IMPACT OF CLIMATE CHANGE ON EVAPOTRANSPIRATION AND RUNOFF IN AWASH BASIN IN ETHIOPIA

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ABSTRACT: Quantitative estimates of hydrologic effects of climate change are essential for understanding and solving potential water resources management problems associated with water supply for domestic and industrial water use, irrigation, power generation, flood mitigation, and agriculture as well as for the protection of the natural environment. Evapotranspiration (ET) is an important part of the hydrologic cycle and an important indicator for climate change. However, the lack of accurate estimation of potential evapo-transpiration (PET) is a major problem for hydrologic studies involving water resources modeling under both stationary and changing climate conditions. The Awash River Basin is the most important river Basin in Ethiopia that covers a total land area of 113,700 km^2, and serves about 10.5 million inhabitants. It covers a wide range of climatic zones from humid subtropical to arid region. The objectives of this research were to study the impacts of climate change scenarios on precipitation and PET of the Awash River Basin, to investigate how these changes can impact the runoff in the basin, and to study the differences in hydrologic responses between the different Awash sub-Basins.

This research starts with a comparison between the estimates of PET using Penman-Monteith and Thornthwaite methods to identify the more appropriate method for the basin. Three Global Climate Models (GCMs): CCCMA-CGCM3.1 (Canadian), CNRM-CM3 (French) and MPI-ECHAM5 (Deutsche) were investigated under two emission scenarios, A2 and B1. Temperature and precipitation data were used for the prediction of future climate impact on PET and runoff in the basin. Finally the Hydrologic Modeling System (HEC-HMS) was calibrated for the Awash basin and then used to predict the impact of climate change on the runoff and the overall hydrologic cycle of the basin using future predictions of precipitation and PET data under A2 and B1 climate change scenarios. Simulations covered the period from 2010 to 2089.

The results demonstrated that the Modified Penman-Monteith is more consistent and reliable than Thornthwaite method for the studied Basin. All Global Circulation Models showed that temperature is rising. Consequently, the result of PET has an increasing trend for all periods throughout the Basin. The calibrated HEC-HMS model was used to predict the impact of the A2 and B1 scenarios on the future flows of the three Awash sub-basins. Based on our results, the impact of climate change on the Upper Awash Basin flow rate is minimal (within the data inaccuracy limit). However, an average increase of over 30% in the Middle Awash Basin can be expected, and an average decrease in the Lower Awash Basin could occur. A2 was found to cause more impact on precipitation and stream flow than B1.

The study has potential usefulness in demonstrating the use of the results from climate change models in the field of applied hydrologic research. It can also aid in water resources management of the region. Thus any water resource project to be implemented in the Lower Awash Basin should consider that the water availability may decrease by 30% in the future and should factor in this possibility in the risk analysis of the water resources master plan of the basin. The modeled increase in the flow rate of the middle and upper Awash Basins should be factored in flood management scenario of the region.

BACKGROUND AND INTRODUCTION

Evapotranspiration (ET) is an important part of the hydrologic cycle and an important indicator for climate changes (Peterson et al., 1995; Brutsaert and Parlange, 1998). The lack of accurate and calibrated estimations of ET poses a number of problems in hydrologic studies and water resources modeling under stationary and changing climate conditions. Within the context of global warming and climate change, the change in ET needs to be studied and calibrated based on local data. In addition, the impact of these changes on the hydrologic cycle needs to be studied. To effectively address these problems, this research project focuses on the study of the impact of climate change over the Awash River Basin in Ethiopia.

The objectives of this research are: (1) to study the impacts of climate change on precipitation and potential evapotranspiration (PET) of the Awash Basin in Ethiopia, (2) to investigate how these changes can impact the runoff in the Basin, and (3) to study the range of hydrologic responses for the different Awash sub-Basins (Upper-, Middle-, and Lowr-Awash sub-basins). The Awash River Basin was chosen for the case study for a number of reasons, primarily because it covers a wide climatic zone (from humid subtropical to arid), its importance to water resources in Ethiopia, and the availability of data for model calibration and validation.

Siam (2010) studied climate change impacts in the Upper Blue Nile catchment. He used three Global Circulation Models (GCMs) (The Canadian CGCM 3.1, the French CNRM-CM3 and the American GFDL-CM2); each tested for the two IPCC scenarios; the mid-high (A2) and the low scenarios (B1). The results of downscaling were used as inputs for the hydrological modeling to predict the upper Blue Nile catchment flows while testing two different approaches; artificial neural network (ANN) and HEC-HMS for flow predictions. The results showed a possible decrease by about 20% under the GFDL model and a probable increase by about 40% under the CNRM model both using the A2 scenario.

Kinfe (1999) made an attempt to investigate the sensitivity of water resources to climate change in the Awash River Basin in Ethiopia. Station-based meteorological data were processed and used in the study. Different sets of temperature and rainfall scenarios were developed using GCM data (both transient and CO_2 doubling). The IIASA integrated water balance model (WatBal) was used to estimate runoff under climate change scenarios. Results of the impact assessment over the Basin showed a projected decrease in runoff, ranging from 10 to 34%, with doubling of CO_2. However, the results did not take into consideration the different climate zones of the Awash sub-basins.

DESCRIPITION OF STUDY AREA

The Awash River Basin is the most important river Basin in Ethiopia that covers a total land area of 113,700 km^2, and serves about 10.5 million inhabitants. The river rises on the High plateau near Ginchi town west of Addis Ababa in Ethiopia and flows along the rift valley into the Afar triangle, terminating in salty Lake Abbe on the border with Djibouti, being an endorheic Basin. The total length of the main course is about 1,200 km. Based on physical and socio-economic factors the Awash Basin is divided into upper, middle and lower basins (Figure 1).

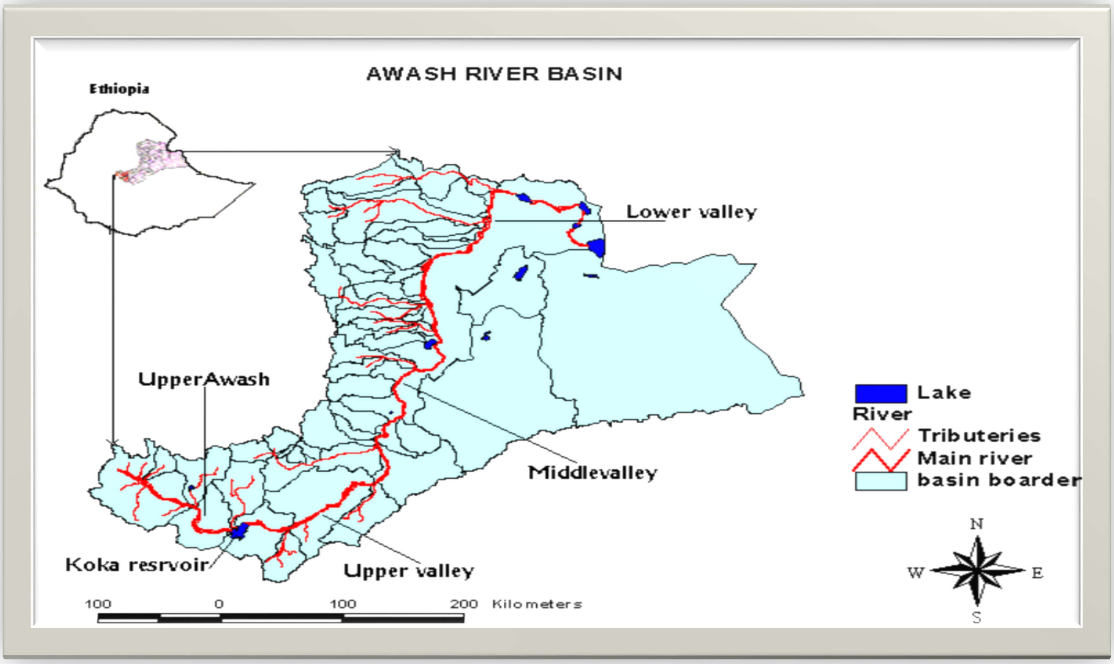

Figure 1. Awash Basin and its classification in zones

The Awash Basin covers the central and northern part of the rift valley and is bounded to the west, southeast and south by the Blue Nile, the Rift Valley Lakes and Wabishebelle Basins, respectively. The study is concentrated on the upper, middle and lower areas of the Basin as the main sub catchments of the Awash River Basin.

The climate of the Awash Basin comes under the influence of the Inter-Tropical Convergence Zone (ITCZ). This zone of low-pressure marks the convergence of dry tropical easterlies and the moist equatorial westerlies. The mean annual rainfall varies from about 1600 mm at Ankober, in the highlands northeast of Addis Ababa (west limit of the Basin) to 160 mm at Asayita on the northern limit of the Basin. The mean annual wind speed at Koka averages 1.2 m/s, the windiest months being June and July with mean monthly values of 1.9 and1.6 m/s respectively (Abrha, 2006).

METODOLOGY

The general methodology in carrying out this study can be summarized as follows:

(i) Digitizing the observed meteorological data; (ii) Pre-processing of data (Outliers, fill missing data, consistency tests); (iii) Calculating PET using different methods (Penman-Monteith and Thornthwaite); (iv) Comparing PET estimation methods and picking the most consistent and reliable method for the Basin; (v) Downloading GCMs data (Temperature and Precipitation); (vi) Calculating the future PET under A2 and B1

Scenarios; (vii) Calibrating the hydrologic modeling (HEC-HMS) with actual measurements; and (viii) using the calibrated model to investigate how the change in PET and precipitation impact the Basin runoff under the A2 and B1 climate change scenarios.

DATA PRE-PROSSECING AND ANALYSIS

The raw meteorological weather variables were collected by the National Meteorological Service Agency of Ethiopia. The records are monthly daily averages from 13 class-one weather stations in the Basin. The weather variables include daily maximum and minimum temperatures, daily average wind speed, sunshine hours and, relative humidity.

Most of the meteorological raw data were in hard copies and not processed. Therefore, the first task was to digitize a bulk of data in a database. The Grubbs and Beck (1972) test (G-B) was used to detect data outliers. Least square regression and simple average methods were used to fill the gaps for each station. The data consistency test was applied to check the quality and fitness of the variables.

Global climate models (GCMs) are representations of earth processes and are performed in powerful computers by climatic research centers over the world. To date, a variety of GCMs have been developed, tested, and their results have been made available to the public (IPCC, 2001, 2007). GCM output, from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007), were obtained from http:\\www.engr.scu.edu/~emaurer/global_data/. These data were downscaled as described by Maurer et al. (2009) using the bias-correction/spatial downscaling method (Wood et al., 2004) to a 0.5 degree grid, based on the 1950-1999 gridded observations of Adam and Lettenmaier (2003).

In this study; three GCMs, CCCMA-CGCM3.1 (Canadian), CNRM-CM3 (French) and MPI-ECHAM5 (Deutsch), for the SRES A2 and B1 emission scenarios (IPCC, 2000) were used. The data were in NetCDF format so that Intel(R) Array Viewer and MATLAB software were used to read and extract the required values. The data were downloaded for the period from 1986 to 2089 on a monthly time step.

The first task was to compare the Global circulation model data with the observed temperature and precipitation data to check the correlation and fitness of the data. The monthly average temperature and precipitation data for the period of (1986-2005) were downloaded from each model and checked with the observed data and was found be in agreement with each other. The inverse distance weighting technique of the grid method (Solomon & Cordery, 1984) was used to obtain sub catchment average temperature and precipitation data.

The analysis of the results revealed an expected increase in temperature for all periods using all scenarios and models (CGCM 3.1, CNRM-CM3 and MPI-ECHAM5). The range of change in temperature was within 0.02 ^{o}C to 0.22 ^{o}C in the short run and 1.65 ^{o}C to 3.31 ^{o}C in the long run in the Basin. Precipitation increases from 1.8 to 9.6% in some models and decreases from 1.5 to 3.8% in other models in the Upper Awash Basin, increases from 21.6 to 48.1% in Middle Awash Basin, and decreases from 2 to 22% in Lower Awash Basin.

PET FORECASTING

The observed Meteorological data were used to calculate the monthly mean daily PET with Penman-Monteith (FAO, 1998) and the Thornthwaite methods. The comparison of the results with the measured values obtained in Melka Werer Research Institute (MWRI) lead to identifying the suitable method to calculate the future PET in the Basin under the studied climate change scenarios. Figure 2 depicts modeled versus measured PET in the Lower Awash basin as an example.

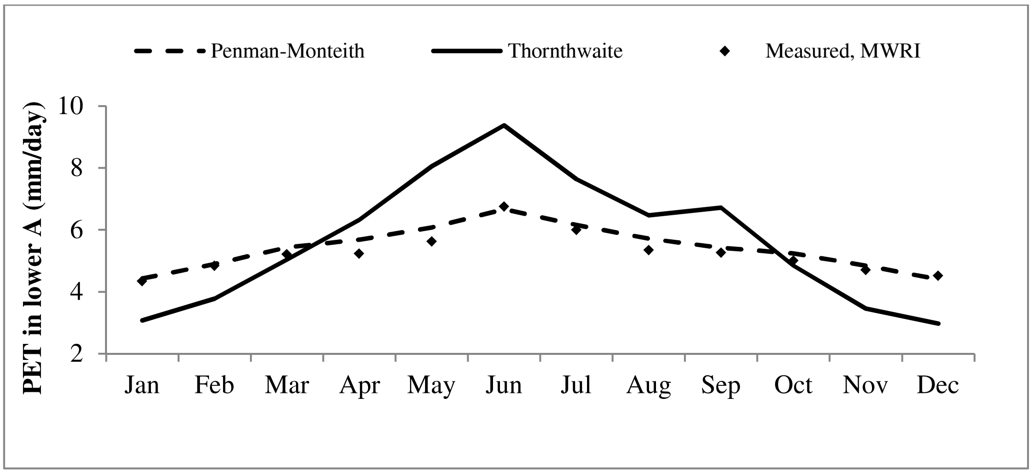

Figure 2: PET comparison in the lower Awash Basin

There are significant differences for the estimation of PET between Thornthwaite and Penman-Monteith methods. On seasonal basis, the overestimation by the former is found in Lower Awash Basin from April to September and underestimation in Upper Awash Basin over the whole seasons. Moreover, the measured values of PET obtained from Melka Werer Research Institute (MWRI) was found to be in better agreement with the modified Penman-Monteith predictions than the Thornthwaite predictions, suggesting that the modified Penman-Monteith method is more suitable for PET predictions in the Basin.

Therefore, this method was used with the downscaled temperature data to calculate the PET of the future period (2010-2089) under the studied climate change scenarios. Results for Upper and Lower Awash Basins are shown in Tables 1 and 2 and on Figures 3 and 4, respectively.

Table 1: Percentage change in PET in Upper Awash Basin

Models	Models and Scenarios			
	CGCM		CNRM	
	A2	B1	A2	B1
2010-2029	1.53	1.28	1.02	0.51
2030-2049	2.81	2.30	2.30	1.53
2050-2069	5.37	3.58	5.11	3.07
2070-2089	7.67	4.09	7.42	N/A

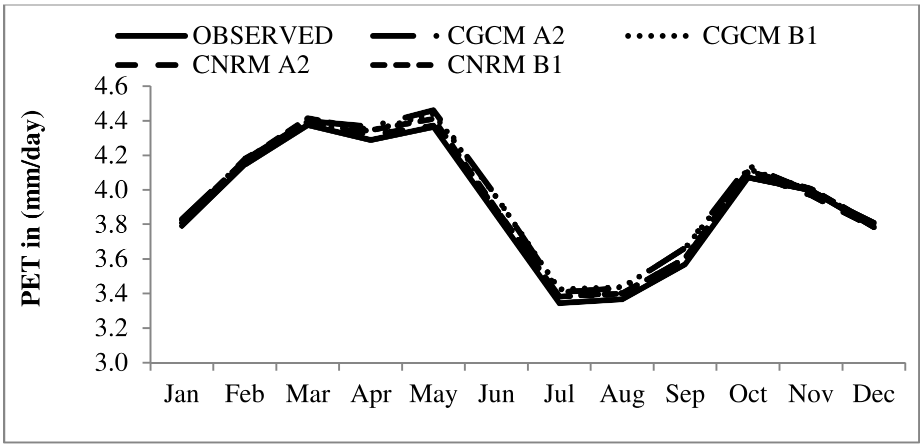

Figure 3a: Monthly average PET in upper Awash Basin (2010-2029)

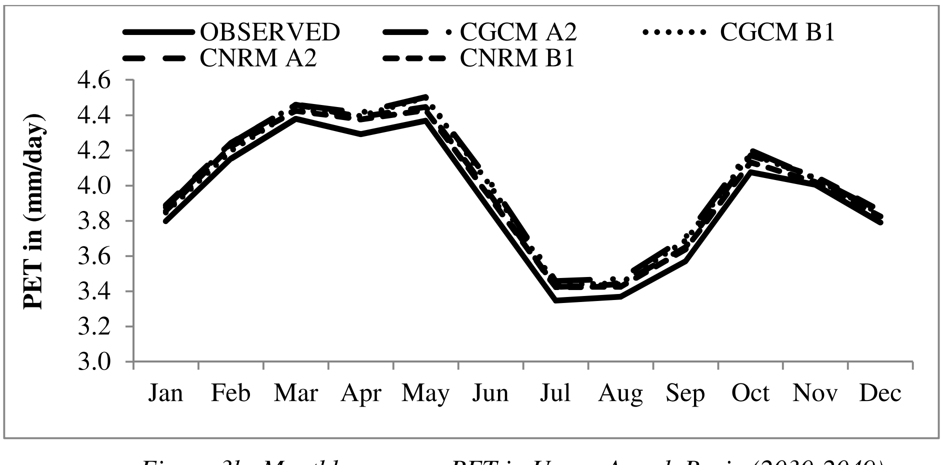

Figure 3b: Monthly average PET in Upper Awash Basin (2030-2049)

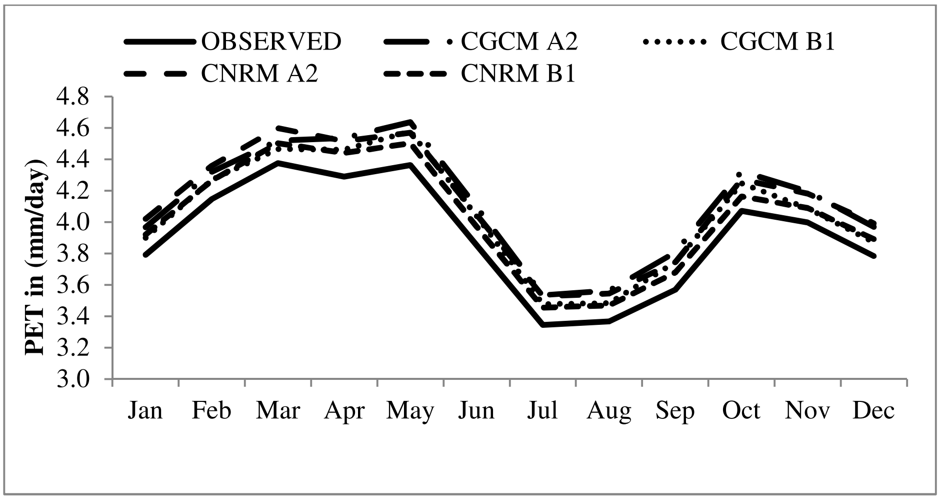

Figure 3c: Monthly average PET in upper Awash Basin (2050-2069)

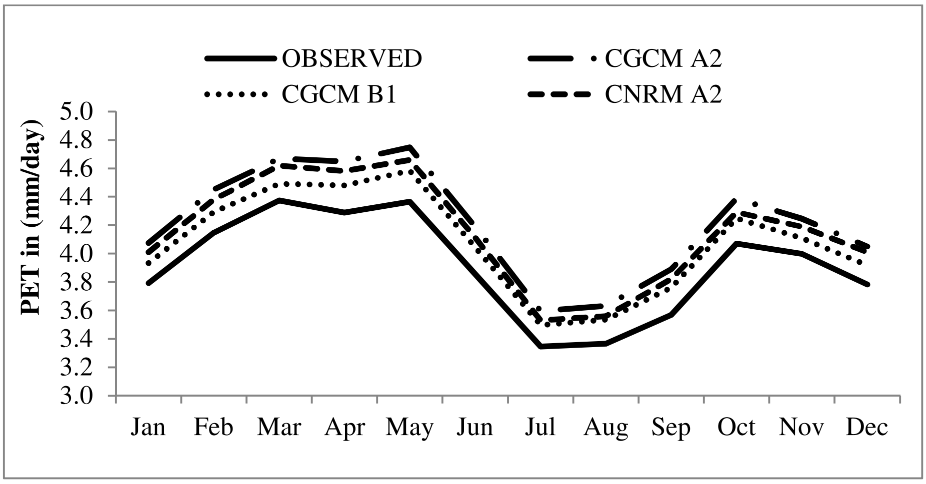

Figure 3d: Monthly average PET in upper Awash Basin (2070-2089)

The range of PET change was found to be from 0.51% to 1.53% in the short run (until 2029) and 4.09% to 7.67% (beyond 2029) in the long run in both models and scenarios (Table 1). All the curves of climate models are more spaced from the reference in the long run than in the short run, which show the rise in global temperature is inevitable.

Table 2: Percentage change in PET in lower Awash Basin

Periods	**Models and Scenarios**			
	CGCM		**CNRM**	
	A2	**B1**	**A2**	**B1**
2010-2029	1.66	1.48	0.55	0.55
2030-2049	2.95	1.84	2.21	1.48
2050-2069	6.09	3.87	5.17	2.95
2070-2089	8.30	4.61	7.38	N/A

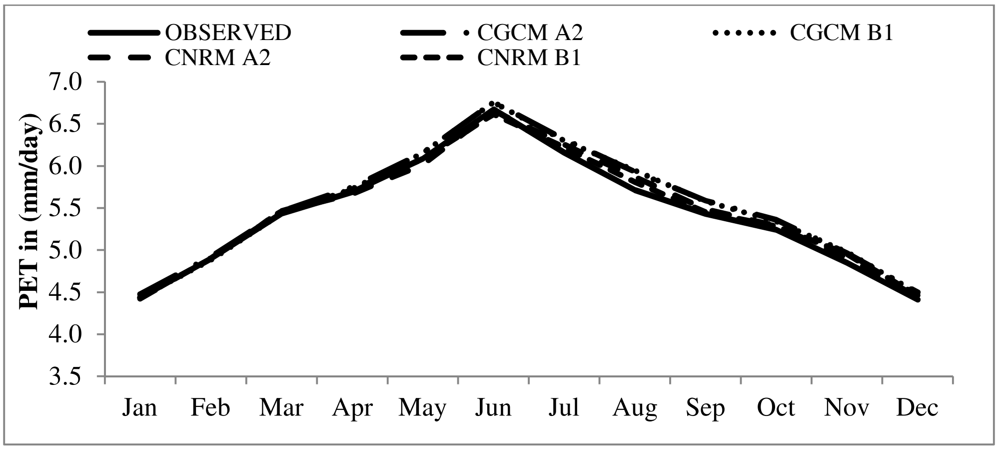

Figure 4a: Monthly average PET in lower Awash Basin (2010-2029)

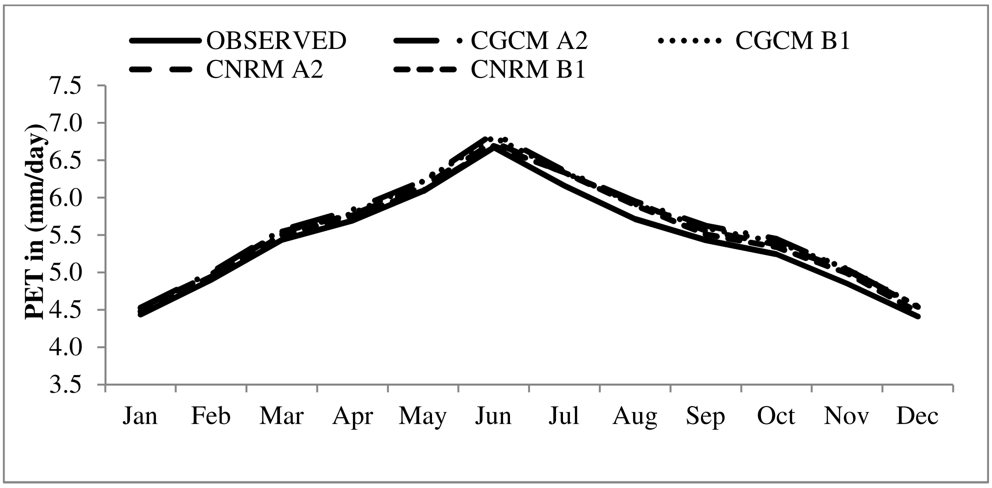

Figure 4b: Monthly average PET in lower Awash Basin (2030-2049)

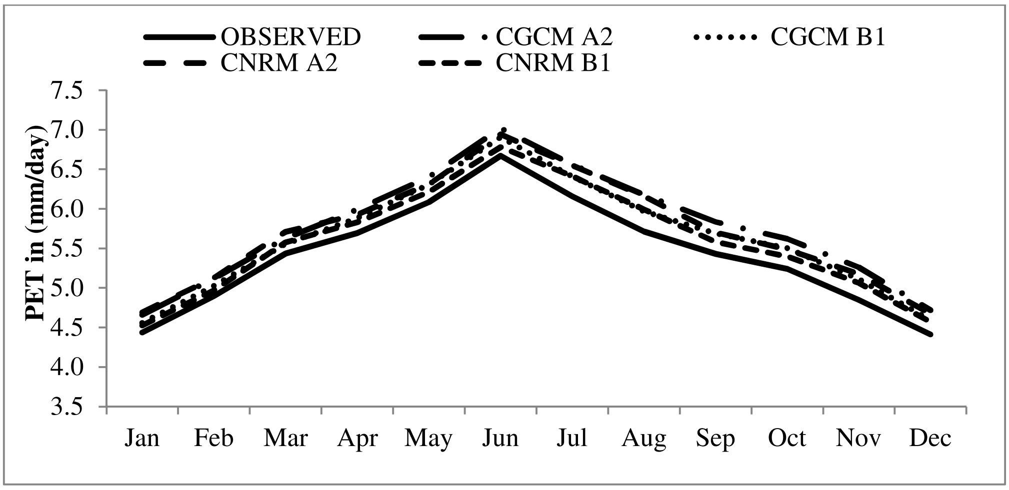

Figure 4c: Monthly average PET in lower Awash Basin (2050-2069)

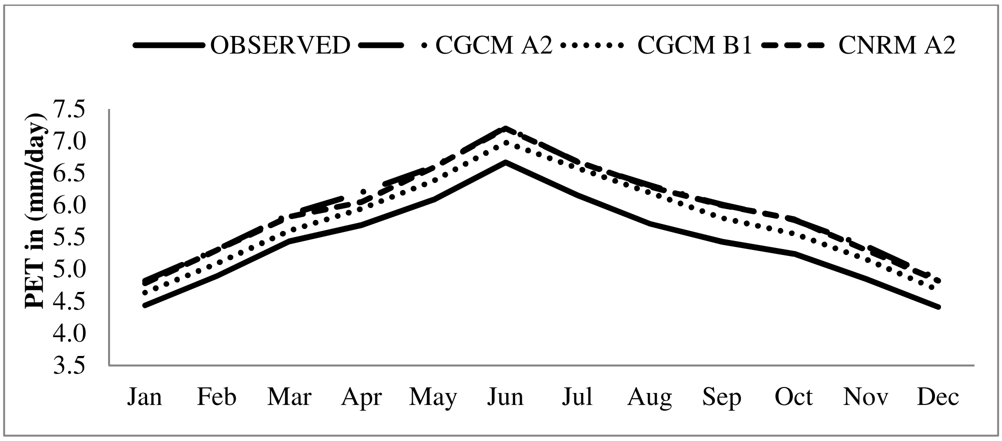

Figure 4d: Monthly average PET in lower Awash Basin (2070-2089)

The range of percentage change in PET was found to be increasing from 0.55% to 1.66% in the short run (up to 2029) and 4.61% to 8.30% in the long run (beyond 2029) (Table 2) in both models and scenarios. The expected increase in temperature for some models does not affect the PET predicted for the future.

HYDROLOGIC MODELING

HEC-HMS was used to simulate future flows of the Awash Basin. The Soil Moisture Accounting (SMA), the Soil Conservation Service (SCS) unit hydrograph and recession methods were assigned for loss, transform and base flow calculations for each sub basin, respectively (USACE, 2000; and 2005).

Sixty percent of the observed flow, rainfall and PET data, from 1986 to 1997 were used for model calibration and the remaining 40% from 1998 to 2005 were used for model validation. The river flow data were obtained from three gauges stations, namely Wongi, Awash and Dubti stations for Upper, Middle and Lower Awash Basins, respectively.

Correlation coefficients, for the calibration data sets, were found to be equal to 0.99, 0.77 and 0.73 for Upper, Middle, and Lower Awash basins, respectively and the subsequent validation results were 0.99, 0.80 and 0.75, respectively.

The monthly average precipitation data, obtained from the GCMs were disaggregated to daily time series using the average daily records of the stations in the Basin (Siam, 2010). The monthly averages PET together with the daily precipitation data were used as inputs for the model. The percentage change in runoff as related to the corresponding change in precipitation is shown in Figures 5 to 10.

It was found that there is an anticipated decrease in runoff of 1% to 4% as predicted by CGCM model and an increase of 4% to 11% in CNRM model for both A2 and B1 scenarios in the Upper Awash Basin (Figures 5 and 6). As expected the high emission scenarios (A2) resulted in the Basin being more vulnerable to climate change impact than the low emission scenarios except in the short run. Precipitation is fluctuating from one year to the other similar to the current conditions. However, the inconsistency between the values may arise from the method of downscaling, the error in disaggregation as well as the quality of the observed data.

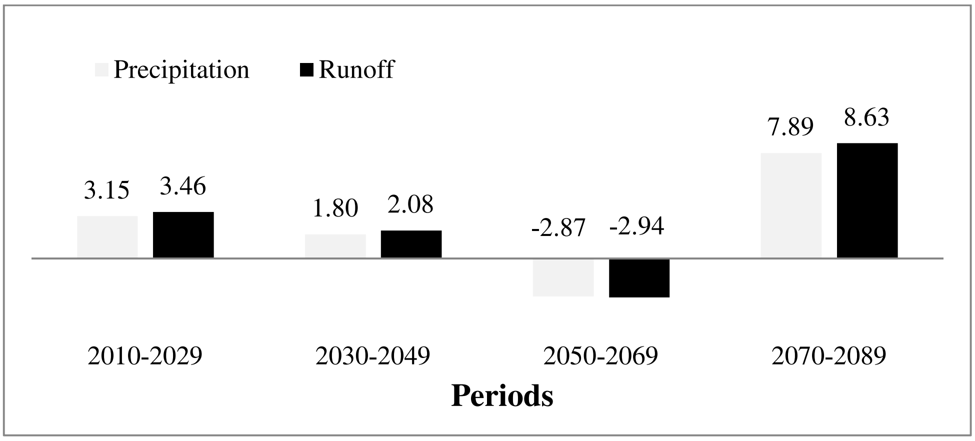

Figure 5: Percentage change in runoff in model CGCM3.1 A2 Scenario in UAB

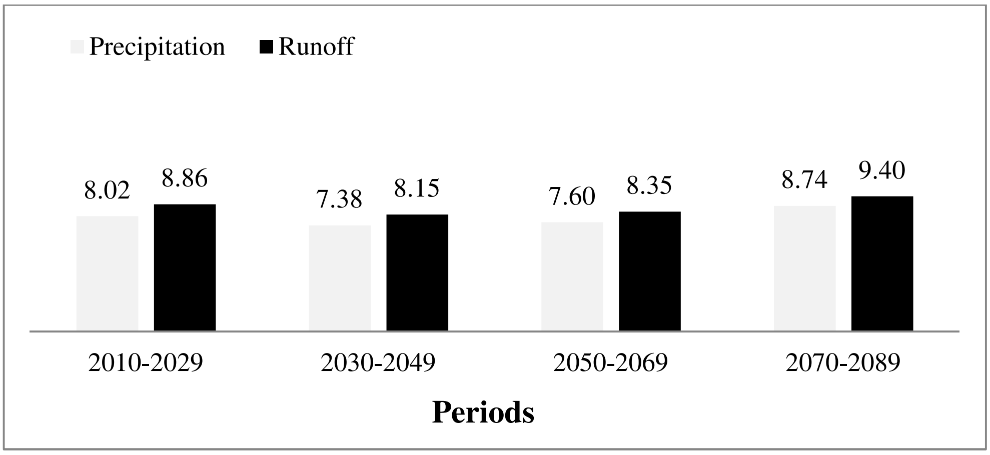

Figure 6: Percentage change in runoff in model CNRM A2 Scenario in UAB

Figures 7 and 8 display an increase in runoff for the Middle Awash Basin of 23% to 38% in the CGCM results and an increase in 37% to 51% in the CNRM results in both A2 and B1 scenarios.

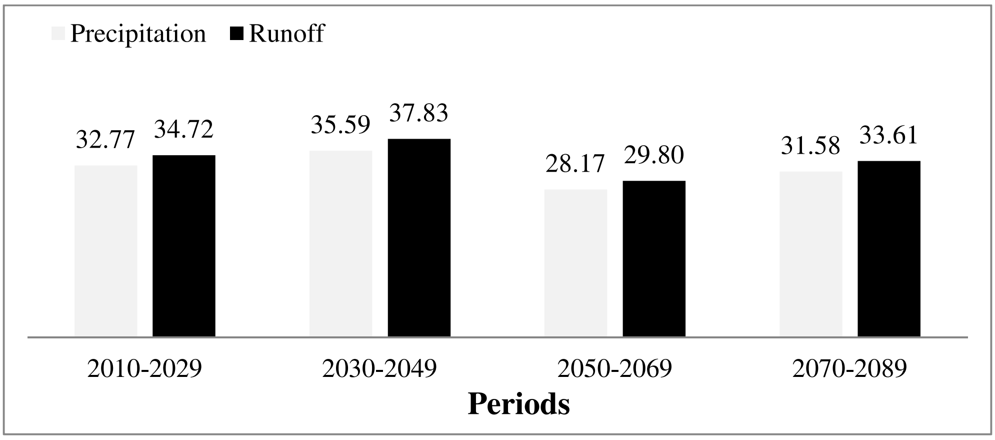

Figure 7: Percentage change in runoff in model CGCM3.1 A2 Scenario in MAB

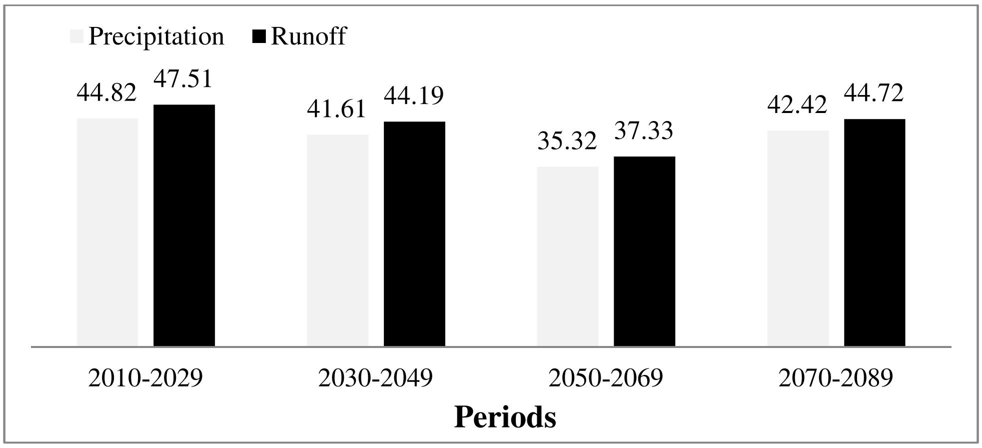

Figure 8: Percentage change in runoff in model CNRM A2 Scenario in MAB

A decrease in runoff in the range of 19% to 27% in the CGCM results and 3% to 23% in the CNRM results were modeled in the Lower Awash Basin for both A2 and B1 scenarios (Figures 9 and 10). All models and scenarios show a decrease in precipitation and consequently, a decrease in runoff. The lower Awash Basin is a more dry and hot than the other two sub-basins, and occupying the largest area of the Basin and may be adversely impacted by climate change.

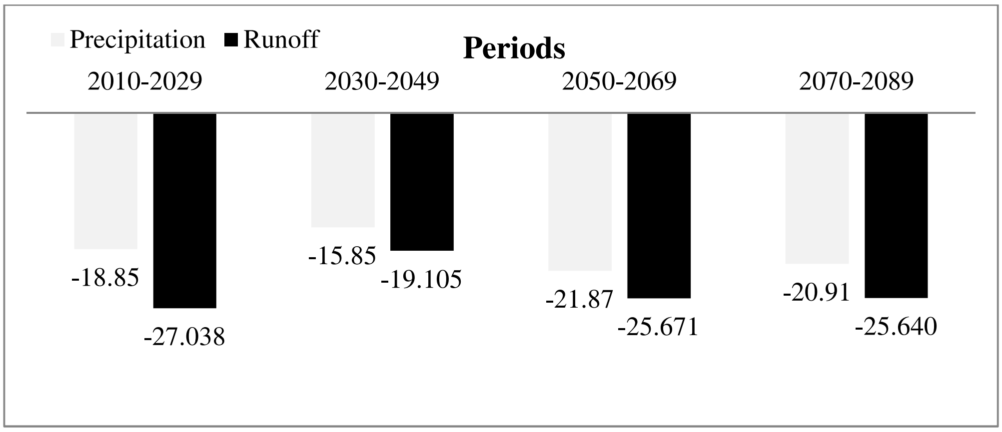

Figure 9: Percentage change in runoff in model CGCM3.1 A2 Scenario in LAB

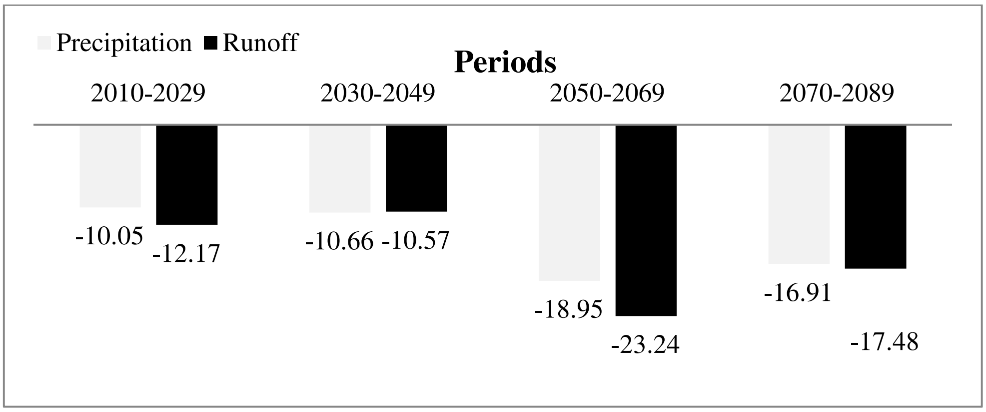

Figure 10: Percentage change in runoff in model CNRM A2 Scenario in LAB

APPLICATIONS IN WATER RESOURCES MANAGEMENT

Quantitative estimates of hydrologic effects of climate change are essential for understanding and solving the potential water resources management problems associated with water supply for domestic and industrial water use, irrigation, power generation, flood mitigation, and agriculture as well as for the protection of the natural environment.

The study has potential usefulness in demonstrating the use of the results from climate change models in the field of applied hydrologic research. Based on the preliminary results, the impact of climate change on the Upper Awash Basin flow rate is minimal (within the data inaccuracy limit). However, an average increase of over 30% in the Middle Awash Basin can be expected, and an average decrease in the Lower Awash Basin could occur. Thus any water resource project to be implemented in the Lower Awash Basin should consider that the water availability may decrease by 30% in the future and should factor in this possibility in the risk analysis of the water resources master plan of the basin. The modeled increase in the flow rate of the middle and upper Awash Basins should be factored in flood management scenario of the region.

CONCLUSIONS AND RECOMMENDATIONS

Based on our conducted methodology and obtained results, the following could be concluded:

- Accurate future runoff prediction requires the simultaneous estimation of a group of parameters in the future; mainly: ET, temperature, precipitation, area, slope….etc.
- The PET estimation has an increasing trend for all periods throughout the Basin, reflecting the consistent increase in future temperature predictions for all the studied models.
- In the current condition the Middle Awash Basin displays an intermediate behavior between Upper and Lower Awash Basins, whereas future prediction of runoff in the sub-basin displays different behavior than the current condition. This might be due to either the uncertainties of GCMs results and the corresponding scenarios or the insufficiency of the observed data.
- Future flow simulation results showed an increase in runoff from 2 to 11% in some models and a decrease from 1 to 4% in other models for the upper Awash, a 23-51% increase for the middle Awash, and a 3-27% decrease in runoff for the lower Awash Basin, reflecting the high uncertainties associated with using GCM results.

- The lower Awash Basin (occupying the largest area of the basin) is more dry and hot than the rest of the basin area, and may be adversely impacted by climate change (an estimated decrease in runoff up to 30% in some model predictions). Therefore, pre-mitigation measures should be taken by the decision makers to tackle the consequences of climate change in the Basin.

For future studies, different climate change models and downscaling techniques should be investigated for each case study as there is no evidence of the superiority of any GCM model or downscaling technique over the other for use in all locations. Each model and downscaling techniques can be better in one location than the other. Thus, there exists a dire need for a practical methodology for the selection of suitable GCMs and downscaling technique in each zone of the world.

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