British Journal of Environment & Climate Change
5(3): 269-284, 2015, Article no.BJECC.2015.020
ISSN: 2231–4784

SCIENCEDOMAIN *international*
www.sciencedomain.org

Will the Bagmati Basin's Future Hydrological Change be linked with Global Climate Change Patterns?

Pradeep Adhikari[1,2,3], Xinhua Zhang[4] and Yang Hong[2,3*]

[1]Department of Geography and Environmental Sustainability, University of Oklahoma, Norman, OK, USA.
[2]School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK, USA.
[3]Advanced Radar Research Center, University of Oklahoma, Norman, OK, USA.
[4]State Key Lab of Hydraulics & Mountain River Engineering, Sichuan University, China.

Authors' contributions

This work was carried out in collaboration between authors PA, YH and XZ. Author PA designed the study, conducted data analysis and modeling, and prepared the manuscript. Author YH oversaw the whole process as the research advisor and author XZ contributed while revising the manuscript. There were series of interactions between the authors to prepare and revise the manuscript.

Article Information

DOI: 10.9734/BJECC/2015/7962

Original Research Article

Received 1st September 2013
Accepted 20th November 2013
Published 2nd September 2015

ABSTRACT

The impact of climate change on society is one of the most serious challenges of this century. Observations have shown that the Earth's hydrologic cycle has intensified during past century as the Earth's temperatures have increased. Such change in hydrology will affect nearly every aspect of human well being, from agricultural productivity and energy use to flood control as well as municipal and industrial water supply. This study therefore, focuses on using climate projection data (precipitation and temperature) from an ensemble of 16 Global Climate Models (GCMs) and Thornthwaite Monthly Water Balance Model (TMWB) to assess changes in the basin hydrology in a high altitude mountainous Bagmati basin of Nepal. This region is considered as one of the most disaster (landslides and flood) prone basins in Hind-Kush-Himalaya due to the summer monsoon. The assessments were conducted for short (2020-2029), medium (2060-2069) and long (2090-2099) terms relative to the base period of the 1990-1999 in high (A2), medium (A1B) and low (B1) emission scenarios. According to GCMs the basin is expected to witness higher temperatures from about 2ºC (B1) to 4.5ºC (A2) and receive higher precipitation from about 7% (B1) to 20% (A2) in 2099. The increased precipitation is primarily expected to occur during the monsoon season, suggesting a wetter monsoon. The results from TMWB modeling show generation of higher runoff,

**Corresponding author: Email: yanghong@ou.edu;*

especially during the wet monsoon season, compared to 1990-1999. This implies that the basin will most likely become more vulnerable to floods and landslides during future monsoon seasons.

Keywords: Climate change; water resources; hydrologic cycle; runoff; evapotranspiration; mountainous basin; flood; landslide.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) mentions negative impacts of climate change on water resources [1]. By the middle of the 21st century, annual average river runoff and water availability at high latitudes and in some wet tropical areas are projected to increase as a result of climate change. A decrease may be observed with time over some dry regions at mid-latitudes and in the dry tropics as well [2]. An increased stress on water resources from population growth, and economic and land-use change, including urbanization, is also expected. By the 2020s, as a result of climate change and population growth, nearly half a billion people could see increased water resources stress as a result of climate change [1,3]. The amount of water available for human uses depends on the runoff, groundwater recharge and aquifer conditions. Climate-induced changes in both the seasonal runoff and inter-annual runoff variability can be as important for water availability as changes in the long-term average annual runoff [4], whereas the runoff is mainly dependent upon precipitation and temperature. The change in climate is expected to bring changes in rainfall characteristics. A warmer climate is expected to accelerate the hydrologic cycle, altering precipitation patterns and timing of runoff. Warm air holds more moisture and increases evaporation of surface moisture [1,5]. The increase in atmospheric water holding capacity results into high precipitation amount and intensity, therefore increasing the chances of flooding after a rainfall event. As the temperature increases, it generally takes the air parcels more time to be saturated with water vapors prior to be perceptible rain drops, thus likely resulting in longer dry spell periods [6,7]. With little or no moisture in the soil to evaporate and thus to cool the air, the incident solar radiation will raise the surface temperature, which could also likely contribute to longer and more severe droughts.

The impact of climate change is expected to vary around the globe. The IPCC AR4 predicts a grimmer picture in southern Asian, where climate change is expected to have a severe impact on agriculture and natural resources, as well as, forestry and fisheries sectors [8]. A similar scenario for the eastern Himalayas has been argued in [9]. Although research about climate change and its impacts on water resources has been one of the overarching themes of climate impact studies during the past two decades, such debates, particularly in the marginalized developing regions of the world, lack clarity. They are far too subjective; both in terms of how one can expect a changing climate will affect local environments and livelihoods of communities. Therefore, any discussion regarding climate change and its impacts follows a very general assumption of cause (low or high precipitation, decrease or increase in temperature, etc.) and effect (drier or wetter climate, drought or flooding, etc.) of scenario, and extrapolation of conditions in the coming decades rather than substantive arguments with concrete facts. This situation leads to a poor planning to mitigate and propose adaptive measures to minimize such impacts [10,11,12,13]. Furthermore, the people in marginalized regions of the world rely mainly on climate-sensitive natural resources, such as rain-fed agriculture. They have a poor capacity to withstand and recover from natural hazards (e.g. floods, landslides and droughts) compounded by global climate change. This research is motivated due to these very realities. This study, therefore, intends to fill existing knowledge gaps by investigating the impact of climate change in one of these marginal regions of the world: a small mountainous basin of Nepal. The objectives of this study are to: determine the projected precipitation and temperature changes in the basin for three IPCC Special Report on Emissions Scenarios (SRESs) A2, A1B and B1 [14] determine potential changes of evapotranspiration and runoff due to changed precipitation and temperature for 2020-2029, 2060-2069 and 2090-2099 over the base decade of 1990-1999; and finally, assess the water availability based on the projected runoff.

This paper has four sections. The first section provides background information, previous works and objectives of the study. The second section explains the study area, data used and methodology. The third section provides analysis on projected temperature and precipitation from the 16 GCMs in the basin and compares it with the historical trend. This section also provides the results from the TMWB modeling on surface water availability. The paper concludes in fourth section.

2. MATERIALS AND METHODS

2.1 Study Area

The Bagmati basin, with an area of 14,384 km^2 [15], is a trans-boundary basin. In Nepal, the Bagmati basin extends from 27º48'-26º44' N latitude to 85°57'-85°2' E longitude, which is only about a quarter of the total area. This will be the study basin. The Bagmati River is the main river in the study basin that originates in the central mountainous region of Nepal at an elevation of around 2,700m and drains southward into Bihar, India to join the Ganges River. Within Nepal, the basin has three distinct climatic zones: subtropical sub-humid zone (<1,000m), warm temperate zone (1,000m-2,000m) and cool temperate humid zone (<3,000m). The basin has a discharge station located at Pandhera Dovan near the Karmaiya town, Nepal for which discharge data is available since 1985 (Fig. 1).

Forest cover, which is about 58% of the study basin area, dominates the northern part of the study basin, followed by cultivated land, which accounts for about 38% of the study basin. The dominant soil type in the basin is loamy soil [16]. The climate in Bagmati is driven by the South Asian monsoon, which is a seasonal reversal of wind flow due to changing low- and high-pressure patterns in the Indian peninsula [17]. The temperature varies from 10ºC to 30ºC and the higher mountains in the basin receive snowfall occasionally during the winter months (November-February). The annual average rainfall in this basin is about 1,500 mm, with 90% of the precipitation occurring during the four monsoon months, June to September [18,19]. The months of October through May are dry; the rainfall occurrence is scanty; and ground water contributes to the flow in the Bagmati River. During the winter, rainfall is governed by the easterly Mediterranean winds.

Rice, wheat, corn and millet are the predominant crops in the study area. In the upper mountainous regions of the basin, corn is a dominant crop, while it is rice in the lower regions [20]. The agrarian economy of the Bagmati basin is very much dependent on the monsoon-fed agriculture. The space-time variation of monsoon rainfall over the Bagmati basin, therefore, has a large bearing on the resources and livelihood in the study area. The basin increasingly faces a number of serious environmental and ecological challenges. Urbanization, due to population growth and migration, in the headwater regions (particularly in the Kathmandu valley, including the capital city of Nepal) has contributed to water quality deterioration both at the middle and lower reaches of the Bagmati River [21,22]. This has impacted human health, as well as, aquatic ecosystems in the basin. As mentioned earlier, the people in the middle mountain region depend on rain-fed agriculture. Increasing population pressure on the fragile mountain slopes has also resulted in the rapid degradation of the natural resources in this basin. As a consequence, deforestation, soil erosion, landslides and siltation are occurring in the upper and middle sections of the basin, whereas, sedimentation and flooding are frequent in the lower stretches of the basin. Understanding basin hydrology due to climate change is, therefore, an important task to mitigate impacts on the environment and the people's livelihood in Bagmati.

2.2 Data

The primary source of climate data for the study includes precipitation (mm/month) and temperature (ºC) data from the 16 Global Climate Models (GCMs) at 0.5º x 0.5º resolutions, which were made available through the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project 3 (CMIP3) [23,24]. The data covers the entire globe and are available for the A2, A1B and B1 Special Report Emissions Scenario (SRES). Each scenario represents a different prediction of the effects of greenhouse emissions depending on factors such as population growth, economic development and technological change. A2 is the most aggressive, A1B is the balanced and B1 is the most conservative emission scenario [14]. The temperature and precipitation data are extracted for the study area of the Bagmati basins. The available data cover the period from 1950 to 2099. For this study the average temperature and precipitation from 16 GCMs is used so as to have the best possible representation of future climate [25]. The seasonal weather in Nepal Himalaya varies considerably from year to year, especially for the monsoon and winter weather regimes, depending on the strength of the Tibetan high and subtropical jet stream (SJT).

Monsoon precipitation in Nepal occurs mainly from cumulus convection; the daily amount of precipitation at each station has a strong random component even if the stations are located at a short distance from each other. In the summer months, the Himalayan region gets much hotter than the Bay of Bengal, thus creating a massive convection cell. The moist air from the Bay of Bengal moves into the Himalayan barriers gets pushed up the mountains cools as it rises, and condenses in the form of rain [26].

The in-situ climatic data in Nepal have relatively short records. Only handfuls of stations have records of more than 50 yrs. Therefore, studies on Nepal's climatology and long term hydrological analysis are sparse. However, from the available studies, it has been found that temperatures in Nepal are increasing at a rather high rate. For 1971–1994, a warming trend, ranging from 0.06 to 0.12ºC per year in most of the Middle Mountain and Himalayan regions after 1977, has been detected [20,27]. The warming is more pronounced in the high altitudes. The magnitude of the long-term trend in precipitation is not as noticeable as temperature. The overall average trend for Nepal indicates that the annual average precipitation is decreasing at the rate of 9.8 mm/decade [28]. Nevertheless, a large inter-annual and decadal variability is observed. The monsoon record for all of Nepal is highly correlated with the Southern Oscillation Index (SOI) series. The exceptionally dry year of 1992 recorded in Nepal coincides with the elongated El Niño-Southern Oscillation (ENSO) of 1992-1993 [29].

The in-situ (gauge) daily precipitation data for this study were obtained from 24 stations within and surrounding the region of the Bagmati basin for 1985-2006. These stations are located mainly on the upper reaches of the basin (Fig. 1). The discharge data were obtained at Pandhera Dovan. There is no discharge-measuring station in Nepal downstream of Pandhera Dovan; although, the river continues to Bihar, India and joins the River Ganges (Fig. 1). The precipitation and discharge data from 1985-1998 are on monthly timescales, and from 1999-2006, they are on daily timescales. These daily datasets were accumulated on a monthly scale, as well. The average monthly temperatures from the 24 stations were also obtained for the same time period of 1985-2006. For the purpose of this research, the individual station data (both temperature and precipitation) were averaged over the basin and also used for the bias correction of the projected climatic data.

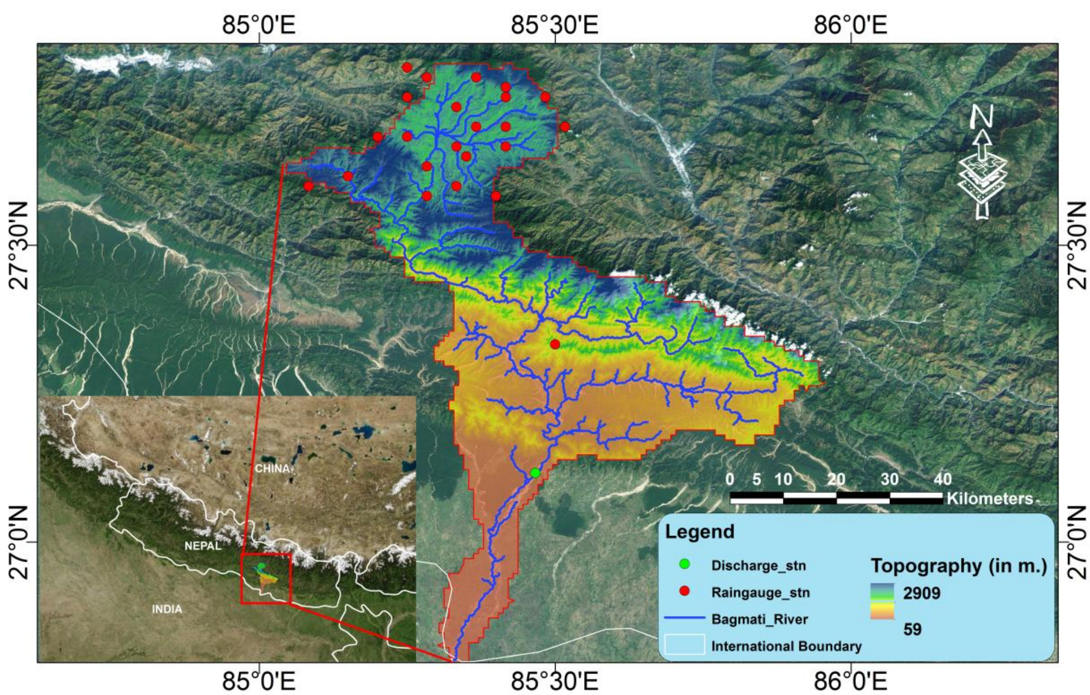

Fig. 1. Location of the study area, the Bagmati basin in Nepal

The precipitation and runoff records show that the basin has a strong seasonal signature driven by the south Asian monsoon. The Bagmati River is fed mainly by monsoon precipitation and natural spring [30]. The months of June to September are wet, while the rest of the months are much drier (Fig. 2b). The basin also has a pronounced orographic effect that impacts the precipitation pattern [22]. As rain gauges stations are concentrated mainly in the northern most part of the basin and virtually none at the higher elevated area immediately south any orographic effects, if any, could not be made. Fig. 2a shows that, during some years, runoff is larger than precipitation, thus indicating the basin might have spring source contribution. The basin average runoff coefficient, calculated on the basis of 1985-2006 data, is about 0.82. This shows that the basin has relatively steeper slopes with a shorter time of concentration. Runoff is generated much quicker after the rainfall.

2.3 Methodology

2.3.1 Bias correction

The basin average monthly time series CMIP3 temperature and precipitation data from the ensemble of 16 Global Climate Models (GCMs) for the period 1950-2099 are extracted for the Bagmati basin. The CMIP3 temperature and precipitation was bias-corrected and spatially downscaled [23,31,32]. Compared to the observed data at the Bagmati Basin, the monthly temperature and precipitation from the CMIP3 simulations are found underestimated by about 18% in all emission scenarios using the Equation 1 (Figs. 3 and 4).

$$\%\,Bias = \frac{\sum_{i=1}^{N} Sim(i) - \sum_{i=1}^{N} Obs(i)}{\sum_{i=1}^{N} Obs(i)} \times 100 \qquad (1)$$

Where, Sim is CMIP3 estimation of monthly temperature/precipitation and Obs is gauge observed data for monthly temperature/precipitation for 1985-2006.

It is observed that the CMIP3 data could not capture precipitation higher than 400 mm/month (which is the case during most of the monsoon seasons) evidently showing limitations of CMIP3 data to capture variability within this basin. The data is then bias corrected with the help of 1985-2006 gauge data. Bias correction helped improve the validation indices for both temperature (Table 1) and precipitation (Table 2).

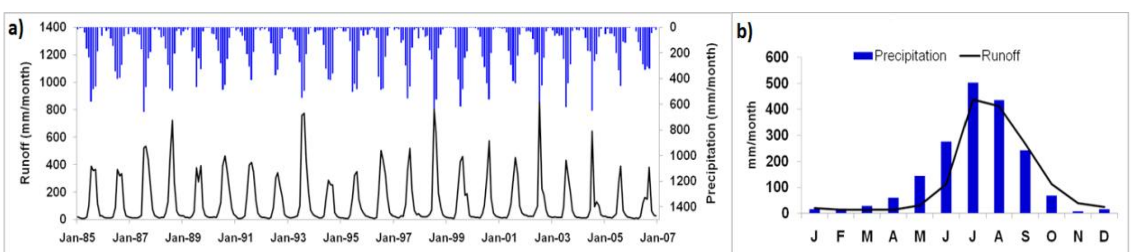

Fig. 2. a) Observed average monthly precipitation and runoff (mm/month) in the Bagmati basin, and b) Seasonal characteristics of precipitation and runoff

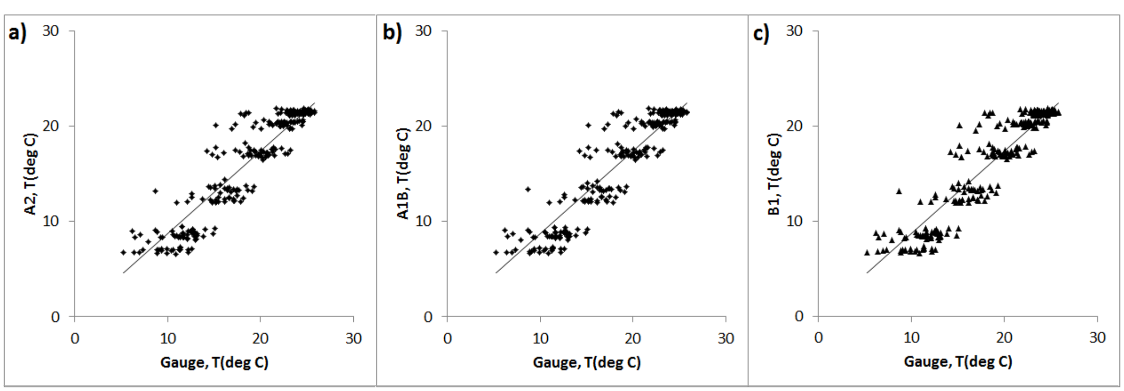

Fig. 3. CMIP3 vs. gauge temperature for 1985-2006 a) A2, b) A1B, and c) B1

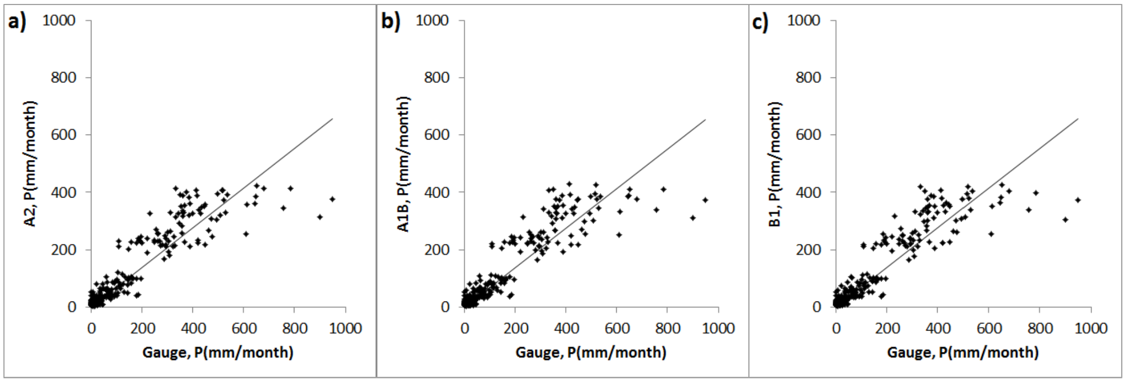

Fig. 4. CMIP3 vs. gauge precipitation for 1985-2006 a) A2, b) A1B, and c) B1

Table 1. Bias correction of predicted temperature improved validation indices

Scenario	Condition	CC	Bias (%)	RMSE(ºC)	Slope
A2	Before bias correction	0.96	-18.08	3.82	0.868
	After bias correction	0.96	0.07	1.75	1.015
A1B	Before bias correction	0.96	-18.19	3.84	0.868
	After bias correction	0.96	-0.07	1.75	1.014
B1	Before bias correction	0.96	-18.13	3.83	0.868
	After bias correction	0.96	0.01	1.74	1.015

Table 2. Bias correction of predicted precipitation improved validation indices

Scenario	Condition	CC	Bias (%)	RMSE(mm)	Slope
A2	Before bias correction	0.93	-18.49	72.73	0.692
	After bias correction	0.93	-0.46	53.06	0.901
A1B	Before bias correction	0.92	-17.63	70.66	0.689
	After bias correction	0.92	0.60	51.89	0.908
B1	Before bias correction	0.92	-18.23	71.52	0.691
	After bias correction	0.92	-0.14	51.94	0.899

Tables 1 and 2 show that both temperature and precipitation are underestimated in the CMIP3 data, although the correlation coefficients (CC) are quite high, above 0.9 in all the cases. The CC assesses the agreement between the CMIP3 data and the ground observation. The root mean square error (RMSE) measures the average error in simulated runoff but gives greater weight to the larger errors. The RMSE value for temperature is 4ºC, while it is more than 70 mm/month for precipitation. The higher values of RMSE in precipitation indicate larger errors, as precipitations higher than 400 mm are underestimated in the CMIP3 data (Fig. 4).

In this study, a second round of bias correction is done based on the bias calculated using Equation 1.First, the bias quantified during the baseline data (1990-1999) is used to correct biases for projected decades of 2020-2029, 2060-2069 and 2090-2099, respectively. Then the bias-corrected projection data is used for the analysis in temperature and precipitation changes and subsequently as an input into the Thornthwaite Monthly Water Balance (TMWB) model for the three projection periods. The TMWB model is a simple non-data intensive, robust model requiring only mean monthly temperature (T), monthly total precipitation (P) and latitude (in decimal degree) of the study area [33,34]. The selection of the model is based on two simple facts. Most of the countries in emerging regions have very limited data. TMWB model is one of the non-data intensive models and it has proven its utility to analyze monthly hydrology in different parts of the world. In this study, the model is calibrated for the period 1990-1999. The calibrated model is validated for the period 2000-2006. The calibrated model is used to determine the actual evapotranspiration (AET) for the base period of 1990-1999. The actual evapotranspiration in the TMWB model is derived from potential evapotranspiration (PET). In the model, monthly PET is taken as the water loss due to a large homogenous, vegetated area with no limitation to water for evapotranspiration. The runoff is produced from surplus from the precipitation. The runoff factor determines the fraction of surplus that becomes runoff in a month. The remaining surplus is carried over to compute total surplus [34].

2.3.2 Model calibration and validation

For model calibration, the quantitative comparison between simulated and observed runoff is carried out using the percentage bias and correlation coefficient. First, reduction of bias is the main objective in order to best match the total runoff volume generated by the model (simulated) to the observations, with the ideal case of a zero bias within the basin for the calibration period. Then, the CC was used for testing the goodness of fit for the simulated runoff. The calibrated model for 1990-1999 shows a bias of about -10.86%, predicting a lower runoff for the decade than gauge observation (Fig. 5a). The model has been able to match the runoff volume fairly well, but it failed to capture the runoff higher than ~400 mm/month. This may be due to underestimation of the higher rainfall in the basin, as noted in earlier in the section.

The seasonal variability of the observed and simulated runoff shows that the model performed better in the drier periods compared to the wetter periods (Fig. 5b). The calibrated model is validated for the period of 2000-2006. The validation indices showed some improvement in the correlation (0.9), but overestimated the runoff volume by 13% (Fig. 5c). The seasonal trend shows that for the validation period, the runoff mostly follows the seasonal trend, except for the pre-monsoon (drier) period from April to June (Fig. 5d).

2.3.3 Benchmarking and projection of hydrologic components

Once the model is calibrated and validated, PET and AET are benchmarked for the base period 1990-1999. Next, the bias-corrected climatic data (P and T) are used as the input into the model to estimate PET, AET and runoff in the A2, A1B and B1 scenarios for the periods of 2020-2029 (short-term), 2060-2069 (medium-term) and 2090-2099 (long-term). Finally, an analysis of the basin average decadal and seasonal variability of the hydrological components (P, T, PET, AET and R) are conducted to determine the states of the hydrologic cycle for short-, medium- and long-term compared to the base period of 1990-1999. To bench mark, gauge data for P, T, R, and simulated values for PET and AET are taken.

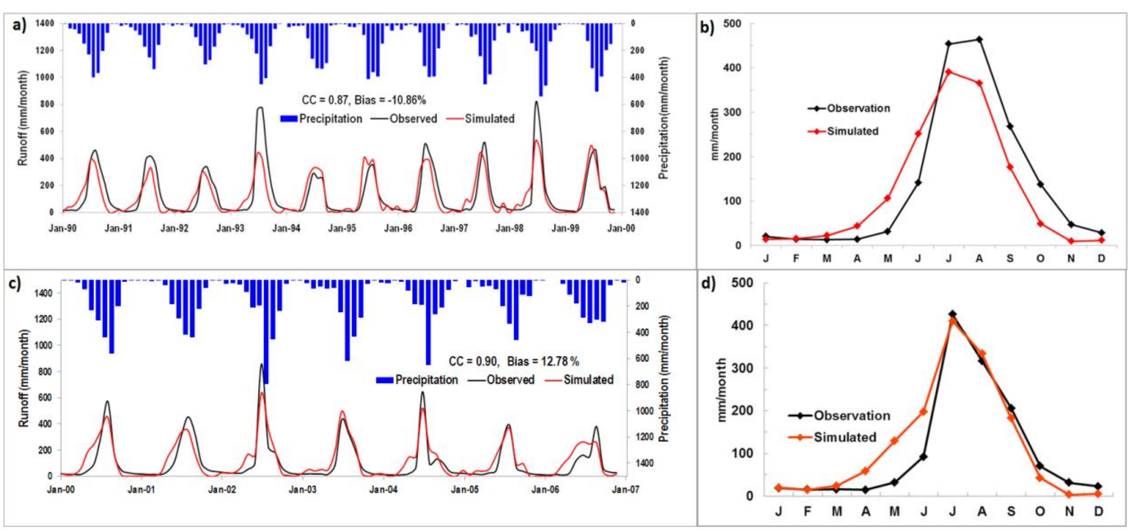

Fig. 5. Calibration and validation of TMWB model a) Calibration for the period 1990-1999, b) Seasonal runoff for calibration period, c) Validation for the period 2000-2006, and d) Seasonal runoff for validation period

3. RESULTS AND DISCUSSION

3.1 Changes in Temperature

The observed temperature data showed an increasing trend until about 1995, which is expected to continue, as shown by the climatic projection data. All scenarios (A2, A1B and B1) have almost the same rate of increase in mean annual temperature until 2030. For the B1 case, the rate of increase in temperature after 2030 is less compared to the A2 and A1B scenarios (Fig. 6). For emission scenarios A2, A1B and B1, the temperature are expected to increase in the basin by about 4.5, 3.5 and 2ºC, respectively, compared to the base period of 1990-1999.

The seasonal changes in temperature (ºC) show a decrease of about 1.2ºC over the months of November to February for the 2020-2029, while from April to October there is a possible increase of up to 1.4ºC. For 2060-2069 and 2090-2099, all months are expected to experience an increase in temperature from 3.7ºC to 5.5ºC compared to 1990-1999 (Fig. 6). It is clear that for all scenarios, the three decades show a very similar tendency: higher seasonal variability-the difference between summer highs and winter lows will all be increasing through at different extents. The difference in 2020-2029 from the latter two decades simply due to the fact that much higher elevated temperature making summer hotter in 2060-2069 and 2090-2099.

3.2 Changes in Precipitation

In Bagmati, climate projection shows a marginal change in average annual precipitation until 2050 compared to the 1990-1999 (Fig. 7a). However, there are some decrements noted during the period of 2030-2040. Again, after 2050, there is a continuously increasing trend in precipitation in all emission scenarios. It can be noted that by the end of 2099, a change of 20%, 15% and 7 % are predicted, compared to the base period of 1990-1999, in average annual precipitation for the A2, A1B and B1 scenarios, respectively.

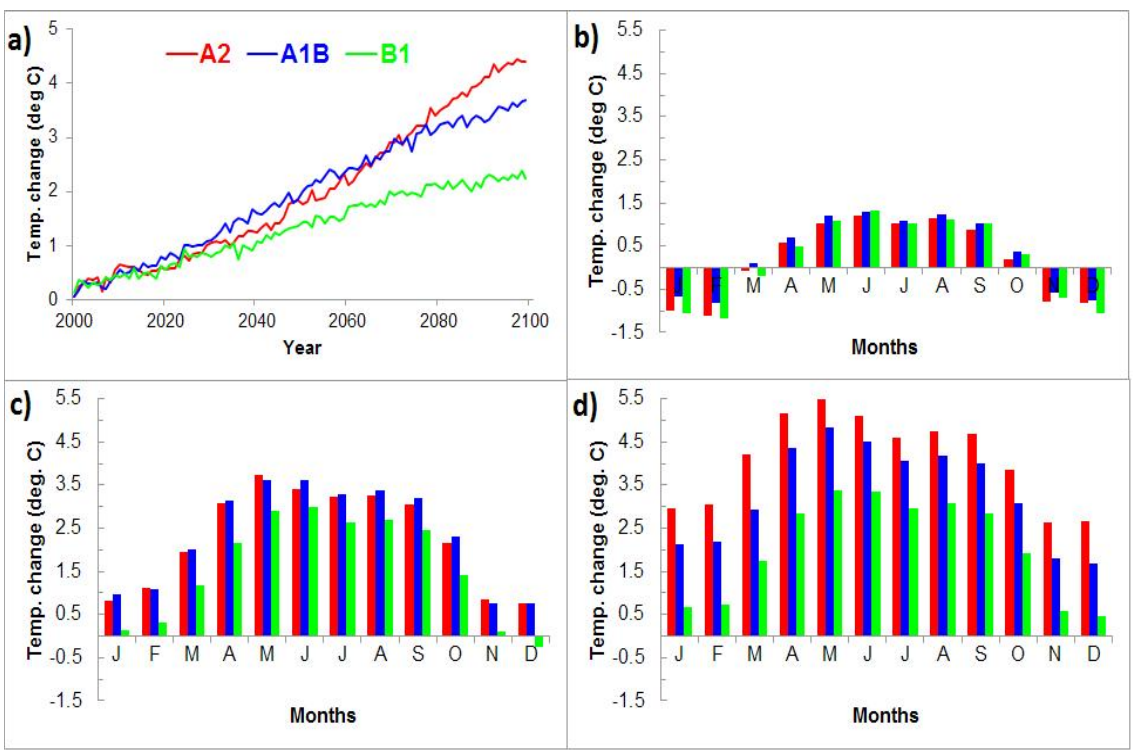

Fig. 6. a) Anomaly in temperature compared to the 1990-1999 for the A2, A1B and B1 scenarios, a) time series for 2000-2099 and seasonal anomalies for b) 2020-2029, c) 2060-2069, and d) 2090-2099

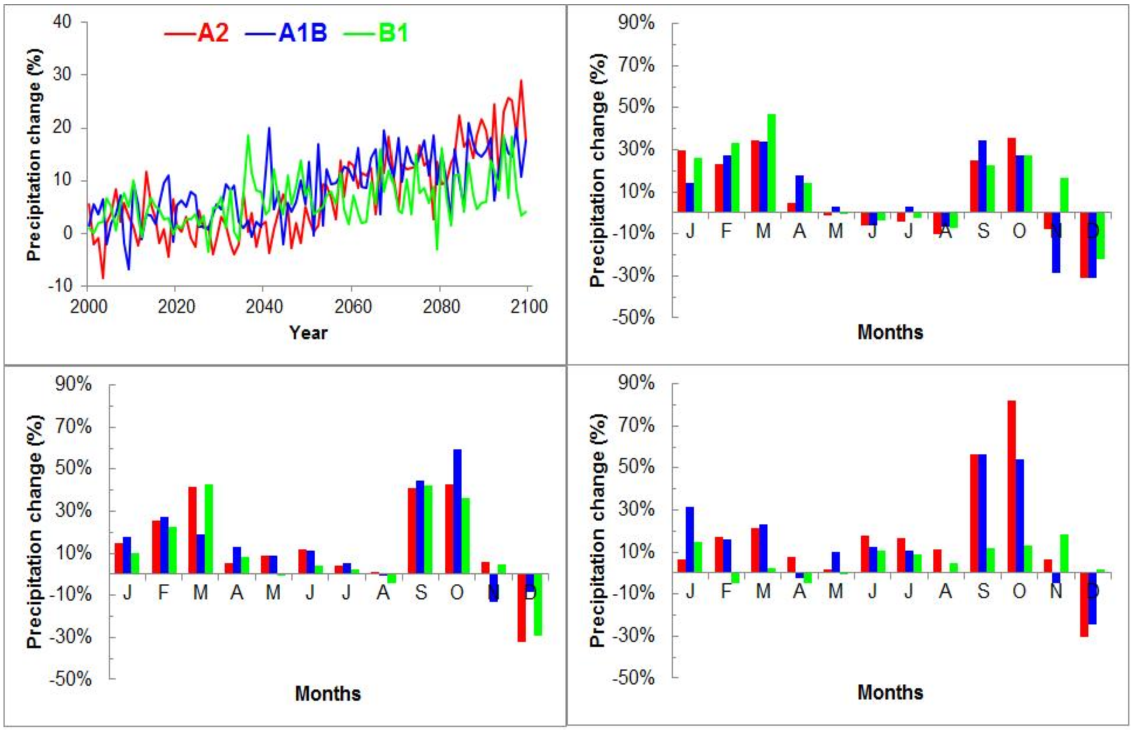

Fig. 7. a) Percentage anomaly in precipitation compared to the 1990-1999 for the A2, A1B and B1 scenarios, a) time series for 2000-2099 time frame and seasonal anomalies for b) 2020-2029, c) 2060-2069, and d) 2090-2099

The seasonal analysis of projected precipitation shows that for 2020-2029 most of the months receive higher precipitation (~30%) in all scenarios, except for June-August and November-December compared to the 1990-1999, when it is lower than the base period. In the decade of 2060-2099, similar wetter seasons are expected, except for December, which is going to be drier. The trend is expected to continue for the periods 2060-2069 and 2090-2099 (Figs. 7c and 7d). A shift from a rainy season towards the end of the year is likely, which may be concluded from the anomaly in the last decade of the 21st century. During this decade, September and October could be the wettest months for A2 and A1B scenarios (Fig. 7d). Compared to 2020-2029 the summer months from May to August are expected to become wetter in 2060-2069 and 2090-2099. Such change may be attributed to the assumptions made while creating emission scenarios: A2, A1B and B1. The main drivers for emission scenario are the demographic development, socio-economic development and technological change. For A1B and B1 scenario, the population peaks in mid-century (2050) while population continuously increases till 2099 [14]. The switches from drier to wetter summer most likely happen around 2050.

3.3 Decadal Anomaly in Hydrology

The calibrated model was first used to benchmark the hydrological components for the base period of 1990-1990 and then was used to project their states in the short (2020-2029), mid (2060-2069) and long (2090-2099) terms. The model inputs (P, T and latitude of the study area), outputs (PET, AET and R) and the predicted anomalies for different emission scenarios are presented in Tables 3a, 3b and 3c.

The Bagmati basin is expected to receive higher precipitations in all emission scenarios compared to the base period of 1990-1999 (Table 3a, 3b and 3c). The increase in precipitation is at its highest, with about 21%, 15% and 10% for 2090-2099 for A2, A1B and B1, respectively. A continuous rise in temperature is predicted over the coming decades. By the end of the 21st century a rise of almost 4ºC (A2), 3ºC (A1B) and 2ºC (B1) respectively is projected, subsequently increasing the AET. With the possibility of higher precipitation with increasing temperature, the

PET is modeled to increase over the coming decades. Such an increase is followed by the same trend as that of temperature. The increase in precipitation accounts for the combined percentage rise on the AET and runoff. At the same time, since the basin has a high runoff coefficient (~0.82), the rainfall translates into the runoff quickly.

3.4 Seasonal Anomaly in Basin Hydrology

Table 4 shows the trend in PET, AET and temperature for the base period of 1990-1999. The month of January has the lowest PET (34 mm), while it is the maximum (130 mm) in July. The PET follows that of the temperature trend in the basin. November through March is the coolest months in the basin, during which both PET and AET are lowest. The value of AET starts to increase in May and peaks around mid-July, coinciding with the peak monsoon season. During the monsoon rain, AET is highest with highest temperature and availability of abundant soil moisture.

Figs. 8, 9 and 10 present the seasonal anomalies of the key hydrological components for different emission scenarios.

Table 3a. Decadal anomaly in hydrologic components for scenario A2

Components	1990-1999	A2: Changes over the base period		
		2020-2029	2060-2069	2090-2099
Precipitation (mm/month)	124.0	0.3 (0.2%)	14.0 (11.3%)	25.7 (20.7%)
Temperature (monthly mean ºC)	16.3	0.5 (3.1%)	2.3 (14.1%)	4.1 (25.2%)
PET (mm/month)	62.5	4.2 (6.7%)	11.4 (18.2%)	19.8 (31.7%)
AET (mm/month)	24.8	0.1 (0.4%)	2.8 (11.3%)	5.1 (20.6%)
Runoff (mm/month)	99.2	0.2 (0.2%)	11.2 (11.3%)	20.5 (20.7%)

Table 3b. Decadal anomaly in hydrologic components for scenario A1B

Components	1990-1999	A1B: Changes over the base period		
		2020-2029	2060-2069	2090-2099
Precipitation(mm/month)	124.0	5.5 (4.4%)	15.1 (12.2%)	18.5 (14.9%)
Temperature (monthly mean ºC)	16.3	0.7 (4.3%)	2.4 (14.7%)	3.3 (20.2%)
PET (mm/month)	62.5	4.7 (7.5%)	11.7 (18.7%)	16.2 (25.9%)
AET (mm/month)	24.8	1.1 (4.4%)	3.0 (12.1%)	3.7 (14.9%)
Runoff (mm/month)	99.2	4.4 (4.4%)	12.1 (12.2%)	14.8 (14.9%)

Table 3c. Decadal anomaly in hydrologic components for scenario B1

Components	1990-1999	B1: Changes over the base period		
		2020-2029	2060-2069	2090-2099
Precipitation (mm/month)	124.0	2.8 (2.3%)	9.4 (7.6%)	12.3 (9.9%)
Temperature (monthly mean ºC)	16.3	0.5 (3.1%)	1.6 (9.8%)	2.1 (12.9%)
PET (mm/month)	62.5	4.2 (6.7%)	8.3 (13.3%)	10.3 (16.5%)
AET (mm/month)	24.8	0.6 (2.4%)	1.9 (7.7%)	2.5 (10.1%)
Runoff (mm/month)	99.2	2.2 (2.2%)	7.5 (7.6%)	9.8 (9.9%)

Table 4. Seasonal P, PET, AET and T for the base period 1990-1999

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
P (mm)	14.1	15.8	22.8	44.7	108.2	257.3	400.2	374.3	180.0	49.9	9.7	11.6
PET (mm)	33.4	38.7	63.2	87.7	115.2	125.8	130.1	116.3	94.1	71.1	47.8	36.1
AET (mm)	3.4	3.9	5.6	10.9	26.4	62.8	97.7	90.3	45.1	12.2	2.4	2.8
TEMP(ºC)	9.3	11.2	14.6	17.5	19.3	20.3	20.6	20.3	19.7	17.3	14.2	10.8

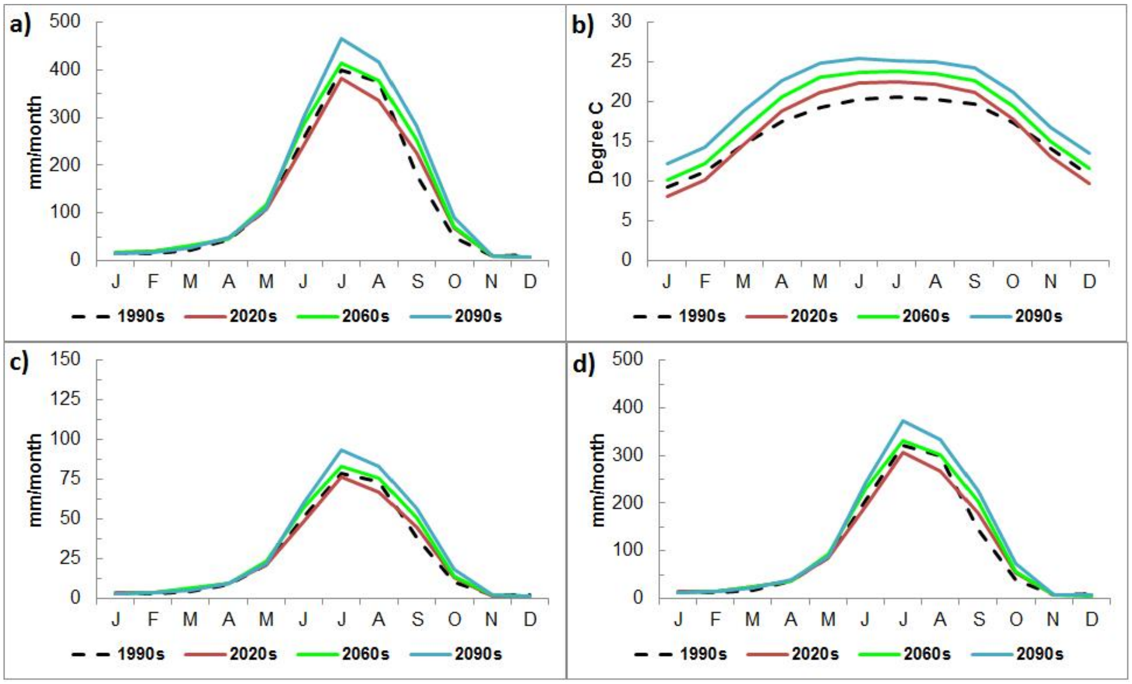

Fig. 8. Projected seasonal changes for the major hydrologic components a) Precipitation, b) Temperature, c) AET, and d) Runoff compared to the 1990-1999 for the A2 scenario

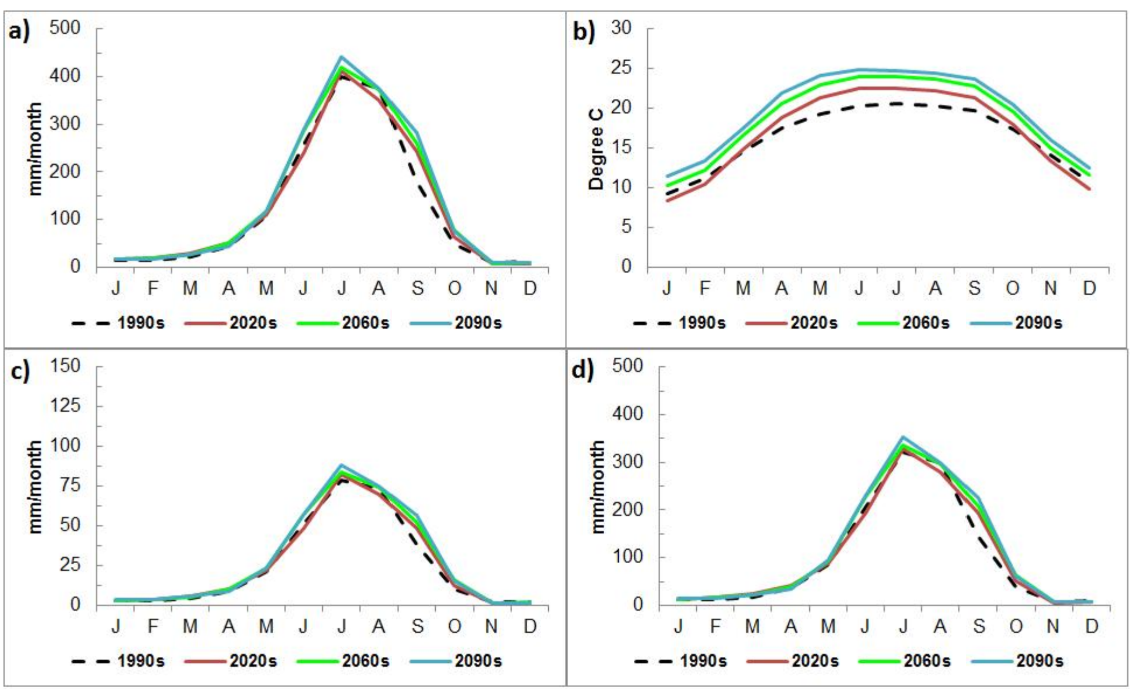

Fig. 9. Projected seasonal changes for the major hydrologic components a) Precipitation, b) Temperature, c) AET, and d) Runoff compared to the 1990-1999 for the A1B scenario

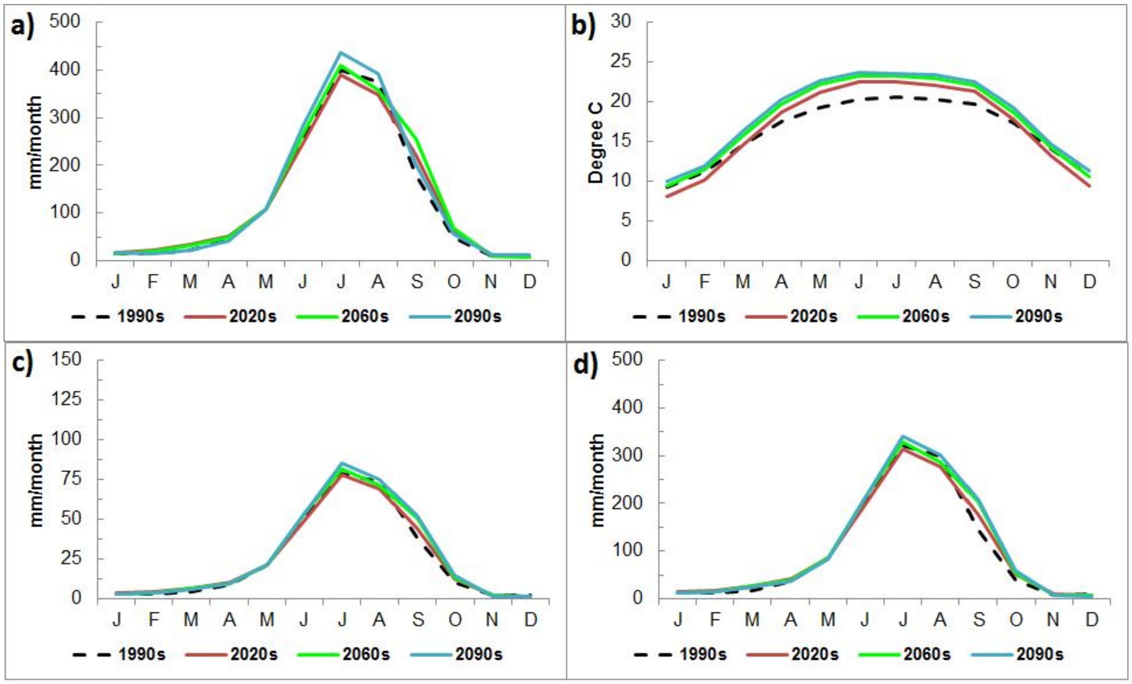

Fig. 10. Projected seasonal changes for the major hydrologic components a) Precipitation, b) Temperature, c) AET, and d) Runoff compared to the 1990-1999 for the B1 scenario

In the A2 scenario, precipitation is almost at the same level as that of the base period (1990-1999) from November to May. For the wetter season, precipitation is higher than the base period. The same trend is observed in AET and runoff. The basin is projected to have more runoff in wetter months, indicating possible flooding in those months. The temperature is projected to increase in all seasons of the selected decades, except for the 2020-2029, which is projected to decrease in the months from November to February (Fig. 8).

For the A1B scenario, precipitation is almost at the same level as that of the base period from November to May, the drier months. However, for the wetter season, precipitation is higher than the base period for 2060-2069 and 2090-2099. A similar trend is observed for AET and runoff. The basin is projected to generate higher runoff in the wetter months of 2060-2069 and 2090-2099, possibly causing flooding (Fig. 9).

For the B1 scenario, precipitation is almost at the same level as that of base period from November to May, as in the A2 and A1B scenarios. The temperature is expected to increase in the summer for 2060-2069 and 2090-2099, but a decrease for 2020-2029 may be observed, particularly in the winter months. For the 2020s, the seasonal precipitation, as well as AET and runoff, is expected to be lower than the base period. For 2060-2069, precipitation, as well as the AET and runoff, is almost at the same level to that of the base period. Though, for 2090-2099, the basin is projected to receive higher precipitation for the wetter season compared to the base period, as well as in 2020-2029 and 2060-2069. The same trend is observed in AET and runoff (Fig. 10).

3.5 Extreme Precipitation

Bagmati basin is probably one of the most disaster-prone, mountainous basins in the Hind-Kush-Himalaya region. The basin has a history of moderate (greater than 0.25 cm/hr) to heavy (0.76 cm/hr) rainfall [35] and is known for its ferocity to induce landslides and floods. The rainfall amount measured on July 19, 1993 (540 mm/day, or2.25 cm/hr) in one of the stations within the basin was a record for Nepal. This was close to the basin average monthly accumulation of 550 mm/month for the month of July in 1993. This event triggered massive landslides and floods killing 1,120 people [36]. This event was compared with that of future decades for the A2, A1B and B1 scenarios (Table 5).

Table 5. Number of predicted extreme precipitation events, compared to the historical 1993 record

Time Period	Scenarios	1993 Monsoon season (J-J-A-S) (≥ 1530 mm)	1993 Yearly total (≥ 1,800 mm)
2020s	A2/A1B/B1	0/1/0	2/7/6
2060s	A2/A1B/B1	8/7/6	10/10/8
2090s	A2/A1B/B1	10/8/7	10/10/10

The values in Table 5 show how many years in the given decades the basin average precipitation is expected to exceed the historical record of 1993 (monsoon season: June-July-August-September and annual) in the basin. The monsoon season precipitation is not expected to exceed the monsoon precipitation of 1993 (which is 1,530 mm) in the 2020-2029, except for one year, in the A1B scenario. Still, in the 2060-2069 and 2090-2099, the monsoon seasons, as well as the annual rainfall totals, are expected to exceed the record in 1993. In the 2060-2069, monsoon season rain is expected to outweigh the 1993 season total in 6 (B1) to 8 (A2) years, while in the 2090-2099, it is expected to exceed in 7 (B1) to 10 (A2) years. The annual precipitation for all future decades is expected to exceed the annual precipitation of the 1993 case, which accumulates to 1,800 mm. In the 2060-2069 and 2090-2099, almost all the years are expected to be wetter while in the 2020-2029; only 2 (A2) to 7 (A1B) years are expected to exceed the records of 1993. With the prediction of higher precipitation in the coming decades, the possibility of higher incidences of landslides and floods are more likely to occur and an increasing risk to life and property in the basin will become a reality, especially during the 2060-2069 and 2090-2099.

4. CONCLUSION

The current research investigated the impact of climate change on the basin hydrology of Bagmati, a mountainous basin of Nepal Himalayas. The study area potentially has orographic effects and lacks a desirable level of in-situ measurements. It should be noted that the gauging stations used in this study are concentrated in the upper reach of the study basin, which may not have captured the spatial variability of the basin, including any orographic effect. Further the CMIP3 has just 3 grid points within this basin. Despite these limitations, this study showed possible states of basin hydrology in future. According to Coupled Model Intercomparison Project 3 (CMIP3) data, the Bagmati basin is expected to receive higher precipitation in all emissions scenarios in the coming decades. The most conservative lowest emission scenario projects an 8% increase in precipitation, while the most extreme one predicts 18%. The temperature is also projected to increase by about 2ºC to 4.5ºC more than the base period (1990-1999) in different scenarios. The projected data, however, underestimated both temperature and precipitation by about 18%, which shows the limitation of CMIP3 data.

It is found out that the summer months from May to August are expected to become hotter and wetter in 2060-2069 and 2090-2099 compared to 2020-2029. Such change may be attributed to the assumptions made while creating emission scenarios: A2, A1B and B1. The main drivers for emission scenario are the demographic development, socio-economic development and technological change. For A1B and B1 scenario, the population peaks in mid-century (2050) while population continuously increases till 2099 [14]. The switches from drier to wetter summer most likely happen around 2050.

The higher precipitation and temperature, as a result of climate change, causes a significant increase in actual evapotranspiration and runoff under all emission scenarios in the Bagmati basin. The seasonal variability shows that in all scenarios and decadal time frames, the basin is projected to receive almost the same amount of rainfall in the drier periods (November-April). However, higher rainfall will occur during rainy seasons, generating more runoff, especially for the mid- (2060-2069) and long-term (2090-2099) time periods, possibly indicating a positive feedback in the basin as the result of climate change. The prediction of higher runoff means surface water availability in the basin over the coming decades may not be a critical issue. Having the seasonal rainfall be at the same level or higher compared to the 1990-1999 means no negative impact on existing levels of rain-fed agriculture practices in the basin. A rise in precipitation, and consequently higher runoff, in the upper mountainous regions of the basin during the wet season may trigger landslides, while lower parts of the basin may have higher incidence of flooding events for 2060-2069 and 2090-2099, increasing risk to life and property. This finding is important because the study basin has a history of high intensity rainfall. When the projected precipitation for 2020s, 2060s and 2090s are compared for all emission scenarios with the 1993 historical precipitation event, the decades of 2060s and 2090s are expected to be wetter both during monsoon season and annually. This shows that the basin likely become more vulnerable to landslides and flooding during 2060-2069 and 2090-2099. Therefore, proper water management and emergency plans need revisiting to minimize possible impacts of climate change, especially the issue of flooding and landslides.

ACKNOWLEDGEMENTS

This study was a part of a NASA Applied Science Global Flood and Landslide Project, NASA SERVIR-Africa Project and School of Civil Engineering and Environmental Science at the University of Oklahoma. The authors would like to extend sincere thanks to the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modeling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset which is supported by the Office of Science, U.S. Department of Energy. Thanks also go to the Department of Hydrology and Meteorology of the Government of Nepal and Ramesh Paudel, Engineer for the Government of Nepal for making available the rainfall, and discharge data at the study basin. Thanks also go to Jill Hardy, a meteorology graduate student at the University of Oklahoma for helping with the editing. The authors would like to extend special thanks to the two anonymous reviewers providing comments on the earlier versions of this manuscript. Those comments helped improve the manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. IPCC. Climate Change, 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, USA. 2007;996.
2. Bates BC, Kundzewicz ZW, Wu S, Palutikof JP, editors. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva; 2008.
3. Parry ML, Canziani OF, Palutikof JP, Van der Linden PJ, Hanson CE, Editors. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press; 2007.
4. US Global Change Research Program. Water: The potential consequences of climate variability and change for the water resources of the United States, The report of the water sector assessment team of the national assessment of the potential consequences of climate variability and change for the U.S. Global Change Research Program; 2000.
5. Chahine MT. The hydrological cycle and its influence on climate. Nature. 1992;359:373-380.
6. Trenberth, KE, Dai A, Rasmussen RM, Parsons DB. The Changing Character of Precipitation. Bulletin of the American Meteorological Society. 2003;84(9):205-1217.
7. Giorgi F, Im ES, Coppola E, Diffenbaugh NS, Gao XJ, MariottiL, Shi Y. Higher hydroclimatic intensity with global warming. J. Climate. 2011;24:5309–5324.
8. IPCC. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland. 2007;104.
9. Gosain AK, Shrestha AB, Rao S. Modeling climate change impact on the hydrology of the Eastern Himalayas: Climate change impact and vulnerability in the Eastern Himalayas, Technical report 4. Kathmandu: ICIMOD; 2010.
10. Chapagain BK, Subedi R, Paudel NS. Exploring local knowledge of climate change: Some reflections, J. Forest and Livelihood. 2009;8(1):108-112.

11. Chaudhary P, Aryal KP. Global Warming in Nepal: Challenges and Policy Imperatives. J. of Forest and Livelihood. 2009;8(1):4-13.
12. Chambwera M, Stage J. Climate change adaptation in developing countries: issues and perspectives for economic analysis, International Institute for Environment and Development (IIED), UK; 2010.
13. Fujikura R, Kawanishi M. Climate change adaptation and international development, Making development cooperation more effective, (eds.), JICA Research Institute, Earthscan Publication, London, Washington DC; 2011.
14. IPCC. Emissions Scenarios: Summary for policymakers, A Special Report of IPCC Working Group III; 2000.
15. Flood Management Information System (FMIS), Water Resources Department, Bihar. (Accessed on February 2012). Available:http://fmis.bih.nic.in/Riverbasin.html#Bagmati
16. Shrestha, MS, Artan GA, Bajracharya SR, Sharma RR. Using satellite-based rainfall estimates for stream flow modeling: Bagmati Basin. J Flood Risk Management. 2008;1:89–99.
17. Gadgil S. The Indian monsoon and its variability, Annual Review of Earth and Planetary Sciences. 2003;31:429-467.
18. Sharma RH, Shakya NM. Hydrological changes and its impact on water resources of Bagmati watershed, Nepal, Journal of Hydrology. 2006;327:315-322.
19. Houze RA, Wilton DC, Smull BF. Monsoon convection in the Himalayan region as seen by the TRMM Precipitation Radar, Quarterly Journal of the Royal Meteorological Society. 2007;133:1389–1411.
20. Shrestha RK. Impact of climate change on crop water use and productivity: A case study of Bagmati River basin, Nepal, A thesis for Master of Science degree at the UNESCO-IHE, Delft, The Netherlands; 2007.
21. Pradhan PK. Population growth, migration and urbanization: Environmental Consequences in Kathmandu Valley, Nepal. In Unruh JD, Krol MS and N. Kliotediotrs. Environmental Change and Its Implications for Population Migration, Kluwer Academic Publishers, the Netherlands. 2004;177–199.
22. Sharma S. Restoration project along the banks of Bagmati River corridor of Kathmandu valley for enforcing sustainable land use planning and development, A research report. Available:www.alcoa.com/global/en/.../Suresh_Sharma_Final_Report.pdf, Accessed on February, 2012.
23. Maurer EP, Brekke L, Pruitt T, Duffy PB. Fine-resolution climate projections enhance regional climate change impact studies, Eos Trans. AGU. 2007; 88(47):504.
24. Meehl GA, Covey C, Delworth T, Latif M, McAvaney B, Mitchell JF, Stouffer RJ, and Taylor KE. The WCRP CMIP3 multi-model dataset: A new era in climate change research. Bulletin of the American Meteorological Society. 2007;88:1383-1394.
25. Supit I, Van Diepen CA, de Wit AJW, Wolf J, Kabat P, Baruth B, Ludwig F. Assessing climate change effects on European crop yields using the Crop Growth Monitoring System and a weather generator. Agricultural and Forest Meteorology. 2012;164:96-111.
26. Yasunari T. Spectral analysis of monsoonal precipitation in the Nepal Himalaya, Journal of the Japanese Society of Snow and Ice, Seppyo. 1976;38:59-65.
27. Shrestha AB, Wake CP, Dibb JE, Mayyewski PA. Maximum Temperature Trends in the Himalaya and its Vicinity: An Analysis Based on Temperature Records from Nepal for the Period 1971-94. Journal of Climate. 1999;12:2775–2787.
28. MoPE.Initial national communication to the conference of parties of the United Nations Framework Convention on Climate Change, Ministry of Population and Environment of Nepal, Kathmandu. 2004;153.
29. Shrestha AB, Wake CP, Dibb JE, Mayyewski PA. Precipitation fluctuation in the Nepal Himalaya and its vicinity and relationship with some large scale climatology parameters, International Journal of Climatology. 2000;20:317-327.
30. Dulal K, Takeuchi K, Ishidaira H. A framework for the analysis of uncertainty in the measurement of precipitation data: A case study for Nepal, Agricultural Engineering International, The CICER Ejournal; 2006.
31. Wood AW, Maurer EP, Kumar A, Lettenmaier DP. Long-range experimental hydrologic forecasting for the eastern United States. J Geophysical Research-Atmospheres. 2002;107(D20):4429.

32. Wood AW, Leung LR, Sridhar V, Lettenmaier DP. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim. Change. 2004;15:189–216.
33. Thornthwaite, CW. An approach toward a rational classification of climate. Geographical Review. 1948;38(1):55-94.
34. McCabe GJ, Markstrom SL. A monthly water-balance model driven by a graphical user interface, U.S. Geological Survey Open-File Report. 2007:2007-1088.
35. American Meteorological Society (AMS). Glossary of Meteorology 2000. Available:http://amsglossary.allenpress.com/glossary (Accessed on February 2012)
36. Dixit A, Upadhya M, Pokharel A, Dixit KM, Rai DR, Devkota M. Flood disaster impact and responses in Nepal tarai's marginalized basins in working with the winds of change towards strategies for responding to the risks associated with climate change and other hazards. In Moench M, Dixit A, editors, ProVention Consortium, Institute for Social and Environmental Transition-International and Institute for Social and Environmental Transition-Nepal, second edition, Kathmandu. 2007;119-157.