Simulating the Hydrologic response to climate change: Sani river basin, Gujarat (India)

Climate change is expected to create many challenges (including water availability) worldwide and projecting its impacts at regional scale allows communities to be proactive in planning for the future. It will help to prepare a future plan for the water resources development and management for the basin. The study was planned for estimating the runoff, evapotranspiration and groundwater recharge by SWAT model and assessing the impacts of climate change on potential surface and ground water resources of basin. The study was undertaken in Sani river basin of Devbhumi Dwarka district which is located in Gujarat state, India. The digital data of various remote sensing satellite images of river basin required for work were collected from BISAG, Gandhinagar. The historical observed hydro- meteorological data (1961-2005) were collected from the State Water data Centre, Gandhinagar and Millet Research station, JAU, Jamnagar. The simulated daily precipitation and daily maximum and minimum temperature for the period of 1951-2005 (control period) and 2006-2100 (future scenarios) by EC-Earth RCM for RCP 4.5 were collected from the IITM, Pune, Maharashtra. The bias corrected simulated data by the RCM was used as inputs for the simulating the hydrologic response of basins by SWAT model. The different water balance components like runoff, evapotranspiration and groundwater recharge for the basins were estimated from the SWAT simulations results. The impacts of climate change water balance components were assessed through the trend analysis using Mann-Kendall method and Sen's slope method. The rainfall, runoff, evapotranspiration and groundwater recharge were found stable in past and will be stable in future too, as there will not be climate change impacts on it for the basin. However, the temperature and reference evapotranspiration were found increasing in the basin.

Keywords: Impact assessment, water resources, SWAT model, satellite image, temperature, precipitation, runoff, groundwater recharge, evapotranspiration

Introduction

Climate change is expected to create many challenges (including water availability) worldwide and projecting the impacts of climate change at regional scale allows communities to be proactive in planning for the future. Impacts of climate change and climate variability on the water resources are likely to affect irrigated agriculture, installed power capacity, environmental flows in the dry season and higher flows during the wet season, thereby causing severe droughts and floods in urban and rural areas. India accounts for about 17.5 percent of the world's population and roughly 4 percent of the total available fresh water resources. Ground water resources provide for more than 60 percent of the irrigated land which has already depleted to large extent in many pockets of the country (Patel and Gajera, 2013). Water is the basic need of life for the human beings and any alteration in its availability is directly going to impact them through various means. Regions having renewable fresh water resources falling below 1667 m^3/person/year are classified as "water stress" regions. Furthermore, regions whose water availability falls below 1000 m^3/person/year can be categorized as chronic 'water scarcity' experiencing region (Kole, 2005). Another major player emerging as potent factor for water security in India is the global climate change. The impacts of climate change on glacial recession, decreasing rainfall pattern in some parts of India, greater but variable rainfall pattern in other parts of the country can lead to drought and flood like situations. Increased evapo-transpiration and reduced soil moisture may increase land degradation and desertification. Above mentioned arguments coupled to the scenario that the water utilization rate in India is 59 percent, much ahead of the 40 percent standard, clearly point to an urgent need to better adopt water management practices in the country to increase the water security for proper transition into a green economy (Kumar and Kumar, 2013). While climate change and global warming is a global phenomenon, its effect varies regionally or on basin scale. It has been observed that an increase in the average temperatures is usually accompanied with reduced precipitation in the catchment of Germany (Menzel and Burger, 2002).

Adaptation is response to climate change to seek possibilities and/or capabilities to impacts (IPCC, 2007). It is also required to include all the climate change vulnerability drivers to respond to the impacts (Lindsey *et al.*, 2010). The Regional Circulation Models (RCMs) is essentially identical to the GCM in the formulation of the grid-scale dynamics and the subgrid-scale physics differing only in horizontal resolution (50 km -300 km) and time step. Its performance in simulations for Europe and India has been documented in Jones *et al*. (1995, 1997), Bhaskaran *et al*. (1996, 1998) and Noguer *et al*. (1998).

Methodology

The study was undertaken in Sani river basin of Devbhumi Dwarka district which is located in Southern region of Gulf of Kutch of Gujarat state. Sani river is of 60 km long and entire basin area nearly 854 km^2. It originates from village Sonardi and meets to Arabian Sea near Gandhavi village.

Arc SWAT 2012 model was used during the study. The satellite data for area of interest were collected from BISAG, Gandhinagar. The input data was in the form of raster dataset. The dataset used namely 90 m SRTM DEM (Geotiff), Land use / Land Cover (raster data set) map and soil map (raster data set). These three are imagery data and others input data. Weather data was collected from State Water Data Centre (SWDC), Gandhinagar and Millet Research station, Jamnagar, Gujarat for observed data of the region and future RCM data from the IITM, Pune, Maharashtra. The collected data was bias corrected using distribution method developing programme in excel spreadsheet. As an input file, SWAT required text file for each and every weather parameter. The weather parameters used for SWAT are rainfall (.txt), temperature (maximum and minimum) (.txt). The study analysis was done for three period scenarios viz. 1951-2005, 2006-2050 and 2051-2100.

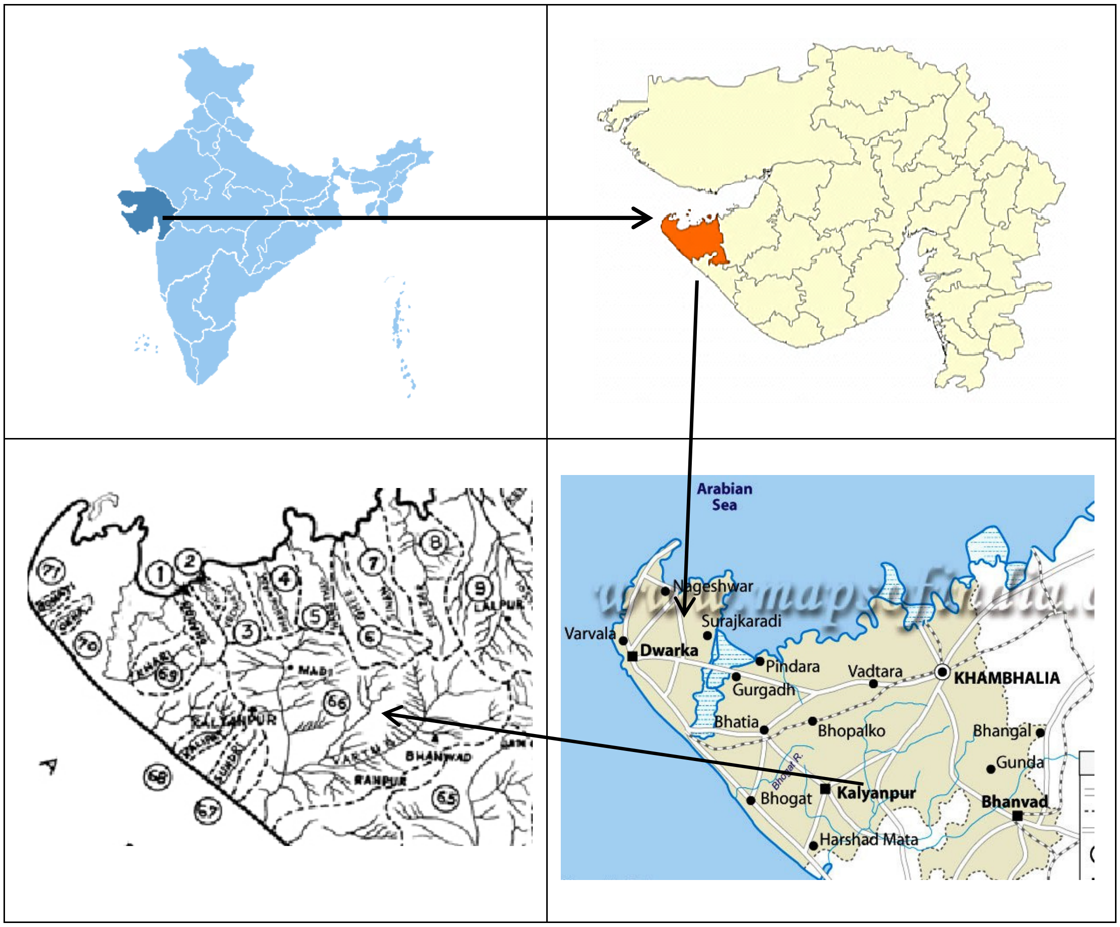

Fig.1 Location map of study area

Regional Circulation Model (RCM) data

The RCM data used for this study were collected from Indian Institute of Tropical Meteorology, Pune, Maharashtra. The RCMs used for this study was EC-Earth with resolution of 25 km for the RCP 4.5 scenario. The daily data of rainfall, daily maximum temperature, daily minimum temperature for historical scenario from 1951-2005 and for future scenario 2006-2100 for RCP 4.5 scenario were collected in the form of .nc file and then converted into .excels format.

Estimation of water balance components using SWAT model

SWAT is a basin-scale, continuous-time model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds. In SWAT, a watershed was divided into multiple sub-watersheds, which were then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. Alternatively, a watershed could be subdivided into only sub-watersheds that are characterized by dominant land use, soil type, and management (Arnold *et al.*, 1996; Arnold and Fohrer, 2005; Neitsch *et al.*, 2001; Gassman *et al.*, 2007). The procedure followed for the SWAT modelling was given in Fig.2.

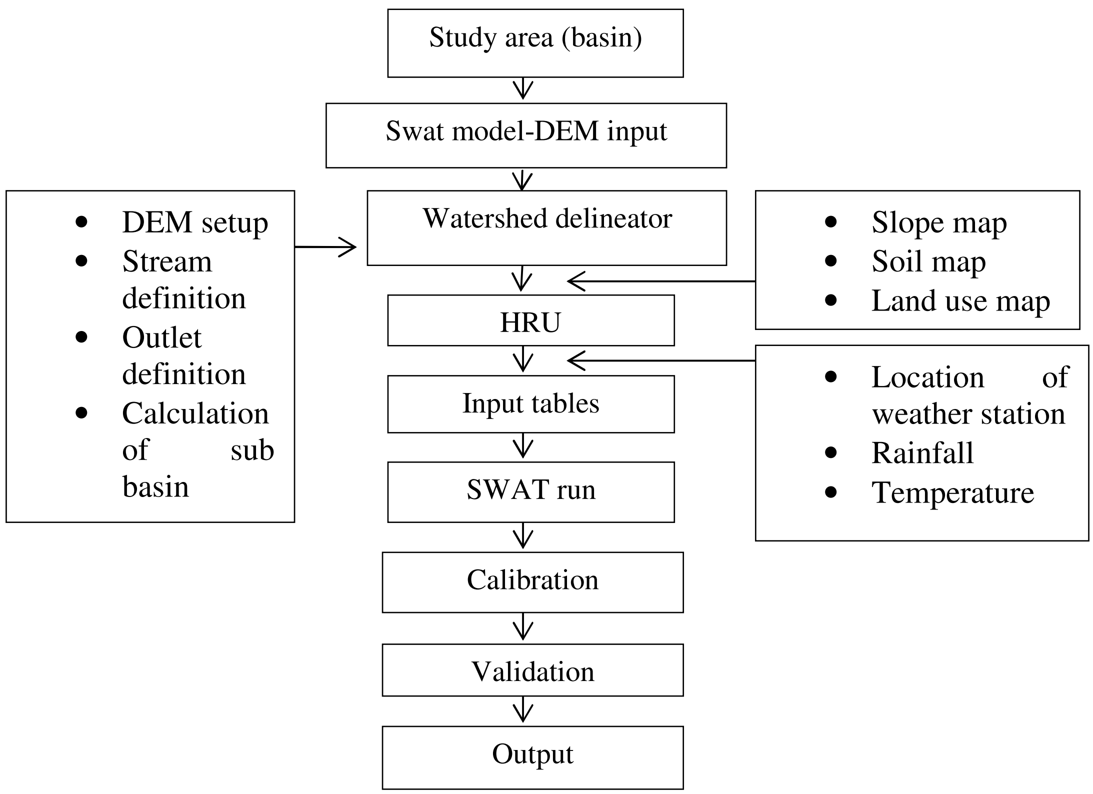

Fig.2: Procedure followed for the SWAT modelling

The water balance components like runoff, evapotranspiration and groundwater recharge were estimated through the simulation of the SWAT model for the weather data of 55 years (1951-2005-control), 45 years (2006-2050-future scenario) and 50 years (2051-2100-future scenario) for the model EC-Earth.

Time series analysis of the water balance components

The time series analysis of the water balance components on the basin scale was carried out using the standard method as described by Kendall (1975) and Gilbert (1987) along with best fit trend analysis.

Mann-Kendall Analysis

The Mann-Kendall test is a non-parametric test for identifying trend in time series data. The test compares the relative magnitude so f sample data rather than the data value themselves (Gilbert, 1987).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign\ (x_i - x_k)$$

Where,
Sign $(x_j - x_k)$ =1, 0 and -1, if $x_j>x_k$, $x_j = x_k$ and $x_j<x_k$ respectively;
n = number of data points in time series.

$$VAR(S) = \frac{1}{18} \times \left[\big(n(n-1)\big)(2n+5) - \sum_{p=1}^{m} t_p\big(t_p - 1\big)\big(2t_p + 5\big) \right]$$

Where,

n =number of data points, m is the number of tied groups (a tied group was a set of sample data having the same value);

t_p= number of data points in the p group.

The normalized test statistic Z was computed as follows.

$$Z = \left\{[S-1]/[VAR(S)]^{1/2}\right\} if\ S > 0$$
$$= 0 \text{ if } S=0$$
$$= \left\{[S+1]/[VAR(S)]^{1/2}\right\} if\ S < 0$$

Sen's slope method

Sen's method for the estimation of slope required a time series of equally spaced data. Sen's method proceeded by calculating the slope as a change in measurement per change in time. The true slope of an existing trend (as change per year) was be determined using the Sen's nonparametric method. The slope m_i between two values of pair of all data was estimated as follows, (Sen, 1968).

$$m_i = \frac{(x_i - x_k)}{(j-k)}$$

Where,

k=1,2, 3, ...(n-1);
j= k+1=2, 3, ...n;
i= 1 to N [N= n (n-1)/2]

The Sen's estimator of slope was estimated using the following expression

$$m = m_{(N+1)/2} \text{ if N is odd}$$

$$m = \frac{1}{2}\left(m_{N/2} + m_{(N/2)+1}\right) \text{ if N is even}$$

To estimate the range of ranks for the specified confidence interval, C was found using following Eq..

$$C_{\propto} = Z_{1-\propto/2} \times \sqrt{VAR(S)}$$

The ranks of the lower (M_1) and upper ($M_2 + 1$) confidence limits was estimated using Eq.

$$M1 = \frac{N' - C_{\propto}}{2}\ ;\ M_2 + 1 = \frac{N' + C_{\propto}}{2}$$

Results and Discussion

Rainfall and Runoff

The daily runoff was obtained from the SWAT run simulation results using the daily rainfall data from 1951 to 2005, 2006-2050 and 2051-2100. The average of rainy season rainfall and runoff estimated for the basin were found as 474 mm and 205 mm for 1951-2005; 419 mm and 194 mm for 2006-2050; 521 mm and 265 mm for 2051-2100 respectively. Therefore, it can be said that the surface water potential in basin can be created by the tune of 175 MCM, 166 MCM and 226 MCM respectively as per the SWAT model estimation if the entire runoff water is harvested and managed properly. Therefore, about 41%, 39% and 53% area of the basin for the period 1951 to 2005, 2006-2050 and 2051-2100 respectively can be irrigated in one season from these surface water resources.

According to trend analysis the overall scenario (1951-2100), the rainy seasonal rainfall and runoff will get increase. However no definite trend was found. Both the rainfall and runoff will be stable in the basin. There will not be any climate change impact on water resources of the Sani river basin, even though warming trend exists.

Evapotranspiration and Reference evapotranspiration

The average reference evapotranspiration and crop evapotranspiration during the rainy season was found as 803 mm and 155 mm; 881 mm and 143 mm and 885 mm and 152 mm respectively for the period 1951 to 2005, 2006-2050 and 2051-2100 respectively. This indicated that the temporal distribution of the rainfall during the rainy season is poor and the crops are facing the water stress during the season. The reference evapotranspiration has increasing trend during all the seasons and periods while crop evapotranspiration is decreasing. The reason is that the amount of rainy seasonal rainfall is found in decreasing trend during the all periods which decreased the moisture status during the monsoon season. The decrease in the moisture status could increase the stress (i.e. decreased stress coefficient) during the monsoon season which resulted in decreased crop evapotranspiration.

Groundwater Recharge

The average groundwater recharge during the rainy season was found as 83 mm, 61 mm and 91 mm for 1951 to 2005, 2006-2050 and 2051-2100 respectively. The Man-Kendall and Sen's slope statistics along with other statistical parameters for groundwater recharge by SWAT model for the period 1951-2100 showed that the groundwater recharge is decreasing non-significantly.

All the SWAT parameters and the trend analysis of these parameters during the periods (1951-2005), 2006-2050 and 2051-2100 are shown in Table nos 1,2 and 3 respectively. And the water balance components during the rainy season were estimated for the years 1951-2005, 2006-2050 and 2051-2100 is shown in Fig. 3, Fig. 4 and Fig.5 respectively by the SWAT model

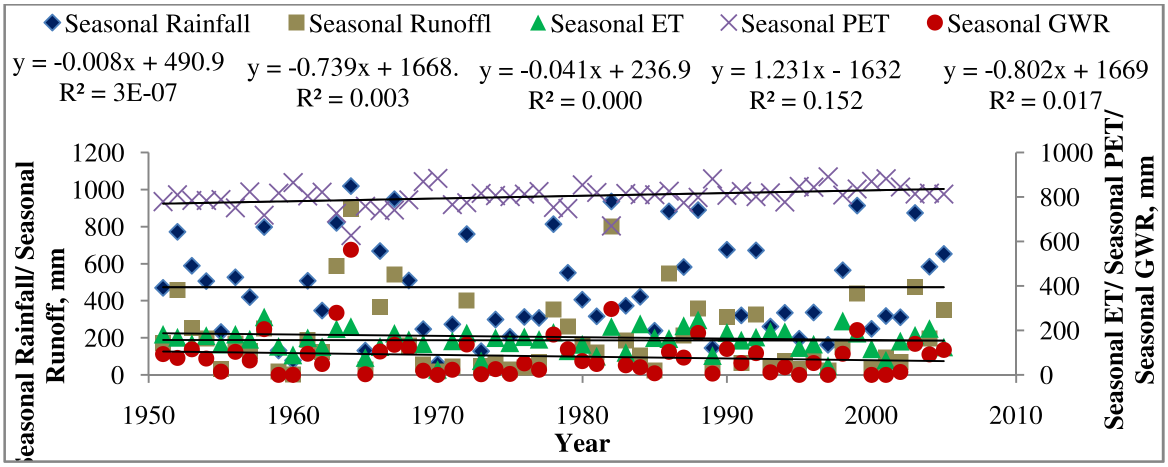

Fig. 3: Water balance components estimated by SWAT during rainy season for Sani river basin during control scenario (1951-2005)

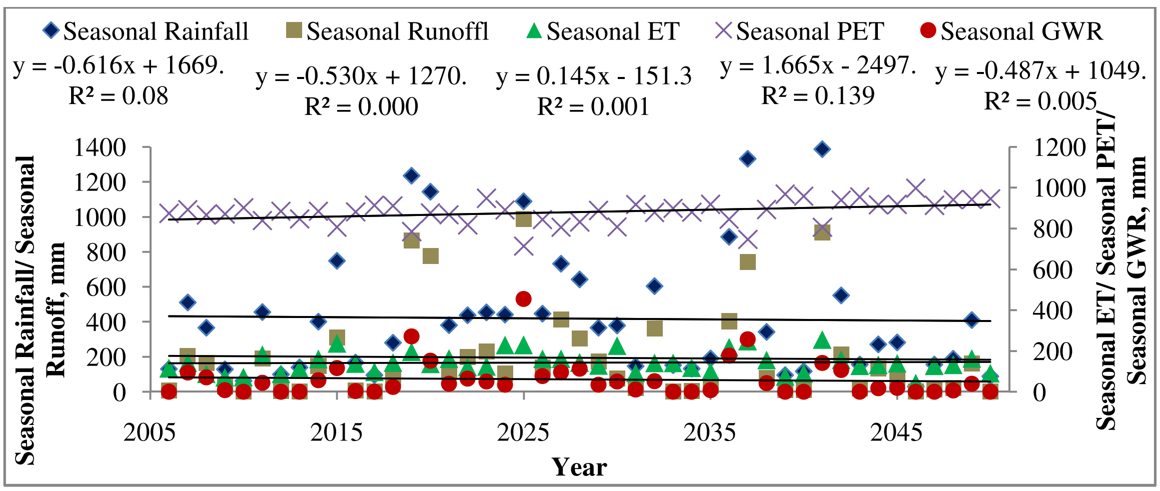

Fig. 4: Water balance components estimated by SWAT during rainy season for Sani river basin during future scenario (2006-2050)

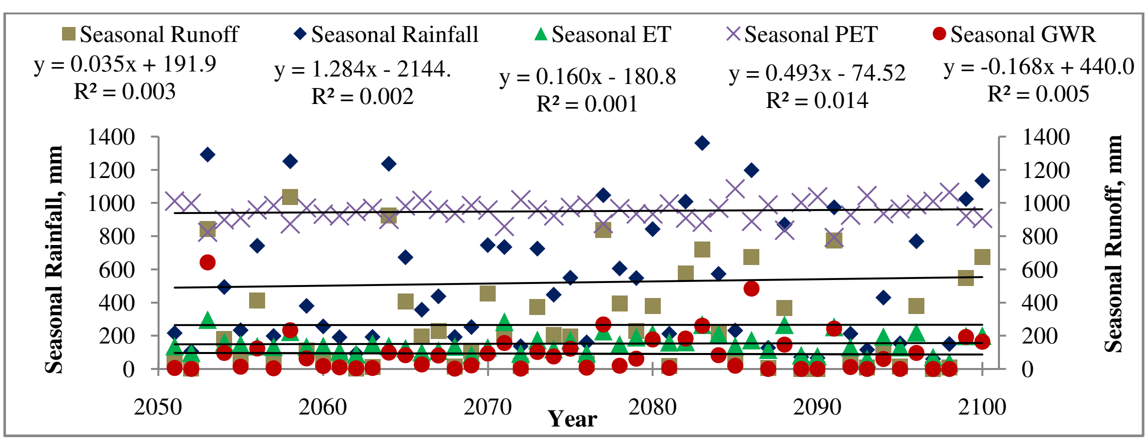

Fig. 5: Water balance components estimated by SWAT during rainy season for Sani river basin during future scenario (2051-2100)

Table 1: Statistical and trend analysis of water balance components for Sani river basin during control scenario (1951-2005)

Statistics		Rainfall Monsoon	Runoff Monsoon	GWR Monsoon	ET Monsoon	ET Summer	ET Winter	ET Annual	RET Monsoon	RET Summer	RET Winter	RET Annual
Mann Kendal (z)		0.19^{NS}	-0.23^{NS}	-0.66^{NS}	0.04^{NS}	-1.35^{*}	-1.77^{**}	-1.25^{NS}	3.21^{****}	0.87^{NS}	1.71^{**}	3.35^{****}
Confi. Level MK Z		57.49	59.18	74.58	51.74	91.15	96.17	89.41	99.93	80.82	95.67	99.96
Sen's Slope(mm/yr)		0.41	-0.28	-0.31	0.03	-0.11	-0.11	-0.53	1.14	0.11	0.43	1.55
Lower and Upper limit of Sen's slope (1%) (mm/yr)	Lower	-5.88	-3.69	-1.84	-1.26	-0.36	-0.29	-1.86	0.21	-0.23	-0.18	0.26
	Upper	6.02	2.76	1.02	1.27	0.11	0.06	0.70	2.13	0.49	1.14	2.77
Lower and Upper limit of Sen's slope (5 %) (mm/yr)	Lower	-4.60	-2.80	-1.47	-0.93	-0.28	-0.23	-1.50	0.46	-0.15	-0.05	0.57
	Upper	4.31	1.85	0.51	0.90	0.05	0.02	0.37	1.86	0.40	0.94	2.45
Slope of best fit trend		-0.008	-0.74	-0.80	-0.04	-0.16	-0.24	-0.53	1.23	0.14	0.39	1.49
R^2 (mm/yr)		0.00	0.003	0.017	0.00	0.04	0.06	0.03	0.152	0.02	0.01	0.003
Mean(mm)		474	205	83	155	33	25	208	803	695	504	1900
Median(mm)		420	150	62	160	33	21	207	810	694	528	1923
Kurtosis		-0.96	2.22	10.71	0.04	1.97	9.75	-0.03	2.12	0.63	-0.75	41.05
Skewness		0.41	1.50	2.69	-0.37	0.26	2.99	-0.32	-0.95	-0.05	-0.89	-6.00
Min. (mm)		61	3	0.00	25	4	12	66	627	648	400	814
Max. (mm)		1018	897	563	261	74	98	316	891	731	577	2048

CV (%)	0.56	0.98	1.16	0.33	0.40	0.62	0.26	0.06	0.02	0.10	0.08
**** Significant at 0.1%, *** Significant at 1%, ** Significant at 5%, * Significant at 10 %, NS = Non Significant, all parameters are in mm.											

Table 2: Statistical and trend analysis of water balance components for Sani river basin during future scenario (2006-2050)

Statistics		**Rainfall Monsoon**	**Runoff Monsoon**	**GWR Monsoon**	**ET**				**RET**			
					Seasonal	**Summer**	**Winter**	**Annual**	**Seasonal**	**Summer**	**Winter**	**Annual**
Mann Kendal (z)		-0.28^{NS}	-0.24^{NS}	-0.72^{NS}	0.75^{NS}	0.87^{NS}	0.60^{NS}	0.95^{NS}	2.98^{***}	0.87^{NS}	1.34*	3.75^{****}
Confi. Level MK(Z)		65.58	64.86	78.44	62.66	80.80	72.47	82.87	99.87	80.80	90.99	99.99
Sen's Slope(mm/yr)		-0.77	-0.218	-0.197	0.333	0.18	0.11	0.39	1.73	0.16	0.55	2.28
Lower and Upper limit of Sen's slope (1%) (mm/yr)	Lower	-9.49	-4.84	-1.93	-1.28	-0.40	-0.30	-1.67	0.24	-0.37	-0.68	0.90
	Upper	6.28	2.83	0.62	1.60	0.92	0.53	2.44	3.10	0.61	1.85	3.98
Lower and Upper limit of Sen's slope (5 %) (mm/yr)	Lower	-7.76	-4.06	-1.53	-0.90	-0.25	-0.19	-1.04	0.65	-0.24	-0.31	1.28
	Upper	4.00	1.42	0.28	1.28	0.67	0.39	1.88	2.71	0.49	1.44	3.48
Slope of best fit trend		-0.62	-0.53	-0.49	0.14	0.47	0.11	0.73	1.67	0.14	0.51	2.25
R^2 (mm/yr)		0.08	0.00	0.005	0.001	0.06	0.00	0.02	0.14	0.02	0.02	0.263
Mean(mm)		419	194	61	143	38	32	207	881	697	526	2024
Median(mm)		366	105	35	138	31	25	180	885	695	545	2027
Kurtosis		1.16	2.65	8.47	-0.10	1.75	1.10	1.18	0.59	-0.40	-0.57	1.02
Skewness		1.36	1.86	2.62	0.56	1.45	1.40	1.11	-0.64	0.24	-0.88	-0.50

Min. (mm)	30	0.00	0.00	43	6	11	110	714	665	410	1828
Max. (mm)	1387	988	454	256	118	88	436	998	731	590	2141
CV (%)	0.85	1.36	1.46	0.36	0.70	0.64	0.34	0.07	0.02	0.10	0.03
**** Significant at 0.1%, *** Significant at 1%, ** Significant at 5%, * Significant at 10 %, NS = Non Significant, all parameters are in mm.											

Table 3: Statistical and trend analysis of water balance components for Sani river basin during future scenario (2051-2100)

Statistics		**Rainfall Monsoon**	**Runoff Monsoon**	**GWR Monsoon**	**ET**				**RET**			
					Seasonal	**Summer**	**Winter**	**Annual**	**Seasonal**	**Summer**	**Winter**	**Annual**
Mann Kendal (z)		-0.02^{NS}	-0.33^{NS}	-0.15^{NS}	0.17^{NS}	-1.14 ^{NS}	-1.97**	-0.03^{NS}	0.88^{NS}	-0.28 ^{NS}	0.15 ^{NS}	0.38^{NS}
Confi. Level MK(Z)		50.67	62.79	56.00	56.64	87.24	97.58	51.33	81.01	61.20	55.98	64.98
Sen's Slope(mm/yr)		-0.10	-0.19	0.00	0.15	-0.18	-0.27	-0.07	0.54	-0.06	0.05	0.19
Lower and Upper limit of Sen's slope (1%) (mm/yr)	Lower	-7.02	-4.32	-1.16	-1.45	-0.60	-0.67	-2.08	-1.19	-0.43	-0.71	-1.53
	Upper	13.15	7.18	2.32	1.96	0.23	0.10	1.69	2.17	0.33	0.85	2.11
Lower and Upper limit of Sen's slope (5 %) (mm/yr)	Lower	-5.02	-2.71	-0.65	-0.98	-0.50	-0.58	-1.54	-0.79	-0.32	-0.50	-1.04
	Upper	10.21	4.43	1.52	1.56	0.12	-0.01	1.21	1.87	0.22	0.64	1.36
Slope of best fit trend		0.035	1.28	-0.17	0.16	-0.14	-0.28	-0.12	0.49	-0.04	0.22	0.038
R^2 (mm/yr)		0.002	0.003	0.005	0.001	0.01	0.08	0.00	0.014	0.00	0.00	0.045
Mean(mm)		521	265	91	152	32	34	212	950	704	546	2089
Median(mm)		433	186	61	137	28	31	209	959	706	571	2113
Kurtosis		-0.85	0.10	7.86	-0.14	5.99	-0.03	0.19	0.28	-0.40	-0.44	41
Skewness		0.65	1.08	2.49	0.57	2.18	0.69	0.41	-0.30	-0.11	-1.08	-6.12
Min. (mm)		59	0.00	0.00	39	5	7	86	792	673	426	824
Max. (mm)		1361	1035	641	296	120	69	364	1086	730	606	2241

CV (%)	0.75	1.10	1.38	0.39	0.7	0.4	0.3	0.06	0.0	0.1	0.09
**** Significant at 0.1%, *** Significant at 1%, ** Significant at 5%, * Significant at 10 %, NS = Non Significant, all parameters are in mm.											

Conclusions

This work substantially will enhance the knowledge of global climate change impacts on the water resources in the study area, which provides a means to adopt future impacts by adopting water management options. The study areas may somewhat experience seasonally limited water availability, rapid socio-economic development, and population growth. The SWAT model simulates the runoff and groundwater recharge appreciably well for the study area. The rainfall and runoff was found stable in past and will be stable in future too, as there will not be climate change impacts on it. The rainy seasonal potential evapotranspiration is significantly increasing due to climate change impacts. The crop evapotranspiration and the groundwater recharge was found stable in past and will be stable in future too and there will not be climate change impacts on it. The result will prove beneficial to the various water project authorities for the better management of the water resources in the basin for future scenarios and to decide sustainable reservoir operating policy for both monsoon and summer season.

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