Assessing impact of Climate Change on Hydrological regime of Himalayan region for Sustainable Management of Water Resources

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Abstract

The Himalayan region is one of the most vulnerable regions to the impacts of climate change. The region is experiencing a range of changes, including rising temperatures, changing precipitation patterns, retreating glaciers, and more frequent extreme weather events. These changes are having significant impacts on the people and ecosystems of the region and pose significant challenges for sustainable development.

To assess the impact of climate change on the Himalayan region for sustainable development, it is essential to understand the region's vulnerability to climate change and the specific impacts that are occurring. One of the key indicators for climate change is changes in regional hydrological regime. In the presented study, these changes are observed through variables affecting hydrological cycle, such as precipitation, temperature etc. Climate change is causing changes in the precipitation patterns in the region, with some areas experiencing more intense rainfall and others experiencing droughts. These changes could have significant impacts on agriculture and food security. Increased frequency of extreme weather events: The Himalayan region is experiencing more frequent and intense extreme weather events, such as floods, landslides, and droughts. These events can cause significant damage to infrastructure and disrupt the region's economy.

The study is based on north-eastern state of India, Arunachal Pradesh. The data acquisition for the areas being highly mountainous is difficult, and hence satellite data is used along with field collected data. The landuse change detection is performed for year 2005, 2010 and 2017. At the same time, the water availability assessment is performed using rainfall runoff and mass balance approach using SWAT hydrological modeling software. The assessment is compared with the observed data in major basins and streams of the region and is used for calibration. The achieved NSE (Nasc-Sutcliffe Error) is 0.61.

The simulation model is used for year 2030, for hydrological assessments in the region using climate predicted data and keeping the latest landuse, 2017. The results shows higher streamflow and the distribution of water availability are changed. The agriculture adapted in the region, is mostly a shifting cultivation, in forest areas. The forest ecology and landuse as well have huge impact on hydrological flows, and thus its important to revise the policy and water laws in the regions. Encouraging sustainable agricultural practices, such as agroforestry and organic farming, can help to improve food security and promote sustainable development.

Overall, addressing the impacts of climate change on the Himalayan region is crucial for promoting sustainable development in the region. By taking a comprehensive approach that addresses the root causes of climate change and promotes sustainable development, it is possible to create a more resilient and sustainable future for the people and ecosystems of the Himalayan region.

1 Introduction

The Himalayan Mountains have an important role in the regulation and distribution of water resources (Nepal, 2016). Climate change has had an impact on the global and regional water resource systems (Ayt Ougougdal, 2020). The SWAT model on future climate, predicted a significant increase in streamflow and water yield due to climate change (Singh, 2017). Understanding the possible influence of climate change on the Himalayan region's hydrological regime is critical for long-term water resource management (Nepal, 2016). Climate change has had a significant impact on agricultural and socioeconomic growth in India's eastern Himalayan region. Mountains communities suffer enormous difficulties as a result of a variety of issues such as geographical obstacles, micro-climates, degradation, and availability to essential services, among others (Bhadwal, 2019). Furthermore, due to topography and rocky terrain, water storage for irrigation is a persistent challenge; thus, rainfed agriculture dominates in hilly places (Poonia, 2021). According to recent studies in the Eastern Himalayas, decreased snow in the mountains and intense but brief periods of rainfall produce increased run-off, inadequate water recharge, and the subsequent drying up of water sources (Sabin, 2020).

Water is susceptible to supply and demand stress due to its importance and scarcity (Allegretti, 2022). Understanding the water cycle and the land-atmosphere feedback system (Hu, 2009) is also critical. Adaptation measures for irrigated agriculture production systems are based on analysing the expected availability of water, particularly in mountain river systems delivering water through gravity schemes, which are common in developing countries (Kaini, 2021). Understanding the interdependence between water users (both anthropogenic and natural) across a river basin is required for large basin planning (Simons, 2020).

2 Data and Methods

2.1 Data Used

Land use and land cover (LULC) is one of the most important elements influencing a catchment's surface and subsurface hydrology (Dinka 2019). The forest classes were gathered from the Forest Survey of India's (FSI) forest class and forest type datasets for 2005 and 2010. remaining than forest classes, the remaining LULC classes were generated using Landsat-8 OLI satellite data from 2005, 2012, and 2017. The LULC map for 2005, 2012, and 2017 was created using a hybrid technique that combined digital picture categorization with visual image interpretation. To improve the quality of visual interpretation, the National Remote Sensing Centre (NRSC), GoI used referenced and published Land Use / Land Cover maps on a 1:50,000 scale for the years 2005 and 2010. Furthermore, long-term coherence (since 2005) of individual classes over a certain pixel/area functioned as one of the important parts of visual picture interpretation and class definition in digital image classification, and 21 LULC classes were generated for three time intervals. The soil dataset was obtained at a 1:50,000 scale from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP). Daily gridded data of meteorological parameters i.e., maximum/minimum air temperature, solar radiation, wind speed, and relative humidity (1x1 degree) and precipitation (0.25x0.25 degree) from 1983-2020 were procured from India Meteorological Department (IMD), GoI.

To capture the regional climatic effects, dynamic downscaling of climate data was performed using the Weather Research and Forecasting model (WRF) regional climate model (RCM). The NCAR coupled model Community Climate System Model Version4 (CCSM4) (http://www.cesm.ucar.edu/models/ccsm4.0/) was used to simulate the future for 10 years (2020-2030). RCP 4.5 scenario initial and boundary conditions will be used to force a regional climate model with a horizontal resolution of 25 km. Researchers in the Himalayan region employ the RCP 4.5 scenario to examine the impact of climate change on water resources, such as calculating streamflow/discharge (Shrestha et al., 2016) and examining the temperature, precipitation, and runoff relationship (Jasrotia et al., 2021). LULC, soil characteristics, topography, and weather parameters such as precipitation, temperature, relative humidity, solar radiation, and wind speed are all inputs to the model. Table 1 contains full lists of data.

Table 1: Sources of data

Subject area	Data basis	Source and map scale
Basic data	Administrative boundaries, stream networks	Survey of India; scale 1: 50 000
Climatic data	Present Climate (1900-2013): Daily precipitation, daily maximum and minimum temperature, solar radiation, wind speed and potential evaporation	Indian Meteorological Department, GoI

	Future Climate (2019-2030): Daily precipitation, daily maximum and minimum temperature, solar radiation, wind speed and potential evaporation	Community Climate System Model (CCSM) V4 (RCP 4.5)
Soil data	Soil type and physical characteristics (composition of silt, sand, clay, rocks), field capacity, bulk density, saturated hydraulic conductivity, depth to water table, soil depth	National Bureau of Soil Survey and Land use planning (NBSS & LUP); scale 1:250 000, ICAR Basar
Land use data	Land use pattern	NRSC/ ISRO 2005 and 2012
Digital Elevation Model	Topography data/SRTM	Survey of India; scale 1:50 000
River Discharge data Monthly/annual Streamflow	Water Resource Department, Arunachal Pradesh India-WRIS (https://indiawris.gov.in/wris/#/)	Central Water Commission, Government of India National Water Informatics Centre (Ministry of Jal Shakti), GoI

2.2 Methodology

The SWAT (Soil and Water Assessment Tool) model was used to simulate the land phase of the hydrological cycle. SWAT has been successfully tested and used for ungauged river basins, owing to its spatially detailed parameterization capability. SWAT is a basin-scale, time-continuous hydrological model that operates at a daily time step (Srinivasan et al., 1998). The model has been widely utilised in studies on water management (Debele et al., 2008), land use changes (Ghaffari et al., 2010), and climate change and its consequences (Jha et al., 2006). The model is best suited for this study because, while it is data demanding and demands a large amount of data, it is also known as a good model in the situation of limited data availability (Ndomba et al., 2008).

Its adaptability and usefulness in predicting various hydrological processes have been widely proven in countries such as India, the United States (Chaubey et al., 2010), Australia (Githui et al., 2012), Greece (Boskidis et al., 2012), and Ethiopia (Betrie et al., 2011). Based on topographic factors, the model divides the entire watershed into sub-basins. The water balance analysis relies heavily on soil hydrologic processes (Rodriguez-Iturbe, 2000). The physical and chemical qualities of soil have a significant impact on hydrologic processes. SWAT employs the water balance equation 1:

$$SW_t = SW_0 + \sum(R_{day} - Q_{sur} - E_a - W_{seep} - Q_{gw}) \qquad \text{Equation 1}$$

Where, SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), and R_{day}, Q_{surf}, ET_a, W_{seep}, and Q_{gw} are daily amounts (mm) of precipitation, runoff, evapotranspiration, percolation, and return flow on day i, respectively, to compute water balance at the HRU level.

Surface runoff is calculated using the Soil Conservation Service (SCS) curve number methodology and the Green and Ampt infiltration method. However, in this study, the SCS curve number was used, which contains information on soil, land use, and management. ET contributes approximately 60% of precipitation to the terrestrial hydrologic cycle (Zheng, 2019). Priestly-Taylor, Penman-Monteith, and Hargreaves are three of the most extensively used SWAT methods for calculating potential evapotranspiration. CO2 concentration fluctuations affect plant development and physiology, resulting in variations in ET, watershed biogeochemistry, and water balance. The Penman-Monteith approach was adopted for ET computation in this work because it accounts for the effects of changing atmospheric CO2.

Each sub-basin is linked by a stream channel and further subdivided into hydrologic response units (HRUs). HRUs in a sub-watershed are unique mixes of soil, slope, and land use. At this level, the hydrology, vegetation, and management practises are all simulated. Furthermore, the model calculates surface runoff independently for each sub-basin, which is subsequently channelled to obtain total watershed runoff. SWAT was used to evaluate the hydrological dynamics of 838 micro-watersheds (see Figure 1). The study was divided into 3270 hydrologic response units (HRUs) based on LULC, soil, and slope.

Due to Arunachal Pradesh's difficult terrain and poor gauging system, the SWAT model parameters were calibrated using the recommended range of parameters suggested in various research studies for the study domain and validated with the few observed stream-flow discharge obtained from WRD, Arunachal Pradesh. The SWAT model was used to extract surface and subsurface hydrological parameters for further assessing the spatial and seasonal fluctuation of surface water (HRUs).

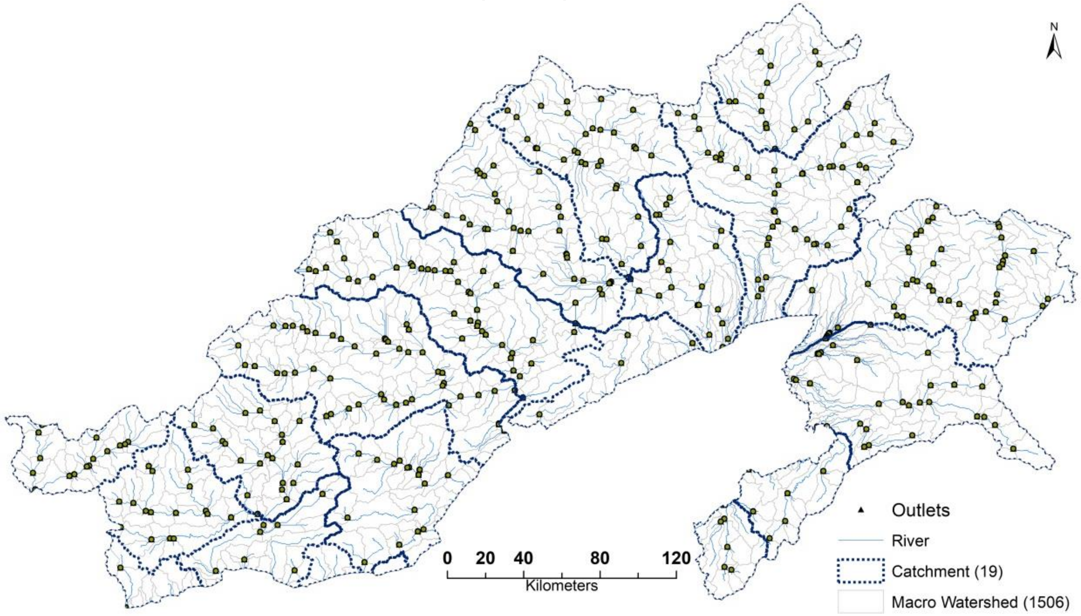

Figure 1: Macro watershed delineation

2.3 Sensitive analysis and model validation

The location of sites where the ground data availability was found of appropriate quality to perform calibration is shown in Figure 2. The data for all three sites is analysed for its consistency, and to out rule any outliers. The discharge in stream for Passighat site was found to be too low when compared with the observed data on its upstream stretches, indicating that the observed data is either manipulated or has some error. Hence, the Passighat location is not used for calibration phase. The data availability ranges for all three sites are given in table 2.

Table 2: Location sites for calibration & validation

1	Passighat	2010 - 2019
2	Daparizo	2015 - 2019
3	Bhalukpong	1990 - 2019

SWAT input parameters are process based and must be held within a realistic uncertainty range. The first step in the calibration and validation process in SWAT is the determination of the most sensitive parameters for a given watershed or sub-watershed. The user determines which variables to adjust based on expert judgment or on sensitivity analysis. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). It is necessary to identify key parameters and the parameter precision required for calibration. The recommended ranges of input parameters are given in table 3.

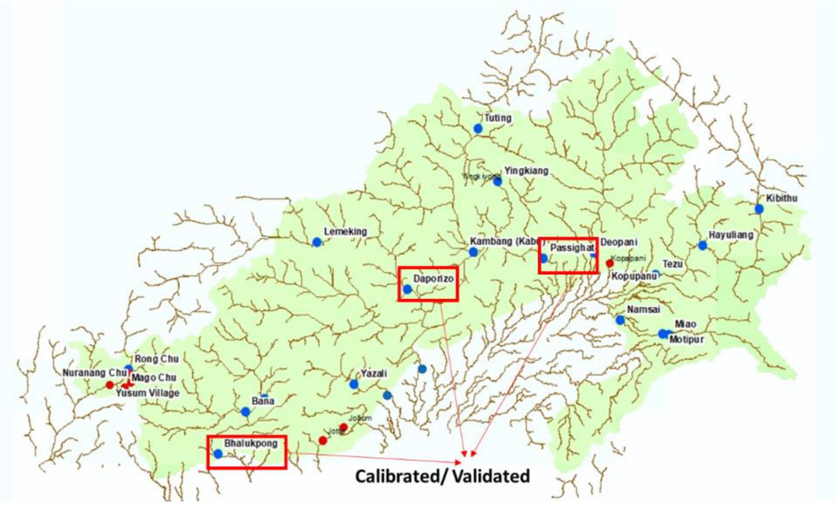

Figure 2: Location map of calibration and validation sites

Table 3: Recommended range for input parameters based on sensitivity analysis

Parameters		Description	Units	Recommended range	SWAT default
Surface response	CN 2	SCS curve number	n/a	35-92	55-83
	ESCO	Soil Evaporation Condensation Factor	fraction	0.1-0.95	0.95
	SOL Z	Soil Depth	Mm	0.2-0.55	600-1100
	SOL K	Saturated hydraulic conductivity	mm/h		1-10.9
	SOL AWC	Available soil water capacity	mm/mm	1.5-208	0.13-0.16
	CH N	Manning’s ‘n’ value for the channel	n/a	0.01-0.1	0.014
Subsurface response	GWDELAY	Time required for water leaving the bottom of the root zone to reach the shallow aquifer	Days	31	31
	GW REVAP	Rate of transfer from the shallow aquifer to the root zone	n/a	0.02	0.02
	REVAPMN	Threshold water depth in shallow aquifer for percolation to deep aquifer to occur	Mm	1	1
	GWQMN	Threshold water depth in shallow aquifer for return to reach to occur	Mm	0-200	0
	ALPHA BF	Baseflow alpha factor	Days	0.01-0.05	0.048
	RCHRG DP	Deep aquifer percolation factor	fraction	0.05-0.1	0.05
Bain response	SURLAG	Surface lag coefficient; controls fraction of water entering reach in 1 day	Days	0.75	4

Two types of sensitivity analysis are generally performed: local, by changing values one at a time, and global, by allowing all parameter values to change. The two analyses, however, may yield different results. Sensitivity of one parameter often depends on the value of other related parameters; hence, the problem with one-at-a-time analysis is that the correct values of other parameters that are fixed are never known (Figure 3).

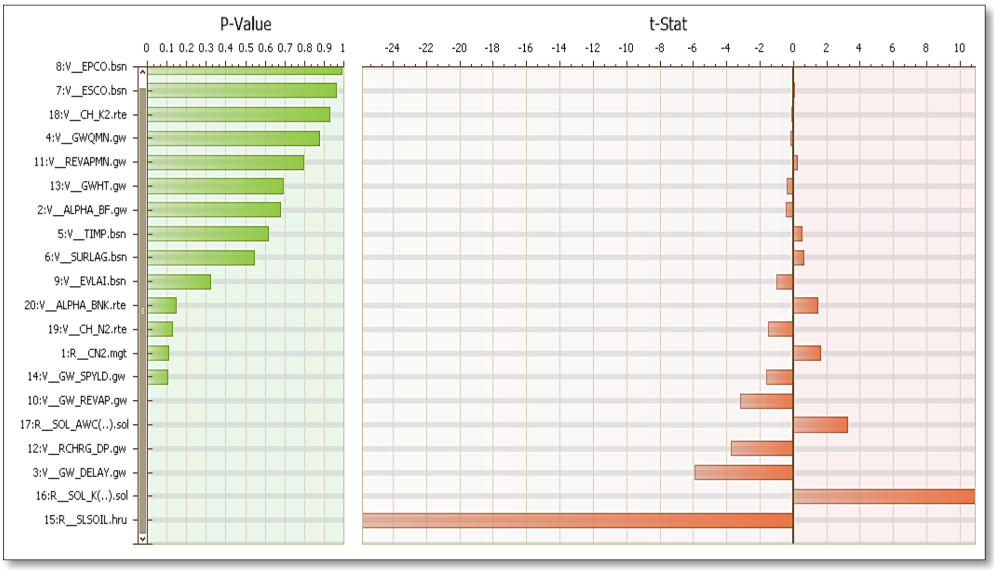

Figure 3: The parameters with lowest P-values were indicated high sensitivity

The 500 simulation was run, with iteration 328 yielding the best simulation value. For calibration and validation, two stations, Daparizo and Bhalukpong, were simulated. The calibration period for Bhalukpong station was 1990-2010, while the validation period was 2011-2019. However, the Daparizo station observed data was only for a short period of time. As a result, the calibration period was 2015–2017, and the validation period was 2019. Monthly and daily time intervals were sinulated for the model. Table 4 lists the evaluation parameters that were used to capture the validation and calibration results.

Table 4: Calibration and validation of model

Evaluation Parameters	Calibration		Validation	
Variable	Daparizo	Bhalukpong	Daparizo	Bhalukpong
p-factor	0.69	0.68	0.13	0.11
r-factor	0.67	0.66	0	0
R2	0.72	0.69	0.78	0.68
NS	0.61	0.6	0.61	0.52
bR2	0.4993	0.5078	0.7096	0.5429
MSE	2.10E+05	1.80E+05	1.40E+05	8.10E+04
SSQR	7.90E+04	6.40E+04	7.10E+04	3.20E+04
PBIAS	26.5	24.8	-17.1	28.7
KGE	0.65	0.68	0.68	0.66
RSR	0.62	0.63	0.63	0.7
MNS	0.47	0.43	0.39	0.27
VOL_FR	1.36	1.33	0.85	1.4
Mean Simulation	651.7	616.25	841.87	396.26
Mean Observed	887.04	819.13	718.88	555.42
StdDev Simulation	605.45	592.13	738	393.03
StdDev Observed	736.29	673.72	591.58	409.76

3 Result and discussion

The dynamic downscaling of climate data is being carried out for two time periods, one in the past and the other for a future time period, 1996-2005 and 2020-2029 respectively. Ten years baseline (1996-2005) of control simulations and 10 years of future simulations (2020-2029) of future simulation has been completed using CCSM4 (Figure 4). The Community Climate System Model (CCSM) version 4 is a coupled climate model for simulating the earth's climate system (http://www.cesm.ucar.edu/models/ccsm4.0/) with initial and boundary conditions. The Weather Research and Forecasting model (WRF) has been used for the dynamic downscaling of climate projections from CCSM4. The advantages of the WRF model over other RCMs (Regional Climate Model) is its portability to different computing architectures, efficient use of large parameter space (such as different cumulus schemes, micro-physics schemes, radiation schemes, planetary boundary layer schemes etc.), it was found that there are 10224 combinations of WRF that can be used for both climate and weather research.

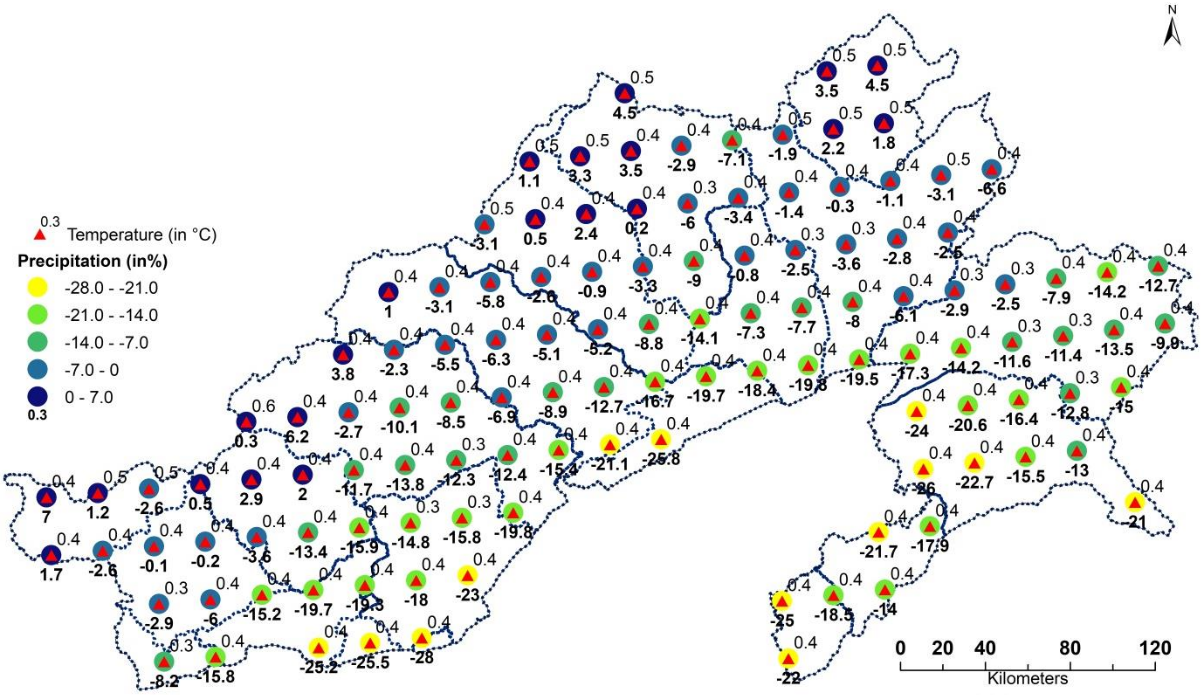

Figure 4: Temperature Difference (in °C) and Precipitation differences (in%) from baseline (1996-2005) to future simulations (2020-2029)

The % of runoff calculated in two scenario, first land practice change: change in land practices during 2005 and 2017 to see the impact of land practices over the runoff and second Climate parameters change: the change of future climatic parameters extracted from climate model over 2017 land practices to see the change of runoff due to climate change (Table 5). Runoff of Brahmaputra, Upper Dibang and L B Subansari river catchment will decreased due to climate change while Lohit, Twang chu, Kameng, Dhansiri and Bishom River decreased their runoff due to land practices. Runoff will increased due to climate change in the catchment of Twang chu, Kemeng Bishom and Dhansiri rivers.

Table 5: Change of runoff in Catchment due to land practices and climate change

ID	Code	Catchment	% of Runoff				
			2005	2017	Change in Land Practice	2030	Climate Change
1	3A2C	Dhansiri River	6.33	1.84	-4.48	4.92	3.07
2	3A2D	Twang Chu	26.97	20.38	-6.60	35.18	14.81
3	3A3A	Bhareli River	3.57	3.04	-0.53	2.05	-0.99

4	3A3B	Bishom River	6.59	1.97	-4.62	5.64	3.67
5	3A3C	Kameng River	10.54	5.78	-4.76	14.80	9.02
6	3A3D	Brahmaputra River	21.03	25.05	4.01	0.90	-24.15
7	3A3E	Disang River	15.38	28.28	12.90	29.25	0.97
8	3A4A	Dikrang (Subansiri) River	4.20	5.35	1.16	6.69	1.34
9	3A4B	R B Subansiri River	9.65	9.28	-0.37	9.36	0.08
10	3A4C	L B Subansiri River	10.78	12.18	1.40	7.34	-4.84
11	3A5A	Brahmaputra River	26.28	26.51	0.23	18.09	-8.42
12	3A5B	Dihang River	23.65	30.17	6.51	29.95	-0.22
13	3A5C	Siang River	34.58	35.74	1.16	33.67	-2.07
14	3A5D	Siyom River	11.01	12.53	1.52	8.84	-3.69
15	3A5F	Tirap River	9.14	10.28	1.15	14.95	4.67
16	3D4A	Lohit River	18.98	16.35	-2.63	15.74	-0.61
17	3D4B	Tellu / Lohit River	37.72	26.53	-11.19	34.26	7.74
18	3D4C	Lower Dibang River	45.88	50.34	4.46	48.62	-1.72
19	3D4D	Upper Dibang River	59.52	69.98	10.46	55.72	-14.26
		Over All	20.10	20.61	0.51	19.79	-0.82

4 Conclusion

Two time land use and land cover practices 2005 and 2017 was simulated under present climatic condition (1985-2019). The annual water balance under 2005 land practice and 2017 land practices was calculated. It was observed that over all water volume increased by 11389.05 MCM. The effect of land practices not uniformly increased the water volume in all districts and catchments. Water volume decreased in Lohit, Tawang chu, Bishom, Kameng, Dhansiri and Bhareli catchements. Similarly Anjaw, Changlang, East and West Kameng and Tawang district associated with above catchment decreased annual water volume due to land practices change between two years 2005 and 2017. This need to formulate with best and optimum land practices to control the water balance as per the state requirement and its association with neighbouring state.

To calculate the impact of future climate on water balance of the area, the future climate parameter was simulated over present land use practices and the water balance for the year 2030 was calculated in SWAT. The input of all climatic parameters was obtained from RCM model under RCP 4.5 scenario.

It is observed that overall 22217.37 MCM water volumes will increase due to change in climatic variables. Some catchment and associated districts will also produce low water volume compared to present climatic condition. The water volume will decreased in future in the catchment of - Bhareli river, Brahmaputra river, R B Subansiri river, Dihang river, Siang river and upper Dihang associated with following districts- East siang, Kurung Kumey, Lohit, Papum pare, Upper Siang and Upper Subansiri. The change in volume either increases or decreases situation requires a better land practices measures to mitigate future climatic condition of water resources.

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