronounced in the winter and autumn months.

The Vaal Water conservation/water demand management (WC/WDM) plans were incorporated into these scenarios to assess the effect of a supply improvement plan to future water balance in the catchment in the context of a changing climate. The results show an unmet demand projection of 10 and 7.5% less than the reference for RCP 8.5 and 4.5, respectively. Water supply was, however, not satisfied for all the time slices under this scenario, despite the incorporation of the South African Department of Water and Sanitation's WC/WDM demand reduction strategy in its entirety (30%), supply was still not completely assured at the end of the near-term (2040) for all the months.

DISCUSSION

We assessed the additional impact presented by climate change on intra-annual water availability, demand and supply in the Vaal catchment. The study suggests that climate change impacts will occur concurrently with other existing catchment stressors such as population growth, economic expansion and governance issues. Using projected climate, five WEAP future scenarios of water use under RCP 4.5 and RCP 8.5 were examined. Analysis from the results confirms that the Vaal catchment is water stressed with impacts of climate change already manifesting in the catchment as concluded in the study by Jury (2016). Concurrent with Jury's (2016) suggestion, we therefore propose that alternative supply and demand trajectories for the catchment are required to ensure sustainable future intra-annual water availability.

The initial step in the study evaluated the intra-annual climatic changes that have occurred in the catchment and estimated future changes. The results confirm a warming trend of between 0.07 and 5 °C, in alignment with the predictions of Nyoni *et al.* (2019). Changes in temperature are expected to trigger changes in precipitation patterns and result in water availability variation. Precipitation is expected to increase slightly in the early term, but a cumulative decrease of between 0.4 and 30.2% reduction is predicted under the two emission pathways, a finding which is corroborated by the Kusangaya *et al.* (2014) study.

To understand how these changes may influence intra-annual water availability the study compared projected changes in water availability under the two climate emission pathways.

The Vaal catchment is a water stressed basin where intra-annual water supply shortfall is predicted for the winter months and many of the summer months beyond 2040. These challenges were further evaluated to understand the impact of the projected change in climate on future intra-annual water availability in the catchment. Monthly simulated river flow analysis, during three future time slices, was compared under the two climate emission pathways. The pattern obtained indicates that the WEAP model was effective in assessing the intra-annual variation in current and future water availability under RCP 4.5 and RCP 8.5. A similar correlation was reported by Kusangaya *et al.* (2014).

Comparing unmet demand for each plausible future scenario of water use under RCP 4.5 and RCP 8.5 showed variation. None of the future scenarios could however assure the total intra-annual water requirements in any of the time slices assessed as climate change is expected to reduce rainfall and increase evaporation due to temperature increases in the Vaal catchment.

Only a few scenarios in the early term were able to meet total demand in the summer and spring months. This agrees with the 2009 reconciliation strategy projections which indicated that the catchment would be experiencing shortages long before 2019 (DWAF 2009). The catchment's water challenge is intensified in the winter and autumn months due to precipitation reduction. This situation is exacerbated by the insufficiency of current water management strategies leading to intensified levels of unmet water demands from 2040.

Land use in the catchment is predominantly for agricultural use, mainly maize production, making temperature and rainfall extremes a limiting factor in crop production in the catchment (Greyling & Pardey 2019). The catchment will therefore benefit from a combination of scenarios such as scenarios 4 and 5 and further augmentation of the river through inter-basin transfers, water loss reduction and wastewater re-use. This could reduce unmet demand during the winter, summer and autumn months. Given the insufficiency of current management and conservation strategies, inter-basin transfers in the winter and autumn months would thus still be required to address future needs.

The intra-annual assessment of the influence of climate change on the catchment, using five plausible scenarios of water uses, suggests future deficits in water assurance in the catchment. Our findings suggest that in certain instances where annual water balance is expected, imbalance may occur at intra-annual levels. Simulated WEAP scenarios also projected that this imbalance may be exacerbated by changing environmental conditions that need to be addressed and planned for. We therefore suggest an update of the Vaal water management strategy for sustainable water availability in the catchment.

CONCLUSIONS

The impact of climate change on intra-annual water availability required to meet current and future water demands in the Vaal catchment of South Africa was investigated in this study. A combination of climate change projection analysis/WEAP hydrological modelling and socioeconomic considerations was used in the assessments. Intra-annual changes in temperature, precipitation and streamflow were assessed and trends in water demand and supply were estimated using the WEAP model. The current and future monthly water availability in the catchment was determined, and the range of water users and uses in the catchment investigated.

Findings from the study highlight the need for integrated water resource planning and optimal allocation of water resources in the catchment. Study outcomes estimate that water resources in the Vaal basin may be insufficient to meet all the current and future intra-annual water demand requirements in the catchment. Water users are therefore currently experiencing limitations, which are likely to be further aggravated by future changes in climate. The most vulnerable sector in the catchment is expected to be the agricultural sector as the highest monthly increases in temperature and decrease in precipitation are to be experienced during the grain planting seasons, leading to higher unmet demand for the sector. The catchment, being an important staple food production region, is already experiencing constraints in grain production as areas planted under maize continue to decline. Failure to meet the water requirements in the sector may therefore impact the country's food security status. The results also highlight the need for a combination of adaptive plans, climatic/non-climatic stressor monitoring, conservation and demand management to reduce future intra-annual uncertainty in water assurance that may hamper economic and developmental expansion in the Vaal catchment of South Africa.

Using the WEAP model allowed for an integrated approach to understanding the impacts of climate change on the hydrological processes in the catchment and the study was able to estimate the nature of future challenges in the intra-annual water availability in the Vaal catchment. The WEAP model allowed us to investigate climate influence alongside other stressors which highlights the fact that climate influence does not occur in isolation to other stressors in the Vaal catchment. The comparative assessment of the different scenarios options for possible interventions did not yield a single concise solution, but suggest the combination of options for an effective policy to ensure water security in catchments. The study highlights the need for additional interventions to reduce current water uses, introduce strategies to increase supply and adapt to climatic changes before the end of the near term as findings identify challenges in water supply before the end of this period.

Despite the predicted uncertainties in water availability found in the study, from a methodological perspective some limitations need to be acknowledged. The calibration and validation outputs from WEAP confirmed that the model was able to simulate observed streamflow accurately, but the lack of up to date water reconciliation data for the catchment was a significant constraint. The incomplete hydro-meteorological data was also a challenge and the study could have also benefitted from access to higher resolution climate data. For future research, we would therefore recommend that simulations in this model are run with data as close to the current date as possible, with higher resolution predicted climate data.

ACKNOWLEDGEMENTS

The authors are grateful for the assistance of the South African Weather Services personnel for providing information and assistance in the collection of data. We also extend our gratitude to the National Department of Water and Sanitation of South Africa for their online hydrological data.

REFERENCES

Adewunmi, J., Ilemobade, A. & Van Zyl, J. 2010. Treated wastewater reuse in South Africa: overview, potential and challenges. *Resour. Conserv. Recycl*. 55(2), 221–231.

De Jong, P., Barreto, T., Tanajura, C., Kouloukoui, D., Oliveira-Esquerre, K., Kiperstok, A. & Torres, E. 2019. Estimating the impact of climate change on wind and solar energy in Brazil using a south American regional climate model. *Renew. Energy* 141, 390–401.

Department of Water Affairs. 2013. *National Water Resources Strategy*, 2nd edn. Available from: www.dwa.gov.za/documents/Other/Strategic%20Plan/NWRS2-Final-email-version.pdf (accessed 28 March 2019).

Department of Water Affairs and Forestry, South Africa, March 2009. Vaal River System: Large Bulk Water Supply Reconciliation Strategy: Second Stage Reconciliation Strategy (March 2009). DWAF Report Number: P RSAC000/00/4406/08. Available from:http://www6.dwa.gov.za/Vaal/documents/LargeBulkWater/05_Water%20Resource%20Analysis_Final.pdf (accessed October 2018).

Department of Water Affairs and Sanitation (DWS) 2015. *Business Case for the Vaal River Catchment Management Agency*. Available from: www.dwaf.gov.za/campaigns/singleCMA/Docs/Annexures/Annexure%20A%20Vaal%20Business%20Case.pdf (accessed 17 March 2019).

Department of Water Affairs and Sanitation (DWS) 2016. *Establishment of the Vaal River Catchment Management Agency.* Staatskoerant, 29 January 2016. No. 39636 57. Available from: https://cer.org.za/wp-content/uploads/2010/05/Establishment-of-the-Vaal-River-CMA.pdf(accessed23 March 2019).

Dosio, A. 2017. Projection of temperature and heat waves for Africa with an ensemble of CORDEX regional climate models. *Clim. Dynam*. 49(1–2), 493–519.

Engelbrecht, C. & Engelbrecht, F. 2016. Shifts in köppen-geiger climate zones over Southern Africa in relation to key global temperature goals. *Theor. Appl. Climatol*. 123(1–2), 247–261.

Grecksch, K. 2015. Adaptive capacity and water governance in the Keiskamma River Catchment, Eastern Cape Province, South Africa. *Water* SA41(3), 359–368.

Greyling, J. & Pardey, P. 2019. Measuring maize in South Africa:the shifting structure of production during the twentieth century, 1904–2015. Agrekon 58(1), 21–41.

Homsi, R. S., Shiru, M., Shahid, S., Ismail, T., Bin Harun, S. B., Al-Ansari, N., Chau, K. & Yaseen, Z. 2020. Precipitation projection using a CMIP5 GCM ensemble model: a regional investigation of Syria. *Eng. Appl. Comput. Fluid Mech.* 14(1), 90–106.

Ilunga, M. 2017. Assessing catchment resilience using entropy associated with mean annual run off for the Upper Vaal catchment in South Africa. *Entropy* 19(5), 147.

Jury, M. 2016. Climate influences on Vaal riverflow. *Water SA* 42(2), 232–242.

Kusangaya, S., Warburton, M., Archer van Garderen, E. & Jewitt, G. 2014. Impacts of climate change on water resources in Southern Africa: a review. *Phys. Chem. Earth A B C* 67–69, 47–54.

Leong, W., Lai, S. & International Technical Postgraduate Conference 2017 Tech-Post 2017 2017 04 05–2017 04 06 2017. Application of water evaluation and planning model for integrated water resources management: case study of Langat river basin, Malaysia. *IOP Conf. Ser: Mater. Sci. Eng*. 210(1),012024-012024. IOP Publishing Ltd., Bristol, UK.

Mahlobo, 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. *Int. J. Climatol.* 39(4), 1805–1821.

Mantel, S., Hughes, D. & Slaughter, A. 2015. Water resources management in the context of future climate and development changes: a South African case study. *J. Water Clim. Change* 6(4), 772–786.

Mosavi, A., Ozturk, P. & Chau, K. W. 2018. Flood prediction using machine learning models: literature review. *Wate*r 10, 1536.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. 2014. Africa. In: *Climate Change2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects* (Barros, V. R., Field, C. B., Dokken, D. J., Mastrandrea, M. D., Mach, K. J., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R. & White, L. L., eds.). Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1199–1265.

Nyoni, N. M. B., Grab, S. & Archer, E. R. M. 2019. Heat stress and chickens: climate risk effects on rural poultry farming in low-income countries. *Clim. Dev.* 11(1), 83–90.

Oberholster, P. J. & Ashton, P. J. 2008. *State of the Nation Report: An Overview of the Current Status of Water Quality and Eutrophication in South African Rivers and Reservoirs: CSIR/NRE/WR/IR/2008/0075/C.* Available from: www.researchgate.net/publication/242668373_An_Overview_of_the_Current_Status_of_Water_Quality_and_Eutrophication_in_South_African_Rivers_and_Reservoirs (accessed 24October 2018).

Otieno, F., Oching, G., Haji, H. & Dzwairo, B. 2009. Integrated water management of the Vaal river catchment. *Civil Eng*. 17(5), 37–40.

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. *Reg. Environ. Change* 17(6), 1585–1600.

Shrestha, M. 2015. *Data Analysis Relied on Linear Scaling Bias Correction (V.1.0) Microsoft Excel File*. Available from: www.researchgate.net/publication/289290337_Linear_Scaling_bias_correction_V10_Microsoft_Excel_file (accessed 05 June 2019).

Statistics South Africa 2010. *Water Management Areas in South Africa*. Discussion document (D0405.8) Statistics South Africa, October 2010. Available from: www.statssa.gov.za/publications/D04058/D04058.pdf(accessed 4 November2018).

Stockholm Environment Institute (SEI) 2015. *WEAP (WaterEvaluation and Planning): User's Guide*. Available from: www.weap21.org/downloads/WEAP_User_Guide.pdf (accessed 19 March 2019).

Walker, N. & Schulze, R. 2008. Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agric. Ecosyst. Environ*. 124 (1–2), 114–124.

Wepener, V., Van Dyk, C., Bervoets, L., O'Brien, G., Covaci, A. & Cloete, Y. 2011. An assessment of the influence of multiple stressors on the Vaal river, South Africa. *Phys. Chem. Earth* 36(14–15), 949–962.