Impact of Projected Climate Change on Streamflow and Sediment Yield – A Case Study of the Chaliyar River Basin, Kerala

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Abstract: It is now widely acknowledged that climate change will affect the hydrological cycle. Changes in rainfall pattern will definitely impact the magnitude and timing of runoff and this, in turn, will affect sediment yield from the catchment as well. Reliable predictions of the rate of runoff and sediment transport are needed for the development of watershed management plans aimed at achieving better soil and water conservation. In this study, the impact of projected climate change on runoff and sediment yield from the Chaliyar river basin, Kerala, India has been investigated. For the analysis using historic data, rainfall data from three rain gauge stations Kottamparamba, Nilambur and Manjeri were used; other meteorological data such as temperature, relative humidity, wind speed, and duration of sunshine hours were available only for the Kottamparamba station. Future precipitation projections for the river basin, generated by downscaling projections of the general circulation model MPI-ESM-LR using the regional climate model (RCM) REMO2009, for various Representative Concentration Pathways (RCPs) outlined by the IPCC, were used in this study. Delta change method was used for bias correction. The downscaled projections for two scenarios, viz., RCP 4.5 and RCP 8.5, for the period 2021-2035 were corrected for bias and then used as input to the HEC-HMS model, which was already calibrated using historic data. The computed values of future streamflow and sediment load closely follows the average monthly trend of the baseline period 1987-2001. Results of the study indicate that annual streamflow is likely to increase by about 27.27% under RCP 4.5 and 42.44% under RCP 8.5. The projected percentage increase in annual sediment load is 37.74% under RCP 4.5 and 34.54% for RCP 8.5. The average increase in streamflow is 30.69 m^3/s for RCP 4.5 and 45.74 m^3/s for RCP 8.5. The average annual increase in sediment load is 250.07 tonnes/cu.m. for RCP 4.5 and 186.59 tonnes/cu.m. for RCP 8.5. The percentage change in monthly streamflow and sediment load is found to be relatively high in the month of July for both the RCPs whereas streamflow and sediment load show significant decrease during the months of January, February and March. The results of the study will be useful in creating awareness as to how projected climate change can affect streamflow and sediment yield at the local level.

Keywords: RCM; RCP; REMO2009; Downscaling; Bias correction; Streamflow; Sediment yield.

1. Introduction

The accumulation of greenhouse gases (GHG) in the earth's atmosphere is a major cause of global climate change. A substantial increase in global temperature could be expected as a consequence of doubling of carbon dioxide (CO_2) concentrations in the atmosphere. According to a report of the IPCC (Intergovernmental Panel on Climate Change), published in 2013, global temperature is likely to increase by 1.8 °C under RCP 4.5 and by 2.4 °C under RCP 8.5 by the year 2100.

Climate change, as exemplified by an increase in temperature and changes in precipitation patterns, is expected to directly impact the hydrological cycle, altering the timing and quantity of water discharge (Barnett et. al., 2005). It is also expected to affect the spatial and temporal distribution of water resources (IPCC, 2007). Altered climate could also significantly impact sediment dynamics in watersheds. The direct impact of climate change on sediment yield is related to changes in precipitation patterns, in terms of increased rainfall erosivity due to a more vigorous hydrological cycle (Maeda et. al., 2010) and changed precipitation amounts (Lee

et. al., 2013). Sediment yield is also related to higher discharges with larger sediment transport rates (Restrepo et. al., 2006), caused by altered precipitation patterns. Increased temperature can also have an impact on the sediment yield. Sediment yields may decrease owing to a decrease in water availability and an increase in soil moisture deficit caused by increased evapotranspiration (Azari et. al., 2015). In contrast, higher temperatures may also increase sediment yield owing to greater snowmelt (Asselman et. al., 2003; Costa et. al., 2017).
The effect of climate change on basin hydrology is normally assessed by forcing climate change scenarios on a calibrated hydrological model (Hosseinizadeh et. al., 2015). In this study, HEC-HMS is used for rainfall-runoff and sediment routing. Projections of the GCM, MPI-ESM-LR, for RCP 4.5 and RCP 8.5 for the study area, downscaled by the RCM REMO2009 for the period 2021-2035 was used in the study. The downscaled projections were bias corrected before it was forced on the calibrated and validated HEC-HMS RR/ MUSLE model in order to obtain the future streamflow and sediment time series.

2. Study Area and Methodology

The study area is the Chaliyar river basin in Kerala, India. Chaliyar is the fourth longest river in Kerala flowing through Malappuram and Kozhikode districts with a total length of 169 km. It originates in the Western Ghats at Elambalari Hills in Gudalur taluk of Nilgiris district in Tamil Nadu at an elevation of 2066 m and empties into the Lakshadweep Sea at Beypore. It lies between $11^0$05' to $11^0$40' North latitudes and $75^0$35' to $76^0$45' East longitudes. The total catchment area of the basin is 2923 km^2 of which 2535 km^2 lies in Kerala and the remaining 388 km^2 falls in Tamil Nadu. On an average, about 3012 mm rainfall occurs annually in the basin. The principal rainy seasons are southwest (June-September) and northeast (October-November) monsoon. The pre-monsoon months (March-May) are characterized by major thunderstorm activity whereas during the winter months (December-February), there is minimal cloudiness and rainfall (Anathakrishnan et al., 1979). The major soil groups in the river basin are gravelly clay, clay, gravelly loam and loam covering 60.73%, 24.56%, 9.85%, and 4.86% of the area respectively. Agricultural land occupies about 74.26% of the total area followed by forests occupying 14.21% of the total area; the remaining area comprises of urban areas, rocky areas and water bodies. There is one CWC hydrological observation station at Kuniyil on this river and four meteorological stations in the basin located at Puthupadi, Kottamparamba, Manjeri and Nilambur. The map of the study area is shown in Fig. 1.
SRTM (Shuttle Radar Topography Mission) DEM of 30 m resolution and relative vertical accuracy less than or equal to 10m was downloaded from the USGS Earth Explorer website (*https://earthexplorer.usgs.gov/*); the date of acquisition of the DEM was 11 February 2000. The landuse map (1:50000) and soil map (1:250000) for the study area were obtained from the Kerala State Land Use Board (KSLUB) for the year 2008. Daily rainfall data from three raingauge stations, viz., Kottamparamba, Manjeri and Nilambur were collected for the period 1987-2004. Daily observed discharge data at the CWC station, Kuniyil, was also collected for the same period. Daily values of maximum and minimum temperatures were collected from the Kottamparamba station. Daily data on sediment concentration (g/l) for the period 1991-2004 were also collected from the river gauge station Kuniyil; this data pertained to three classes, viz., coarse, medium and fine. Downscaled daily projections of the RCM, REMO2009, (including precipitation, maximum temperature, minimum temperature, wind speed, relative humidity and number of sunshine hours) for RCP 4.5 and RCP 8.5 were obtained from the CORDEX IITM website for the time periods 2021-2040 and 1986-2005 and this was used in the study.

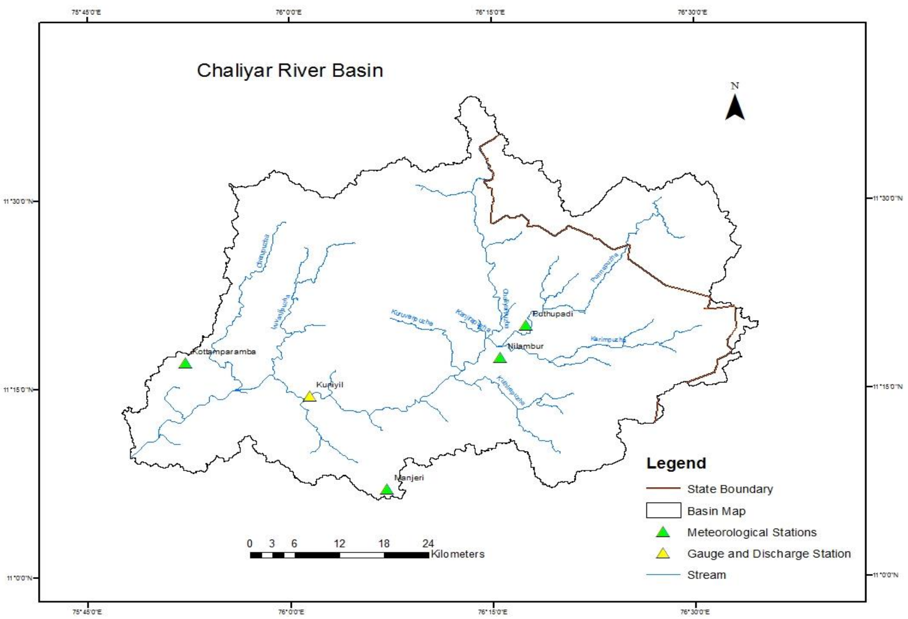

Fig. 1 Study area

Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) was developed by the Hydrologic Engineering Centre of the US Army Corps of Engineers (USACE). It is designed to simulate the complete hydrologic processes of dendritic watershed systems. The software can handle many conventional hydrologic analyses such as rainfall-runoff modelling, sediment transport modelling and water quality modelling. For hydrologic modelling, HEC-HMS uses separate models to compute each component of the runoff process. These include loss models, transform models, baseflow models, and routing models (channel flow models). Loss model determines the amount of rainfall excess after subtracting the losses due to interception, infiltration, depression storage, and transpiration from the total rainfall. The various loss models available in HEC-HMS are initial and constant loss, deficit and constant loss, SCS curve number, Green and Ampt, and Soil Moisture Accounting (SMA). The transform models convert the excess precipitation into watershed outflow. The various transform models available are Clark's Unit Hydrograph (UH), Synder's Synthetic UH, SCS UH, Modclark and kinematic wave. The baseflow models available in HEC-HMS are constant monthly, exponential recession and linear reservoir. The routing models simulate one-dimensional open channel flow, thus predicting the time series of flow, stage, or velocity, given upstream hydrographs. The routing models available in HEC-HMS are kinematic wave, lag, Muskingum and Muskingum-Cunge. Additionally, there is a canopy model that accounts for interception and evapotranspiration loss due to the presence of plants in the basin.

The Modified Universal Soil Loss Equation (Williams, 1975) was developed from the original Universal Soil Loss Equation (USLE). The original equation was based on precipitation intensity, and consequently could not differentiate between storms with low or high infiltration. The modifications to the original USLE equation changed the formulation in such a way that calculation of erosion was based on surface runoff instead of precipitation.

$$Sed = 11.8\left(Q_{surf} \times q_{peak}\right)^{0.56} \times K \times LS \times C \times P \quad (1)$$

where Sed is the sediment yield from a rainfall event in metric tons, Q_{surf} is the surface runoff volume (m^3), q_{peak} is the peak runoff rate (m^3/s), K is soil erodibility factor (dimensionless), LS is the topographic factor (dimensionless), C is the cover factor (dimensionless) and P is the practice factor (dimensionless). In addition to these, HEC-HMS also requires sediment threshold, exponent and the grain size distribution curve.

The uniform equilibrium method is used for routing the sediments through the reach. It assumes that sediment entering from the upstream basin elements is translated instantaneously through the reach without any temporary lag for the sediment passing through the reach. The transport capacity for each grain size is calculated to determine the deposition or erosion state. The available sediment is computed subject to the limitations on deposition and erosion. Erosion is limited when the reach length to flow depth reaches a value less than 30. Deposition is limited by the flow depth and fall velocity. This method requires width and depth of the bed along with an active layer factor as its parameters. The width should be typical of the reach and is used in computing the volume of the upper and lower layers of the bed. The depth should be typical of the total depth of the upper and lower layers of the bed, representing the maximum depth of mixing over very long time periods. At each time step, the upper layer depth is calculated by multiplying the d_{90} of the sediment in the upper layer with the active layer factor.

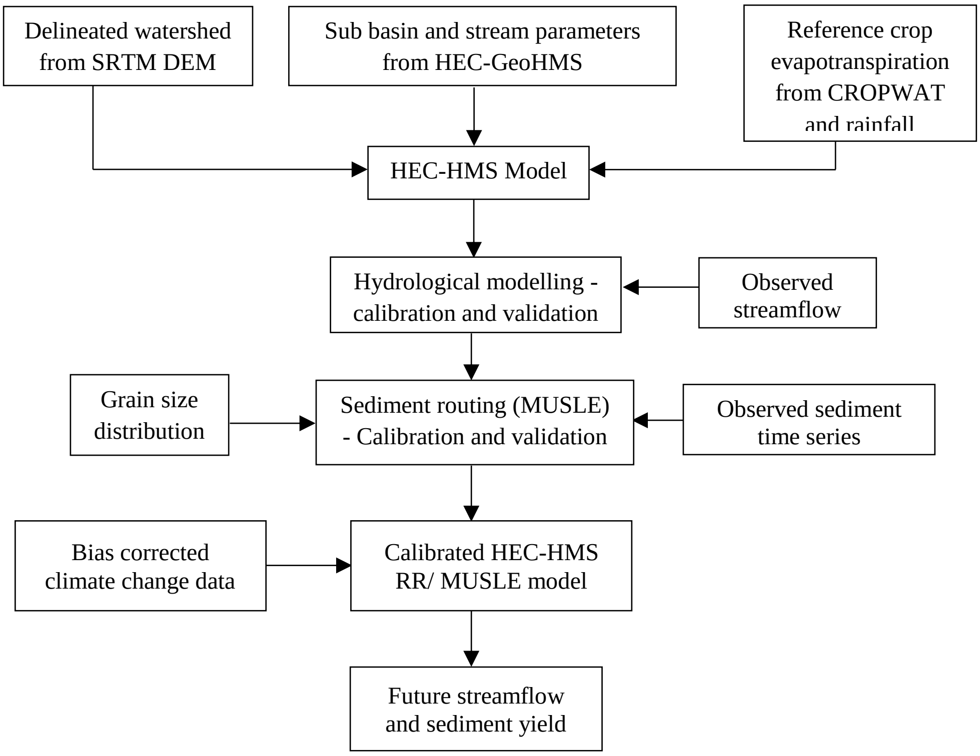

Fig. 2 Flowchart of the overall methodology

Fig. 2 presents the detailed methodology adopted in this study. The watershed was delineated from SRTM DEM using HEC-GeoHMS and the total area was found to be 2935 km^2. With the delineated watershed, the HEC-HMS model setup was created with 27 sub basins and 39 reaches (Fig. 3). The typical cross-sections required for each reach were generated from DEM using HEC-GeoRAS. Daily rainfall data from Kottamparamba, Nilambur and Manjeri were used in the meteorological model in HEC-HMS along with their Thiessen weights. Daily reference crop evapotranspiration was computed using CROPWAT using the data of the maximum and minimum temperatures, relative humidity, wind speed and number of sunshine hours at the Kottamparamaba meteorological station. The curve number grid was generated in HEC-GeoHMS using the reclassified land use map and the reclassified soil map. The time of concentration was obtained from this grid.

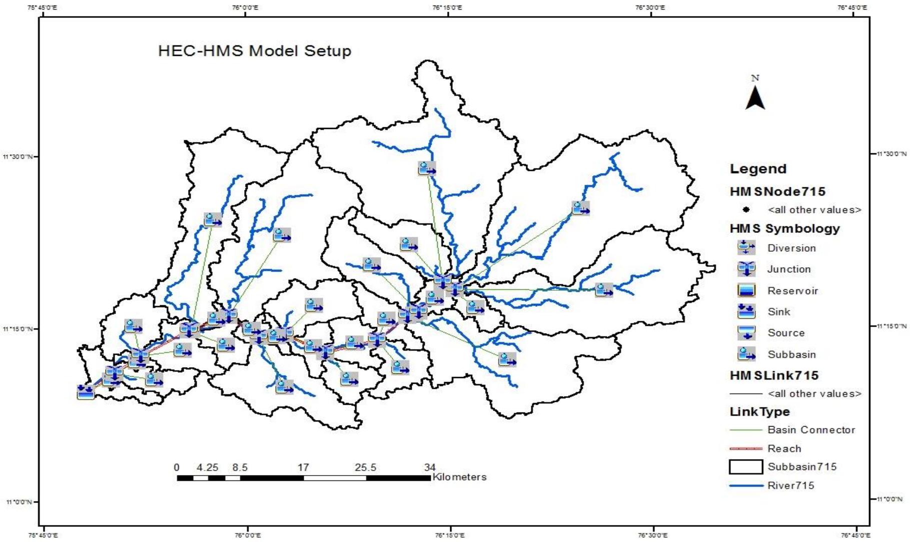

Fig. 3 HEC-HMS model setup

The methods chosen for rainfall-runoff modelling with HEC-HMS along with the respective parameters are listed in Table 1. Due to inadequacy of data, among these parameters, only the time of concentration was determined directly; all the other 12 parameters listed here could not be accurately determined, and its values were fixed by model calibration. Since discharge data at only one gauging station was available, the parameters in the RR model were kept the same for all the subbasins.

Table 1. Parameters used for RR modelling

Sl. No.	Model	Method	Parameters required
1.	Loss	Deficit and constant loss	Initial deficit (mm), maximum deficit (mm), constant rate (mm/h) and percentage imperviousness
2.	Canopy	Simple	Initial storage (%), maximum storage (mm) and crop coefficient
3.	Transform	Clark unit hydrograph	Time of concentration (min) and storage coefficient (min)
4.	Baseflow	Exponential recession	Initial discharge (m^3/s), recession constant and ratio to peak
5.	Routing	Muskingum Cunge	Manning's n

MUSLE was adopted as the erosion model and the uniform equilibrium method was used for routing the sediments through the reach. The grain size distribution for the major soil types in the study area was determined using the guidelines outlined in the CSIRO Land and Water Technical Report (2001). The MUSLE topographic factor was determined using the equation by Wischmeier and Smith (1962); the cover factor and practice factor were determined from the tables of Wischmeier and Smith (1978), and the soil erodibility factor from the table of

Stewart et. al (1975). In this study, only the topographic and erodibility factors were assigned sub basin wise depending on the slope, length and soil type of the sub basin. Since there is large variation in the MUSLE parameter values reported by different authors and for different climatic regions, it can be treated as a calibration parameter whose values are fixed after calibration, except for the topographic factor (which depends on the length and slope of the sub basin). The cover factor, practice factor and enrichment ratio were kept the same for all the sub basins since there is only a single gauging station within the catchment. In the uniform equilibrium method, the bed width was assumed as 300m, the bed depth as 3m and the active layer factor was taken as 2.
Climate models exhibit systematic error (biases) due to the limited spatial resolution, simplified physics, thermodynamic processes and numerical schemes and incomplete knowledge of climate processes. Errors in climate projections due to this can be rectified using suitable bias correction methods before using these projections in impact studies. In the present study, the delta change approach was adopted for bias correction of the RCM projections. The delta change approach is based on transferring the mean monthly change signal between the RCM control and the RCM scenario period to an observed time series. The change signals between the RCM baseline and scenario period are derived from the mean monthly values and are applied to the daily time series. This approach is used in order to avoid considerable variability in the day to day change signals which would have occurred if daily change factors are used. Precipitation is typically corrected with a multiplier and temperature with an additive term on a monthly basis.

$$P_{daily}^{sce,corr} = P_{daily}^{obs} \times \frac{\bar{P}_m^{sce}}{\bar{P}_m^{con}} \qquad (2)$$

$$T_{daily}^{sce,corr} = T_{daily}^{obs} + (\bar{T}_m^{sce} - \bar{T}_m^{con}) \qquad (3)$$

where $P_{daily}^{sce,corr}$ is the corrected daily meteorological variable for the scenario period, $T_{daily}^{sce,corr}$ is the corrected daily temperature for the scenario period, $\bar{P}_m^{con}$ is the monthly average of the meteorological variable for the control period, $\bar{P}_m^{sce}$ is the monthly average of the meteorological variable during the scenario period, $\bar{T}_m^{con}$ is the monthly average of the temperature for the control period and $\bar{T}_m^{sce}$ is the monthly average of the temperature during the scenario period.

3. Results

Calibration and validation of the rainfall runoff model

Calibration of the HEC-HMS model for streamflow was performed using observed streamflow data for nine years (1991-1999). Results of model simulations performed during calibration were checked for R^2 and NSE values and graphically analyzed for agreement between the computed and observed streamflows. The parameter values were changed till a reasonably good match was obtained between the observed streamflow and the computed streamflow. Both manual and automatic calibration were performed. For automatic calibration, peak weighted RMS error was chosen as the objective function and univariate gradient algorithm was chosen as the optimization method. The final calibrated values of the RR parameters are presented in Table 4. The performance parameters adopted in the study are: percentage error in simulated volume (PEV), percentage error in simulated peak (PEP), Nash-Sutcliffe efficiency

(NSE), coefficient of determination(R^2) and percentage bias (PBIAS). The criteria suggested by Moriasi et. al. (2007) was used for model rating. The performance measures of the model along with PEV and PEP during calibration are presented in Table 5. These values indicate that the performance of the model is good. Peak flow is underestimated while the runoff volume is overestimated in the calibration period.
The performance of the HEC-HMS model was further validated using observed data from 01 January 2000 to 31 October 2004. Peak flow was underestimated while the runoff volume was overestimated in the validation period also. The performance measures of the model along with the values of PEV and PEP during validation are presented in Table 5. These values indicate that the performance of the model is good.

Table 4. Calibrated rainfall-runoff model parameters

Model	Parameter	Calibrated value
Loss	Initial deficit (mm)	5.6
	Maximum storage (mm)	18
	Constant rate (mm/hr)	0.646
	Percentage impervious area	1.3
Transform	Storage coefficient (min)	55.89
Baseflow	Initial discharge (m^3/s)	11
	Recession constant	0.917
	Ratio to peak	0.426
Routing	Manning’s n	0.035 –channel 0.04-left and right banks
Canopy	Initial storage (%)	16
	Maximum storage (mm)	8
	Crop coefficient	0.8

Table 5. Comparison of computed and observed streamflow during validation

Performance measure	Calibration period	Validation period
NSE	0.76	0.66
R^2	0.87	0.75
PEV (%)	-1.71	-6.13
PEP (%)	+22.43	+42.67
PBIAS	+1.61	-18.07

Calibration and validation of sediment routing model

Calibration of the MUSLE cum routing model was performed using sediment data for nine years (1991-1999). For calibration purpose, the observed sediment concentration in g/l was changed to tonnes/cu m, since the HEC-HMS results are in tonnes/cu m. Simulation results are read from the HEC-HMS model using the data management program HEC-DSSVue. From the results of the daily simulation, the monthly sediment load was computed for the calibration period and thus the finer daily variations are smoothened. The model simulation results during calibration were checked for R^2 and NSE values and graphically analyzed for agreement between the computed and observed sediment concentrations. The parameter values except for the topographic factor were adjusted manually, till a reasonably good match was obtained between the observed and computed sediment loads. The performance measures of the model during calibration are presented in Table 7. These values indicate that the performance of the model is satisfactory. The computed sediment time series shows reasonably close agreement with the observed sediment time series. The calibrated values of the MUSLE model parameters are presented in Table 6. The model was validated using the observed data from 01 May 2001 to 31 October 2004. Sediment load is overestimated during the validation period. The performance measures of the model during validation, presented in Table 7, indicate that the performance of the model is satisfactory.

Projection of future streamflows and sediment loads

Streamflow and sediment load for the period 2021-2035 were projected using the calibrated and validated HEC-HMS model for the two scenarios RCP 4.5 and 8.5. The bias corrected precipitation projections at the three rainfall stations Kottamparamba, Nilambur and Manjeri and the potential evapotranspiration for the future scenarios were input to the validated HMS model to compute runoff. Landuse was assumed to be unchanged and the model parameters were kept constant for the future period. The MUSLE parameters were also kept the same.

Table 6. Calibrated MUSLE parameters

Sl. No.	Parameter	Value
1.	Erodibility factor	0.49-clay, 0.67-loam and 0.32-gravelly clay
2.	Cover factor	0.0009
3.	Practice factor	0.43
4.	Threshold	1.3 (m^3/s)
5.	Exponent	1.84
6.	Enrichment ratio	1

Table 7. Performance measures of the model during calibration and validation

Performance measure	Calibration period	Validation period
NSE	0.61	0.59
R^2	0.78	0.77
PBIAS	+22.26	+42.70

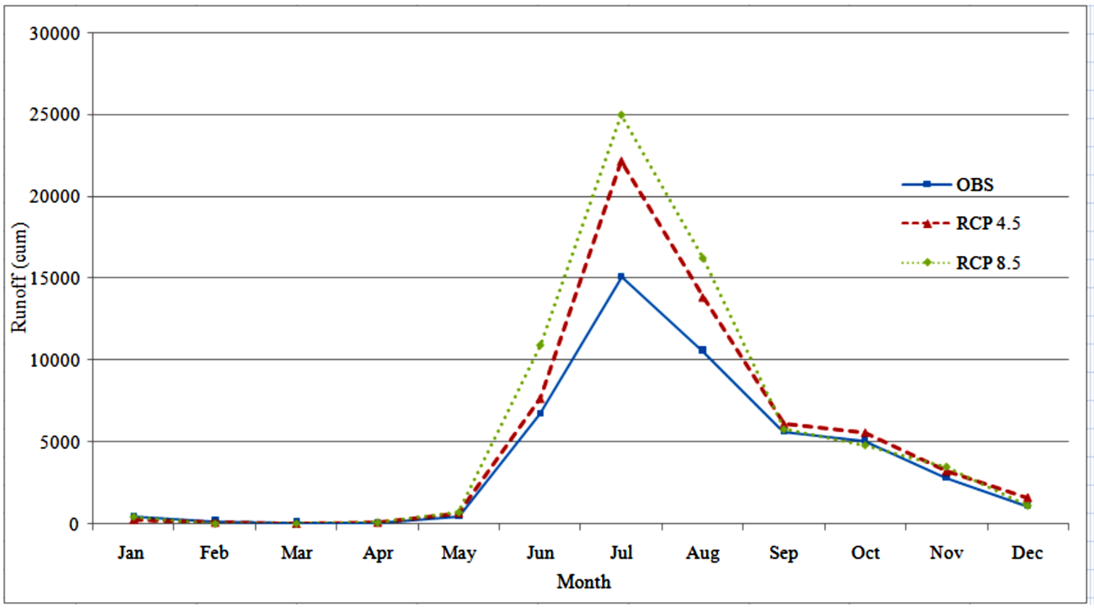

Fig. 4: Plot of monthly average streamflow for the baseline period (????????) under RCP scenarios 4.5 and 8.5

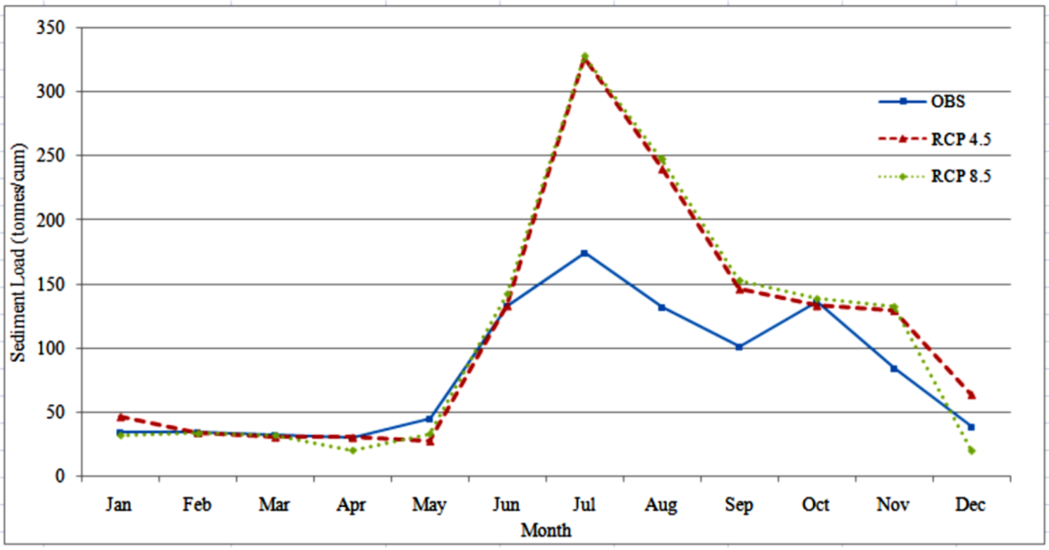

Fig. 5 Plot of monthly average sediment load for the baseline period and under RCP scenarios

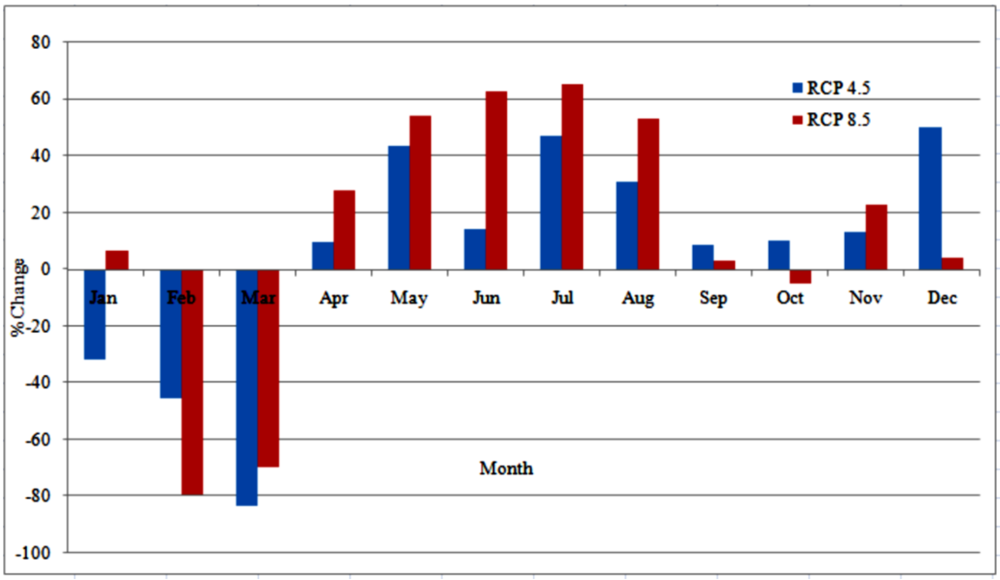

Fig. 6 Percentage change in monthly average streamflow

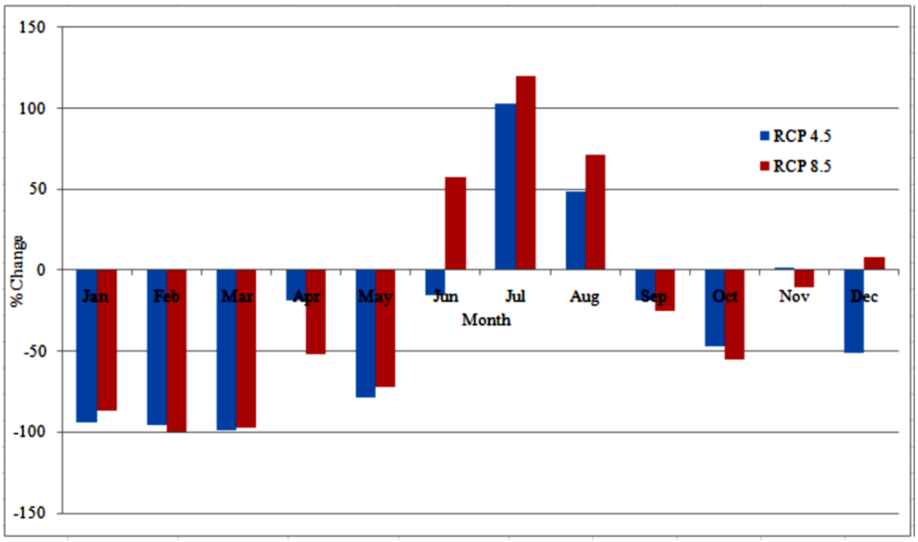

Fig. 7 Percentage change in monthly average sediment load

Table 8. Projected changes in streamflow

Runoff	**RCP 4.5**			**RCP 8.5**		
	Winter	**Summer**	**Monsoon**	**Winter**	**Summer**	**Monsoon**
Change	+19.82%	+17.85%	+27.68%	-3.18 %	+29.98%	+44.28%
Annual Change	+27.27%			+42.44 %		

Table 9. Projected changes in sediment load

Sediment load	**RCP 4.5**			**RCP 8.5**		
	Winter	**Summer**	**Monsoon**	**Winter**	**Summer**	**Monsoon**

Change	+35.97%	-16.58%	+45.64%	-19.95%	-20.23%	+49.89%
Annual Change	+37.74 %			+34.54 %		

4. Discussion

Both streamflow and sediment time series follow the overall trend exhibited during the baseline period 1987-2001 as shown in Figs. 4 and 5. Streamflow showed an annual increase of 27.27% under RCP 4.5 and 42.44% under RCP 8.5. It exhibited a higher increase during the month of July in both the scenarios; sediment load also showed a greater increase during the month of July. Streamflow and sediment load exhibited a drastic decrease during the months of January, February, and March. The percentage increase in annual sediment load was 37.74 under RCP 4.5 and 34.54 under RCP 8.5. The average annual increase in streamflow was 30.69 m^3/s for RCP 4.5 and 45.74 m^3/s for RCP 8.5. The average annual increase in sediment load was 250.07 tonnes/cu.m. for RCP 4.5 and 186.59 tonnes/cu.m. for RCP 8.5. Percentage seasonal changes in runoff and sediment load are presented in Table 8 and Table 9 respectively. The percentage change in monthly runoff and sediment load are presented in Fig. 6 and Fig.7 respectively.

5. Conclusions

In this study, streamflow and sediment load for the period 2021-2035 were computed using the calibrated and validated HEC-HMS model for two scenarios, viz., RCP 4.5 and RCP 8.5. Results of the study indicate that annual streamflow is likely to increase by about 27.27% under RCP 4.5 and by about 42.44% under RCP 8.5. The projected percentage increase in annual sediment load is 37.74% under RCP 4.5 and 34.54% as per RCP 8.5. The average increase in streamflow is 30.69 m^3/s for RCP 4.5 and 45.74 m^3/s for RCP 8.5. The average annual increase in sediment load is 250.07 tonnes/cu.m. for RCP 4.5 and 186.59 tonnes/cu.m. for RCP 8.5. The percentage change in monthly streamflow and sediment load is found to be higher in the month of July under both the RCPs; streamflow and sediment load shows significant decrease during the months of January, February and March.

In this study, land use was assumed to be unchanged during the future periods due to difficulty in extrapolating future land use and the corresponding model parameters were kept constant. Land-use land-cover modelling should be carried out to obtain projections of future land-use and land-cover change under different scenarios. Also, projections from only a single GCM were used. The reliability of model predictions can be improved by using multiple climate models and by running the model for more scenario periods. Uncertainty in the GCM projections should be assessed and its impact on predictions of the hydrologic model should be investigated.

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