INNOVATIVE ENERGY TECHNOLOGY SYSTEMS AND ENVIRONMENTAL CONCERNS: A SUSTAINABLE APPROACH
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Sub-catchment Wise Spatio-temporal Analysis of Streamflow/ Water Yield on a Himalayan Catchment under the Changing Role of Temperature

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Abstract

This study presents an assessment of the impacts of increasing temperature phenomenon on a series of indicators of hydrological regimes across the Himalayan catchment, using a distributed hydrological model SWAT (soil water assessment tool) with climate scenarios constructed using CANCM4/RCP24 (Fourth Generation Atmospheric General Circulation Model) climate model. The main aim of this study is to assess the climate vulnerability in terms of increasing temperature phenomenon on the resultant water yield. This study mainly identifies two-decadal (1991-2008 and 2015-2035) variations in daily temperature and daily precipitation on a part of Satluj river catchment (from Rampur to Kasol gauge station), which is situated in the western Himalayan region. The outcomes of this study show that the water yield is projected to increase in future for almost all the scenarios considered. The maximum magnitude of the change was recorded for water yield during current (11% to 16%) and third scenarios (26% to 60%), respectively. We observed that these changes were not consistent throughout the year and fluctuate as per winter, summer and monsoon seasons.

Keywords: temperature, climate scenarios, precipitation, water yield, hydrological modeling.

1. Introduction

The range of emission scenarios presented to the Intergovernmental Panel on Climate Change (IPCC), CO_2 concentrations are expected to increase from the baseline concentration of 330 ppm (parts per million) to 549 ppm, 856 ppm, and 970 ppm for the different greenhouse gas emission scenarios, by the end of the twenty-first century (Bindoff et al., 2007; IPCC 2007). The uneven climate changes accelerated the hydrologic cycle, precipitation pattern, magnitude and timing of streamflow in the downstream portion of the river catchment (Schuol et al., 2008). Due to the intimate linkage between the hydrologic cycle and climate, climate change can influence hydrological components as well as streamflow/runoff (Sun et al., 2014). Projected changes in climate are expected to change precipitation pattern and freshwater flow regimes in the form of high intensity and high volume runoff (Escurra et al., 2014; Kanawade et al., 2014). Climate change has affected the natural immovability of snowmelt runoff and rainfall runoff processes (Manandhar et al., 2013).

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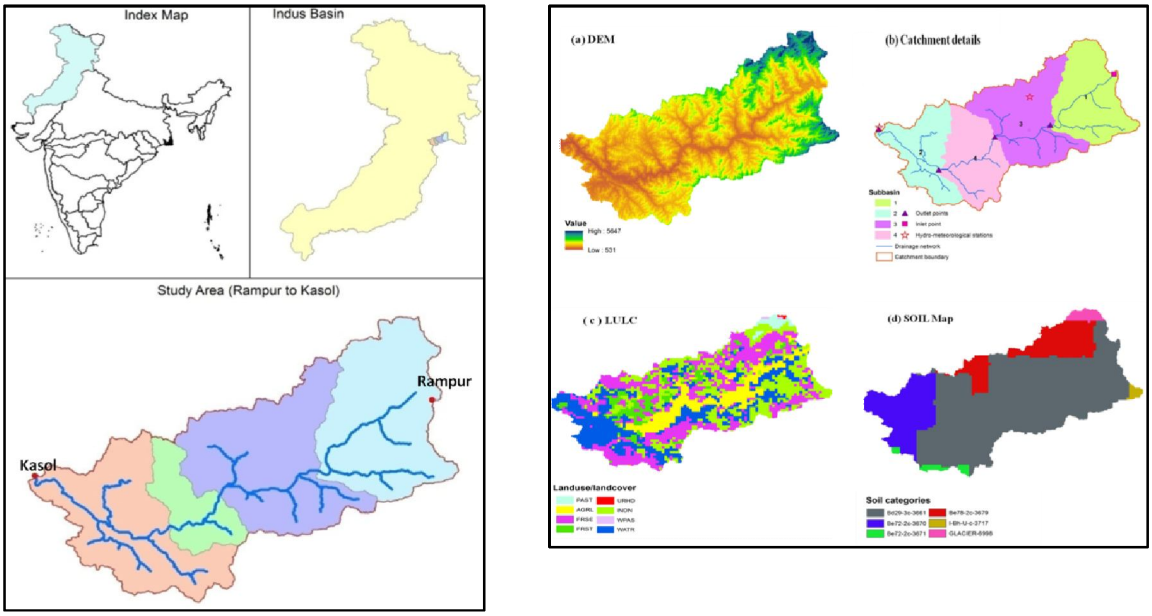
Hydrological characteristics and parameters could be explored significantly by dividing the whole catchment into sub-catchments (Saurral et al., 2008). Apart from the above considerations, it is assumed that the model parameterization and sensitivity analysis are also the necessary tasks in the accurate prediction of hydrological scenarios (Abbaspour et al., 2011). Therefore, this study examines long term time series analysis (1991-2035) under daily extreme temperature and precipitation conditions over the Himalayan catchment, for two different periods (1991-2008 and 2015-2035) and three hydrological scenarios. For this region, a distributed hydrological model SWAT with special integration with SWATCUP (SWAT calibration and uncertainty program) as an inbuilt function of multi-objective optimization techniques (e.g. SUFI2-sequentially uncertainty parameter fitting approach) was utilized for the streamflow simulation, calibration and validation of the time series prediction scenarios. For each hydrological scenario, trends are presented spatially and temporally especially at sub-catchment level.

2. Materials and Methodology

2.1. Study Area

The current study area (from Rampur to Kasol) is a part of Satluj river system situated at western Himalayan regions of India (see Fig. 1). The Rampur meteorological/gauge station is considered as an inlet and Kasol meteorological station selected as an outlet of the catchment. The Satluj river is mostly fed by snowmelt and rainfall during the summer and by groundwater flow during the winter. The topography of this catchment corresponds to moderate hilly terrain (531 meter elevation) to high hilly terrain (5647 meter).



(a) **(b)**

Fig. 1: (a) Study area map and (b) Thematic Parameters.

2.2. SWAT Model Description

SWAT ((http://swat.tamu.edu/) is a physically based, continuous-time, long-term simulation, lumped parameter and deterministic model which contains various landuse and soil parameters. SWAT model is fully capable to compute long term time series for large as well

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as small catchments. The hydrologic cycle as simulated by SWAT is based on the water balance equation as Equation (1) (Arnold et al., 1998).

$$SW_{\mathrm{t}} = SW_{\mathrm{a}} + \sum_{i=1}^{n}\left(R_{\mathrm{day}} - Q_{\mathrm{sur}} - E_{\mathrm{a}} - W_{\mathrm{seep}} - Q_{\mathrm{gw}}\right) \quad (1)$$

where SW_t is the final soil water content (mmH_2O), SW_o the initial soil water content (mmH_2O), t time in days, R_{day} amount of precipitation on day i (mmH_2O), Q_{surf} the amount of surface runoff on day i (mm H_2O), E_a the amount of evapotranspiration on day i (mmH_2O), W_{seep} the amount of percolation and bypass exiting the soil profile bottom on day i (mmH_2O) and Q_{gw} is the amount of return flow on day i (mmH_2O).

In this study, streamflow (at outlet point)/water yield (at sub-catchment scale) is computed using a modification of the SCS curve number (USDA Soil Conservation Service 1972) method and ET is measured using Penman-Monteith method (Neistch et al., 2011). The detailed methodology related to SWAT model processes and parameters is well defined in the SWAT user manual (Neistch et al., 2011). SWAT model requires large number of physical and daily hydro-meteorological data sets such as daily precipitation, daily minimum and maximum temperature, humidity, wind speed, solar radiation, digital elevation model (DEM), landuse/landcover (LULC) map and soil map (opted from FAO, food and agricultural organization) (FAO, 2007). The main steps are involved in the model setup viz. data preparation, sub-watershed discretization, HRU definition and overlay, writing database files, SWAT run and model simulation. SRTM (shuttle radar topographic mission) DEM was used as an initial input parameter to determine the slope and drainage properties of the catchment.

2.3. GCM data sets and Delta method for near term forecasting

For the near term climate scenarios (2015-2035) of water yield, daily precipitation and daily air temperature data, generated by CGCM4 (The Fourth Generation Atmospheric General Circulation Model) based on CANCM4/RCP 24 experiment, were utilized. The atmosphere model output is provided on a 128x64 Gaussian grid (approximately 2.81° latitudes x 2.81° longitudes) (Thornton et al., 2009). The statistical correlation (Mahmood and Babel, 2013) between the CANCM4/RCP24 experiment and observed data sets for temperature and precipitation variables was analyzed. The second hydrological scenario (2015 to 2035) was generated by CANCM4/RCP24 experiment. The third scenario for the same year (2015 to 2035) was considered as a hypothetical scenario, generated based on the CANCM4/RCP24 experiment and daily observed data sets by applying Delta method of downscaling approach (Hamlet et al., 2010).

3. Results and Discussion

3.1. Catchment characteristics, Calibration, Validation and Sensitivity analysis

To explore the watershed characteristics, the Satluj river catchment (Rampur to Kasol) divided into 4 sub-catchments based on their unique slope, LULC and soil categories (see Fig. 2). The basic hydrological characteristics and their parametric values responsible for the streamflow simulation are considered significantly under this current assignment. Table 1 shows the SWAT model simulated watershed characteristics during monthly simulation for baseline scenarios/current scenario (1991-2008). In this study, global sensitivity analysis has been performed using two objective functions namely P-value and R^2. In this study, parameters sensitivity results were evaluated on daily basis using observed and measured streamflow data during model calibration. In this study, the streamflow sensitivity analysis was done at main outlet of the Satluj river catchment (Kasol).

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Table 1: SWAT simulated water balance components.

General details	
Simulation length (years)	20
Warm up (years)	2
Hydrological response units	42
Sub-catchment	4
Output Time step	Daily/Monthly Average
Precipitation method	Measured using gauge data
Watershed area (Sq.km)	3296.8
Water balance ratio	
Water yield/precipitation	0.42
Baseflow/total flow	0.25
Water yield/total flow	0.45
Percolation/precipitation	0.26
Deep recharge/precipitation	0.01
ET/precipitation	0.36
Water balance components	
Average curve number	79.8
ET and transpiration	382
Precipitation	1373.5
Surface runoff	304.78
Lateral flow	112.99
Return Flow	259.02
Percolation to shallow aquifer	283.42
Revap from shallow aquifer	10.24
Recharge to deep aquifer	14.17

The P-values (ranges from 0 to 100%) calculated based on the minimum and maximum coefficient values corresponding to each and every parameter. Table 2 shows minimum, maximum and model fitted coefficient values corresponding to every streamflow calibration parameter. Out of thirteen parameters, temperature lapse rate (A_TLAPS.sub), curve number coefficient (R_CN2.mgt) and effective hydraulic conductivity (V_CH_K2.rte) were optimized as high sensitive parameters for the streamflow (see Table 2). In this study, daily minimum and maximum air temperature is considered as the most important climate driven parameter. Thus, the temperature lapse rate (A_TLAPS.sub) is considered an important parameter for the streamflow calibration. In this study, the temperature lapse rate (A_TLAPS.sub) has been taken as the model calibration parameter (Neistch et al., 2011).

Table 2: Parameters optimum value and their sensitivity on daily basis.

SI. No.	Parameter	Description	Fitted Value	Minimum Value	Maximum Value	P-Value
1	R__HRU_SLP.hru	Average slope steepness	0.179	0.174	0.230	0.857

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2	R__SOL_K.sol	Soil hydraulic conductivity	0.320	-0.412	1.250	0.844
3	R__PLAPS.sub	Precipitation lapse rate	277.000	50.000	300.000	0.776
4	V__GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow	0.971	0.833	1.057	0.676
5	V__CH_N2.rte	Manning roughness coefficient for main channel	0.329	0.236	0.344	0.643
6	R__SOL_BD.sol	Moist bulk density	1.405	1.225	1.516	0.501
7	V__GW_REVAP.gw	Groundwater 'revaporation' coefficient	0.026	0.004	0.040	0.381
8	A__ALPHA_BF.gw	Baseflow alfa factor coefficient	0.862	0.579	0.894	0.172
9	R__SOL_Z.sol	Depth from soil surface to bottom layer	2813.739	100.000	4000.000	0.105
10	V__GW_DELAY.gw	Groundwater delay time	10.456	-88.570	200.000	0.036
11	A__TLAPS.sub	Temperature lapse rate	-4.100	-7.000	3.500	0.027
12	V__CH_K2.rte	Effective hydraulic conductivity	27.034	22.120	75.000	0.018
13	R__CN2.mgt	Curve number coefficient	0.789	-1.020	80.000	0.000

The SWAT simulated water balance components show moderate runoff conditions over the catchment (see Table 1). Calibration (1991-2000) and validation (2001-2008) of streamflow for baseline/current scenario on monthly basis were done at outlet of the catchment (Kasol) utilizing observed/measured discharge data. The goodness-of-fit of the model was tested using R^2 objective function on a monthly basis with special integration of SUFI2 approach in SWATCUP. The R^2 is defined as the value of the coefficient of correlation according to Bravais-Pearson (Zhang et al., 2014). The R^2 was found satisfactory for both calibration ($R^2 = 0.934$) and validation ($R^2 = 0.931$). The linear regression plots and simulation hydrographs were drawn based on the comparison between SWAT simulated/ calibrated/validated streamflow versus observed/measured discharge data sets as shown in the Figures (3a, 3b, 3c and 3d). The overall comparison between observed and simulated flows during both calibration and validation periods appear good, except some outliers during the extreme high flow periods.

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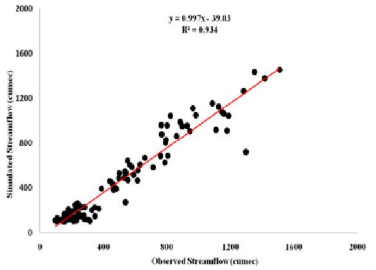
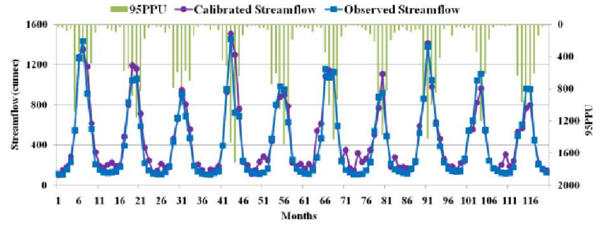


(a)



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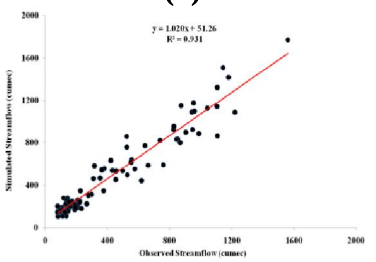

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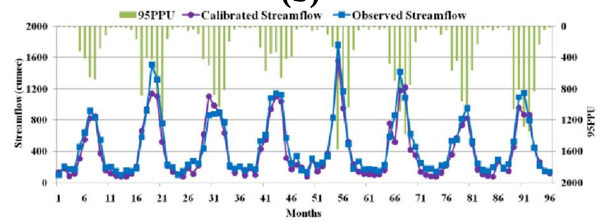

(d)

Fig. 3: (a) Calibrated regression plot (1991-2000), (b) calibrated streamflow hydrograph (1991-2000), (c) validated (2001-2008) regression plot and (iv) validated streamflow hydrograph (2001-2008).

3.4. Sub-catchment wise monthly comparison of Water Yield

The near term scenario (2015-2035) were grouped into two scenarios; (i) second scenario and (ii) third scenario. For this study, three most versatile variables namely minimum temperature, maximum temperature and precipitation were used for the near term hydrological scenarios generation. The others basic inputs (e.g. DEM, LULC and Soil) were kept constant at the same time during model forecasting. To highlight the variations among all the hydrological components at each sub-catchment level, in a temporal domain, a spatio-temporal analysis was performed for all the scenarios. Figures (4a and 4b) show spatio-temporal variations in the water yield component at each sub-catchment level. The water yield shows considerable variations in their unit as per current, second and third scenarios, which also shows significant changes throughout the year. The magnitude of change is recorded maximally (as 11% to 26 %) for precipitation and 16% to 60% for water yield during comparison between current scenario and third scenario, shown in the Fig. 4a. The current and second scenarios show significant changes in the water yield component across the sub-catchments (see Fig. 4b).

These spatial variations were found inconsistent throughout the year and fluctuated during winter, summer and monsoon periods. As per the comparison among all the scenarios, the water yield has shown significant increment in their amount in the time series plots (1991-2035) (see Fig. 4b). The cumulative depth of the annual average precipitation and water yield ratio were computed for all the scenarios (e.g. 1991-2008 and 2015-2035), shown in the Table 3. This ratio shows significant increment during all the scenarios (see Table 3). The current scenario is recorded lowest ratio, while, the third scenario has shown maximum ratio (see Table 3). The overall findings under this current study show the changing role of temperature and precipitation over the hydrological components in the long term time series domain.

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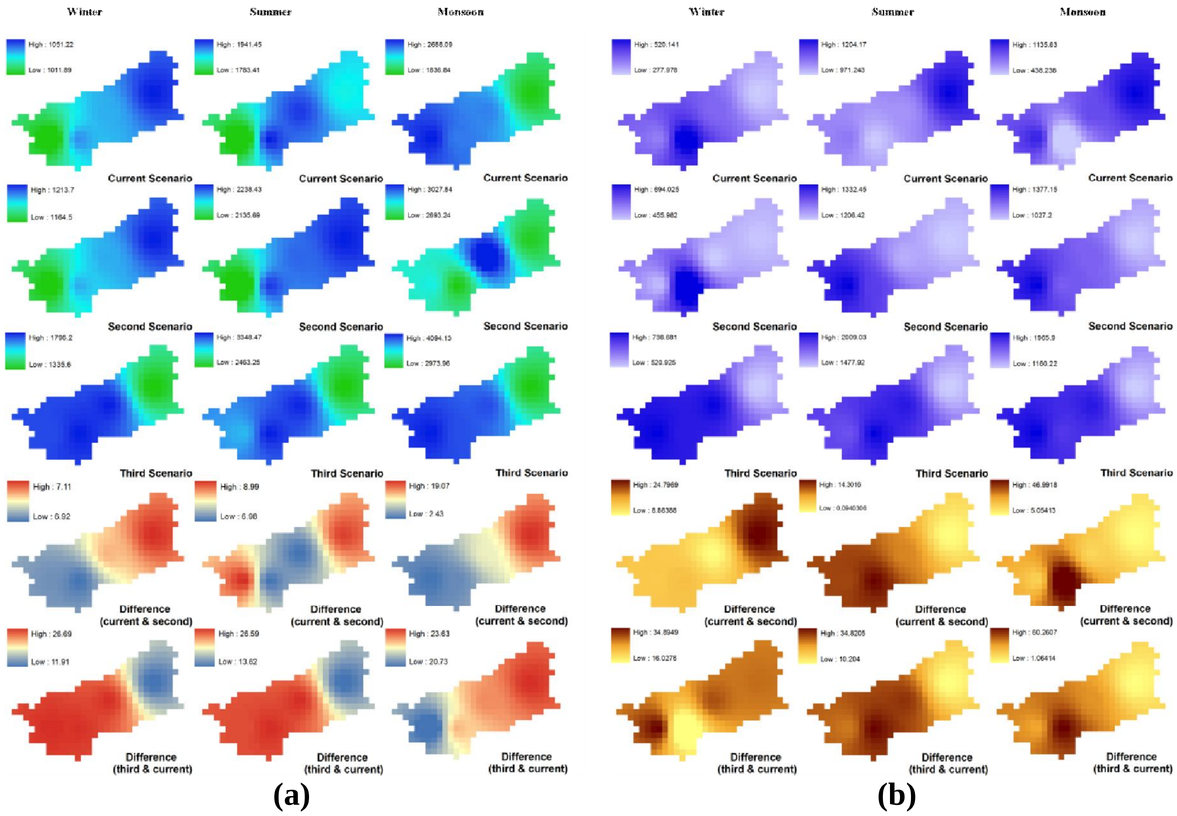

Fig. 4: (a) Seasonal variations in mount of precipitation (average annual depth in mm) over Satluj catchment under different climatic scenarios, (b) seasonal variations in amount of water yield (average annual volume in mm) under different climatic scenarios.

Table 3: Sub-catchment wise total (sum of all the years) cumulative water balance ratio of main hydrological components under different climatic scenarios.

Current Scenario (1991-2008)				
Sub-catchments	**Basin Area (Sq.km)**	**Cumulative Precipitation (mm)**	**Cumulative Water Yield (mm)**	**Ratio**
Subbasin 1 (Inlet)	878.79	14350.807	5645.468	0.39
Subbasin 2 (outlet)	672.53	22158.821	12422.564	0.56
Subbasin 3	1035.5	14279.561	5344.541	0.37
Subbasin 4	709.71	14341.356	4936.507	0.34
Second Scenario (2015-2035)				
Subbasin 1 (Inlet)	878.79	16508.572	6805.944	0.41
Subbasin 2 (outlet)	672.53	25488.726	15261.089	0.60
Subbasin 3	1035.5	16426.608	6387.237	0.39
Subbasin 4	709.71	16497.683	6220.931	0.38
Third Scenario (2015-2035)				
Subbasin 1 (Inlet)	878.79	24755.79	13219.598	0.53
Subbasin 2 (outlet)	672.53	38228.459	26163.223	0.68
Subbasin 3	1035.5	24632.872	12704.759	0.52
Subbasin 4	709.71	24739.467	12315.438	0.50

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4. Conclusion

The distributed hydrological model SWAT with special integration of SWATCUP and SUFI algorithm is able to represent spatio-temporal hydrological assessment of streamflow and other water balance components over the Himalayan catchment reasonably fit. The main aim of this study is to assess the changing role of temperature over various water balance components in spatio-temporal domain at sub-catchment scale. The changing role of temperature is assessed mainly using two different climate data sets; (i) real time measured (1991-2008) and GCM based data sets (2015-2035). The thirteen different hydrological parameters were tested to assess the streamflow sensitivity during calibration. Several parameters namely, temperature lapse rate (A_TLAPS.sub), curve number coefficient (R_CN2.mgt) and effective hydraulic conductivity (V_CH_K2.rte) are recorded as most sensitive parameters. The sensitivity index of these calibration parameters has helped in the accurate prediction of the various hydrological scenarios. The current scenario based on the measured and real time hydro-meteorological data sets has shown significant increment in the water yield and precipitation intensity. The second scenario based on the CANCM 4/RCP24 showed larger increment than the current scenario.

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