CLIMATE CHANGE IMPACT ASSESSMENT ON HYDROLOGICAL REGIME OF KRISHNA BASIN

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KEY WORDS: Hydrological Modeling, VIC, Climate Change, RCPs, Hydrological Extremes

ABSTRACT: The impact of climate change on water availability and hydrological extreme over the Krishna Basin has been analyzed in the present study. Variable Infiltration Capacity (VIC) model has been used to simulate the hydrological response of the basin under observed climatic data and future predications. The soils, vegetation, topographical and meteorological inputs for the model were derived from remote sensing based and observed data/products. The model calibration and validation has been performed using observed river discharge data. The coefficients of determination (R^2) of 0.95 were achieved during calibration process and R^2 of 0.84 has been achieved during validation process. The meteorological forcing consisting future climatic inputs for the entire century (2006-2100) have been extracted from RCP 4.5 and RCP 8.5 scenarios of IITMRegCM4-4 predictions. Hydrological response of the basin to future climatic inputs has been simulated using calibrated VIC model. The analysis of future meteorological inputs indicates increasing trend in annual minimum and maximum temperature and precipitation over the basin under RCP 4.5 and RCP 8.5. The analysis of hydrological response of the basin indicates the increasing trend of 13.8 and 27.8 cumec/year in annual discharge in RCP 4.5 and RCP 8.5, respectively. The probable hydrological extreme events were found to increase under RCP 4.5 and RCP8.5 as compared with past records of 1985-2005. The percentage increase in peak discharge was observed in the range of 57.67% -76.78% and 68.48% -77.53% under RCP 4.5 and RCP 8.5, respectively. The study highlights the increase in annual water potential and hydrological externs in the basin under future climatic scenario.

1. INTRODUCTION

Water is an indispensable resource for humanity and all other living beings. About 71% of the earth's surface is covered by water. However, only 3% of that is fresh water. Availability of fresh water is highly dynamic in space and time, this makes its conservation and management planning necessary for survival of any society. India is a tropical country with a vast diversity of climate, topography and vegetation. Rainfall, the main source of fresh water, in India varies considerably in its place of occurrence as well as in its amount. Water resource management requires system of integration of scientific approaches that include hydrological components and its interrelationship which include climate variability, land cover change, irrigation and flow regulation, etc. Climate is an average weather of an area, which average over a long period at least 30 years. Even the small changes in climate may upset the hydrological cycle, resulting in floods and droughts over different regions, may cause sea level rise, changes in agricultural productivity, famines and death of humans as well as livestock's. A comprehensive knowledge and understanding of the various hydrological components within hydrological cycle is required in studying the effects of these changes. Precipitation, a primary component of hydrological cycle, strongly affects runoff, evapotranspiration, and baseflow relative to other climatic variables (Bosch and Hewlett, 1982).The extreme weather events leading to decreased water availability in rural areas are expected to increase under climate change. The impact of climate variability over the coming years will have an impact on food and water security in significant and highly uncertain ways (DušanTrninić., 2010). Modeling water cycle for future climatic scenario would help understand these impacts. The mathematical representation of the components of water cycle is called hydrological modeling. The estimation of hydrology components of water cycle (soil water storage, surface runoff generation, sub-surface drainage and evapotranspiration) plays an important role in the prediction of long-term water and energy balances (Lohmann et al., 1998a, b).The physical based distributed hydrological model which may be a grid based model is far more accurate in estimating these water cycle components at a basin scale, than other lumped models. The Variable Infiltration Capacity (VIC) Model is a macro scale hydrologic model for water and energy balance, developed at the University of Washington and Princeton University (Wood. et al., 1992; Liang et al., 1994). VIC is one of such model which uses physical elements to represent exchanges of latent heat with atmosphere but uses conceptual estimation to simulate runoff, precipitation and infiltration process. Hence, in the present study VIC model is used to assess the impact of climate change on water availability and hydrological extremes in the Krishna River basin.

2. STUDY AREA AND DATA USED

2.1 Study Area

The Krishna Basin extends over the states of Maharashtra (26.36%), Karnataka (43.8%), Andhra Pradesh and Telangana (29.81%). Krishna Basin occupies nearly 8% (258948 km^2) of geographical area of India. Figures 1 shows the location and drainage network of Krishna Basin. The basin has a maximum length and width of about 701 km and 672 km and lies between 73°17’ to 81°9’ East longitudes and 13°10’ to 19°22’ North latitudes. The basin is bounded by Balaghat range on the north, by the Eastern Ghats on the south and the east and by the Western Ghats on the west. Major part of the basin (75.86%) is covered with agricultural area. Approximately 10% of the basin area is covered by forest, wasteland covers around 7% of the total basin area and around 4% of the basin area is covered by water bodies. Average annual surface water potential of this basin has been assessed to be 78.1 BCM. Out of this, 58.0 BCM is utilizable water. The basin comprises of seven sub-basins, which have been further clustered into 391 watersheds each of which represents a different tributary system (Dadhwal, 2014). The Krishna basin has a tropical climate, dominated by the southwest monsoon, which provides most of the precipitation for the basin. The south-central part of the basin is truly arid. The high rainfall zone along the Western Ghats forms the western boundary of the Krishna basin for a distance of about 708 km and many channels, big and small, carry the drainage of this area into the Krishna River. The annual rainfall varies from 3048 mm to 1016 mm in this area. East of the Western Ghats, the annual rainfall decreases rapidly to less than 600 mm. During the three months, March to May, the rainfall in the most parts of the basin varies from 20 mm to about 50 mm June to September are the four months of the south-west monsoon during which all parts of the basin receive their maximum rainfall. The actual rainfall varies widely from year to year. There are also variations in the incidence and distribution of rainfall in time and space. Krishna basin shows a variable rainfall across the basin. Year 1975 shows highest average annual rainfall of approximately 1400 mm in the basin, whereas 1972 data shows least rainfall in past 45years. Most of the agricultural area in the basin depends on rainfall. To protect the agricultural sector from erratic nature of rainfall, large-scale irrigation development has been planned and executed in the basin over past three to four decades. However, the water available in the river is always affected by the occurrence of rainfall in basin. The available water of the basin is also utilized by other water users (drinking water supply, urban and industrial supply, etc.), all of these sectors are competing with each other for water use as most parts of basin are water deficit eitherspatially or temporally. Additionally, changing climate has posed daunting task of planning for future, which has inherent challenge of uncertainty. So, in the preset study water resources availability in the basin has been analyzed for two different climate change scenario, along with this the analysis of status of hydrological extremes has also been done in comparison of existing situation.

2.2 Data Used

The digital elevation model of Shuttle Radar Topographic Mission (SRTM) with 90m resolution is used in this study. This DEM was acquired from USGS – Earth Explorer (https://earthexplorer.usgs.gov/) for basin delineation, drainage network extraction (Figure 1) and estimation of other topographical inputs. Mean elevation values for each VIC grids were derived from DEM. The Land used land cover (LULC) map (Figure 2) of year 2005, acquired from ISRO-GBP LULC project, is used in the present study to setup the hydrological model representing present situation. The soil map acquired from National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) was at courses scale of 1: 2, 50,000. The soil map was rescaled to 1:50,000 scale under ISRO-GBP LULC project, this rescaled soil map (Figure 3) is used in the present study to parameterize the hydrological mode for the entire basin. This soil map gives the information about the types of soil spread over the basin, its depth and its parameters. The observed daily river discharge data for major stations (Vijayawada and Huvengidei) in the Krishna basin is downloaded from http://india-wris.nrsc.gov.in. The discharge data is used for model calibration and validation process. Figure 1 shows the location discharge stations considered for calibration and validation in the present study.

The observed meteorological data on daily maximum temperature, minimum temperature, rainfall and wind speed was obtained from India Meteorological Department (IMD), Pune in the form of gridded data products. The future climatic predications of Coordinated Regional Downscaling Experiment (CORDEX) for Representative Concentration Pathways (RCP) 4.5 and RCP8.5 are used in the present study (Chaturvedi, 2012). These dataset are available at The Indian Institute of Tropical Meteorology (IITM), Pune in NetCDF format. The meteorological input forcing files for each model grid of VIC model over Krishna Basin were generated using these two data sets (observed and future predictions).

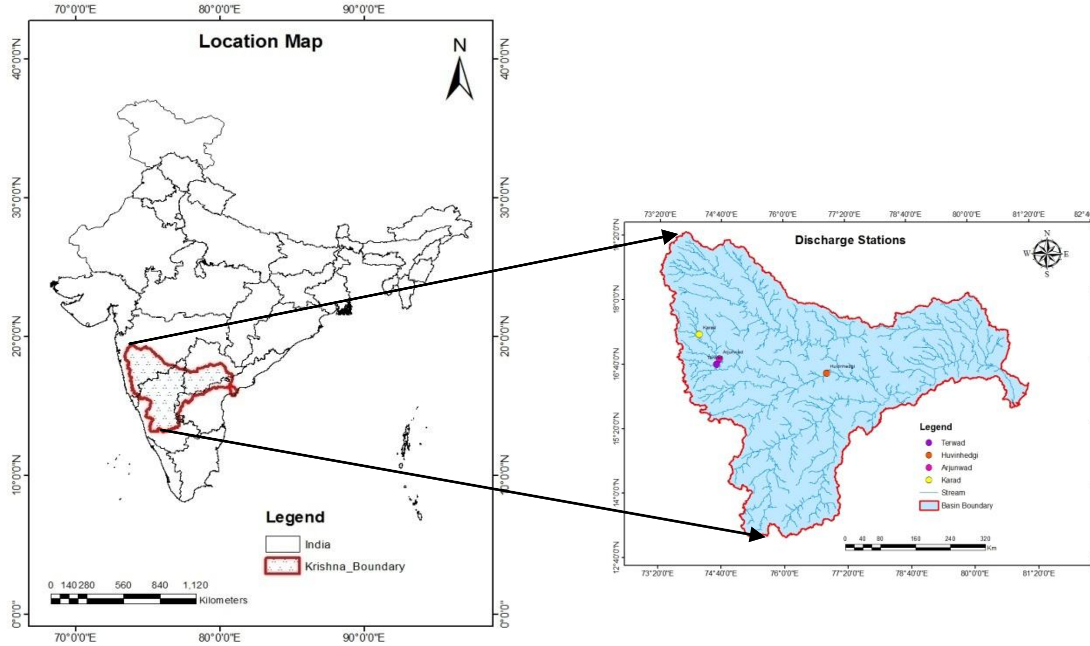


Figure1: Location map, drainage network and location of gauging stations of Krishna basin

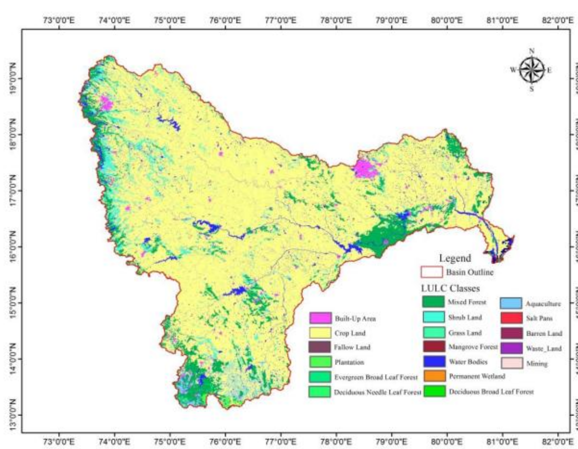


Figure 2: LULC map of Krishna basin

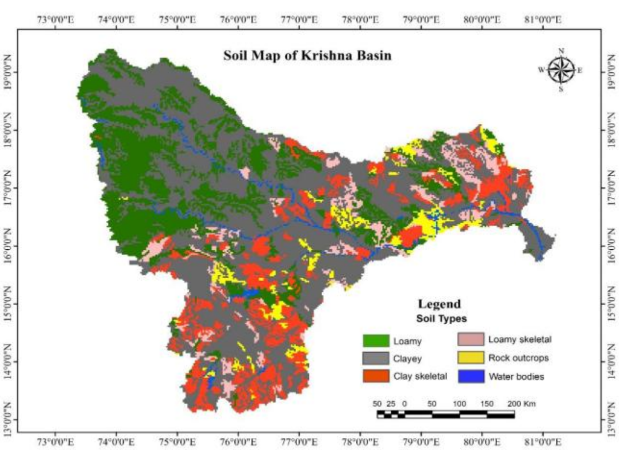


Figure3: Soil texture map of Krishna basin

4. METHODOLOGY

The VIC is a macroscale land surface hydrological model developed as a soil–vegetation–atmosphere transfer schemes (SVATS) for general circulation models (GCMs) by (Wood., E. F et al., 1992; Liang et al.1994). Compared to other hydrological models, it has various distinguished features such as the sub-grid variability in soil moisture storage capacity as a spatial probability distribution, sub-grid variability of land cover land use (LULC) and drainage from a lower soil moisture zone (base flow) as a nonlinear recession (Zhao et al., 1980 and Dumenil et al., 1992). Further details of the VIC model can be found in the literature (Lettenmaier 2001; Liang et al. 1994; Liang 1994; Liang et al. 1996, Garg et al., 2017b). The model has been used for a large number of hydrological studies in different climatic environments (Liang et al. 1994, 1996; Abdulla et al. 1996; Nijssen et al. 1997; Wood et al. 1997; Lohmann et al. 1998; Lohmann et al. 1998a, b; Maurer et al. 2001a; Liang et al. 2004;Yuan et. al. 2004; Hurkmans et al. 2009; Dadhwal et al. 2010; Aggarwal et al. 2012; Garg et al. 2012; Aggarwal et al. 2013; Nikam et al. 2015; Shiradhonkar et al. 2015; Garg et al. 2016; Garg et al. 2017 and Nikam et al. 2017). The VIC model runs in various modes, namely energy balance, water balance and routing. In the present analysis, the three layers VIC (VIC-3L) model has been run in water balance mode, driven by precipitation, maximum temperature, minimum temperature and wind speed at a daily time-step. It has been applied to simulate daily hydrological parameters (surface runoff, evapotranspiration, three layer soil moisture and baseflow) for each grid cell independently. The input parameter generation and model setup for the Krishna Basin is been elaborated below.

4.1 VIC Model Inputs

The main inputs files required for running VIC model are Soil parameter file, Vegetation parameter file, Vegetation library and meteorological forcing files. The path to all the inputs along with operational options (e.g. mode, time step, time span of model run, outputs required, etc.) are specified in global parameter file of the model. The brief information regarding each input file prepared in the present study is given below;

The soil parameter file, which describes the infiltration and water storage properties of the soil type with covers the dominant part of each model grid cell, was gendered using digital soil texture map prepared from NBSS & LUP soil maps shown in Figure 3. Soil texture map was overlaid and rasterized with the grid map to extract dominant soil type in each grid. All other parameters except c, elevation, depth, time zone offset, rough, and annual precipitation are a function of soil texture and were derived using soil hydraulic properties index defined in VIC model documentation (www.hydro.washington.edu).The vegetation parameter file describes the vegetative composition of each grid cell, and uses the same grid cell numbering as the soil file. This file cross-indexes each vegetation class (from any land-cover classification scheme) to the classes listed in the vegetation library. To prepare this file, land use land cover map of year 2005 was overlaid on the grid map and the number of vegetation classes as well as fraction of grid covered by those classes was extracted. Root depths for land cover types were accepted as recommended by Canadell et al. (1996).The vegetation library file contains detailed temporal information of biophysical parameters of all the vegetation types influencing water and energy balance process. The standard values of all these parameters were assembled based on Global Land Data Assimilation System database (http://ldas.gsfc.nasa.gov/gldas/GLDASmapveg.php).

VIC needs a dedicated meteorological forcing file for each model active grid cells. These files contain meteorological variables mandatory to force the VIC model like daily precipitation, daily minimum temperature, maximum temperature and wind speed. Meteorological inputs were prepared using IMD's gridded rainfall and temperature datasets. Daily meteorological parameters for all the active grids in the river basin are extracted for the period 1951 to 2012. Meteorological forcing files are prepared using these extracted values. The future meteorological forcing were generated using the future climatic predications of Coordinated Regional Downscaling Experiment (CORDEX) for Representative Concentration Pathways (RCP) 4.5 and RCP8.5. An interactive tool developed by Gupta et al. (2012) has been used to generate all the input files for the VIC model in the present study.

4.2 VIC Model Setup

The VIC model is a semi-distributed macro-scale model that solves hydrological fluxes and coupled water and energy balance equations in a grid to calculate different hydrologic components (Liang et al., 1994). VIC is a grid based model considers sub-grid heterogeneity by dividing each grid into a number of tiles. Each tile generates different responses to Precipitation in the form of infiltration, soil moisture storage, runoff and evaporation. A streamflow routing model developed by Lohmann et al. (1996) is activated after the computation of water balance calculations for each grid within the basin, which generates the runoff within the each grid and transfers to the outlet/discharge station. In the present study, the grid of 25km x 25km is used to run the model. It was identified that 383 active grids are to be run for analysis. To run VIC model over Krishna Basin, Global parameter file is the main input file of VIC model which sets simulation options, such as start/end dates and modes of operation, locations of the input files and output files. The model is run in water balance mode in the present study at daily time step.

Calibration and validation of the model is done using observed data from two observation stations mentioned above. Like other physically based hydrologic models, the VIC model also has many parameters that must be specified. Gao et al. (2009) have suggested six model parameter *viz.* the infiltration parameter (b_i), Ds_{max}, the maximum velocity of baseflow; Ds, the fraction of maximum baseflow velocity; Ws, the fraction of maximum soil moisture content of the third soil layer at which non-linear baseflow occurs and depth of soil layers (d_1,d_2, d_3) as calibration parameters. The infiltration parameter *bi* controls the partitioning of rainfall into infiltration and direct runoff. A higher value of b_i gives lower infiltration and yields higher surface runoff and vice-versa. The top soil layer depth d_1 is usually specified a priori and affect the water available for transpiration and baseflow, respectively. Thicker soil depths have slower runoff response - baseflow dominated - with higher evapotranspiration, but result in longer retention of soil moisture and higher baseflow in wet seasons. Ds_{max}, Ds, and Ws, are baseflow parameters which determine how quickly the water stored in the third soil layer is evacuated as baseflow (Liang et al. 1994). The three baseflow parameters and the third soil layer depth (d_3) (Nijssen et al., 2001, Su et al., 2005) are used with only minor adjustment during the calibration, while the infiltration parameter (b_i) and the second soil depth (d_2) are targeted for intensive calibration. Parameters b_i and d_2 are calibrated independently.

The grid based runoff fluxes are routed using a stream flow routing model developed by Lohmann et al. (1996). The inputs files for this routing scheme are flow direction, derived from DEM hydro-processing, the fraction and station files, derived using model active grid file and location information of observation stations used for calibration and validation. The model is calibrated for Huvindegdi observation station and then validated for overall outlet Vijayawada. The calibrated and validated model parameters are used to set-up VIC model to analyze the response of Krishna Basin towards past/observed meteorological condition (1985-2005) and future predictions (2006-2100). The primary hydrologic outputs of the model are runoff, evapotranspiration and baseflow from each grid cell. For simulation of future prediction of stream flow, only the meteorological inputs were changed, other files pertaining to vegetation and soil parameters remains unchanged in the present study.

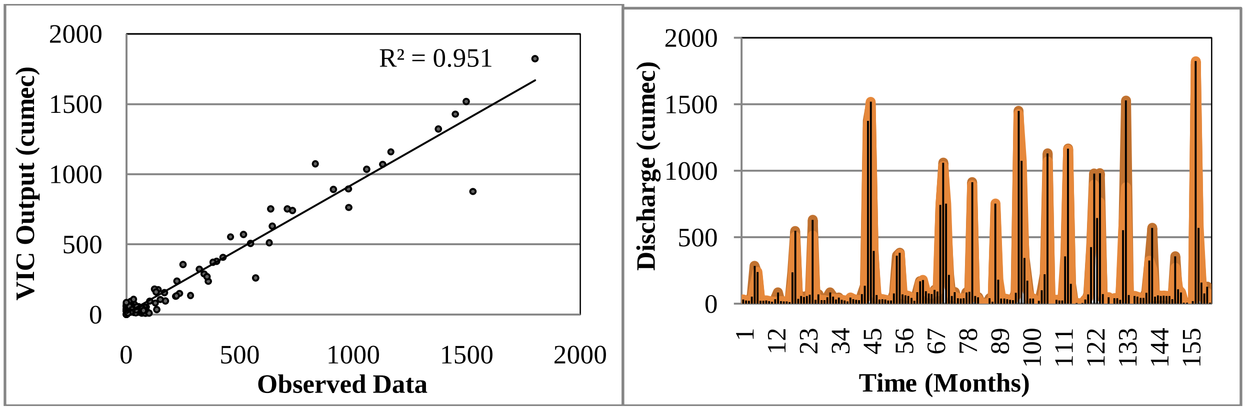
5. RESULTS AND DISCUSSIONS

To access the impact of climate change on Krishna basin VIC model is used in the present study. The basin is discretized in square grids of 25× 25 km and total 383 active grids were selected to represent the basin area. Input parameters for each grid, the soil parameter, vegetation parameter and the meteorological forcing were derived using soil map, land use map and IMD data (1951 – 2013), respectively. To compare VIC model simulated runoff with observed streamflow, the stimulated runoff is routed through the river network using a routing model developed by Lohmann et al., (1996). Runoff was routed to the outlets at two stations namely Huvinhedgi, and Vijayawada. These outlets were chosen based on the consistent availability of the observed data. The routed monthly runoff is compared with the monthly observed discharge data. The simulation results obtained while calibrating and validating the VIC model were analyzed and simulated streamflow were compared with the observed discharge at outlet station to look for the model efficiency in representing hydrological conditions accurately.

5.1 Model Calibration and Validation

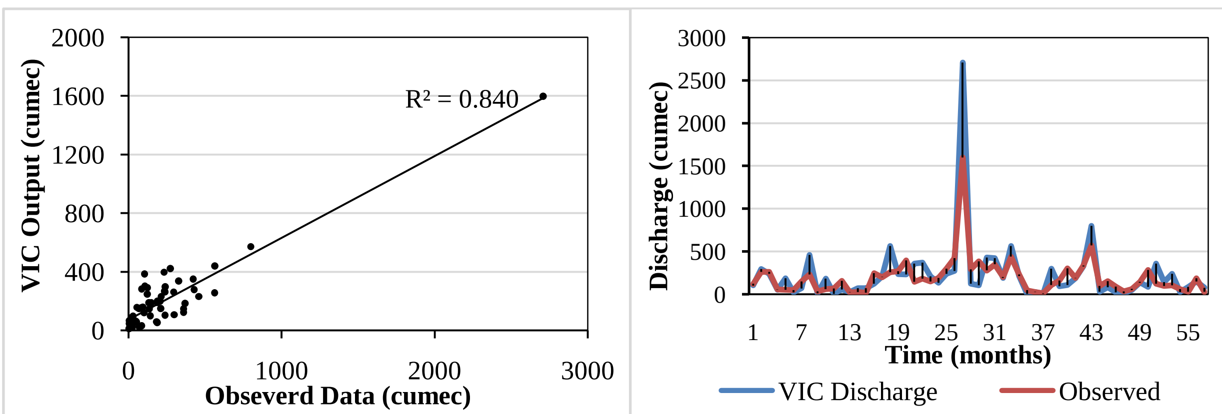
Model calibration may be defined as the procedure of adjusting model parameters which cannot be determined exactly through available methods. The valid initial ranges of calibration parameters were taken from Garg et al. (2017).Out of all the calibration parameter *bi* is the most sensitive parameter (Demaria et al., 2007; Gao et al. 2009) hence *bi* has been used as a primary calibration parameter and values of other parameters are used to fine tune the model results. The calibration has been done in an iterative process in the present study and consistent results were obtained after around 25 iterations. The combination of calibration parameters giving best results was found to be bi = 0.4, Ds = 0.8, Ds_{max} = 25, Ws = 0.001, d_1 = 0.2 (m) and d_2= 0.6 (m) for the present study.

A good relation between the observed and simulated discharge was found with the coefficient of determination (R^2) value of 0.95 post-calibration at Huvinhedgi station. Along with R^2 the Nash–Sutcliffe model efficiency, ME (Nash and Sutcliffe, 1970) value was estimated to analysis the accuracy of model results and the ME value was 0.94 for Huvindegdi. In general value of ME ranges from -∞ to 1. Theoretically, a value of ME equal to 1 is considered as a perfect match between observed and simulated datasets, but in practical terms this rarely happens (Nearing 1998). Quinton (1997) reported that a value of ME greater than 0.5 can be considered as a satisfactory performance of the model in field conditions. In present case value of ME is 0.94 along with R^2 ranging from 0.95. These values of R^2 and ME indicate scientifically acceptable behavior of model. The Relative Root Mean Square Error (RMSE) also estimated for the post-calibration results for the Huvindegdi station and the value of RMSE are are found to be 77cumec. The scatterplot and hydrograph between observed and simulated discharge for the calibration site is given in Figures 4 a&b. After the acceptable level of accuracy was obtained through calibration process, the model was validated for same time period however, for different gauging station, Vijayawada, which is considered as outlet of entire Krishna basin. The R^2 value of 0.84 was obtained during validation process (Figures 5 a&b). In basin level hydrological modeling R^2 in the order of 0.8 to 0.9 are very commendable, and hence it was assumed to be satisfactory in the present study. The calibrated and validated VIC model setup for Krishna basin has been utilized to simulate and analyse the response of river basin towards future climatic scenario.



(a) (b)

Figure 4: Post-calibration Comparison of Simulated and Observed Discharge at Huvinhedgi a) Scatterplot, b)Hydrograph



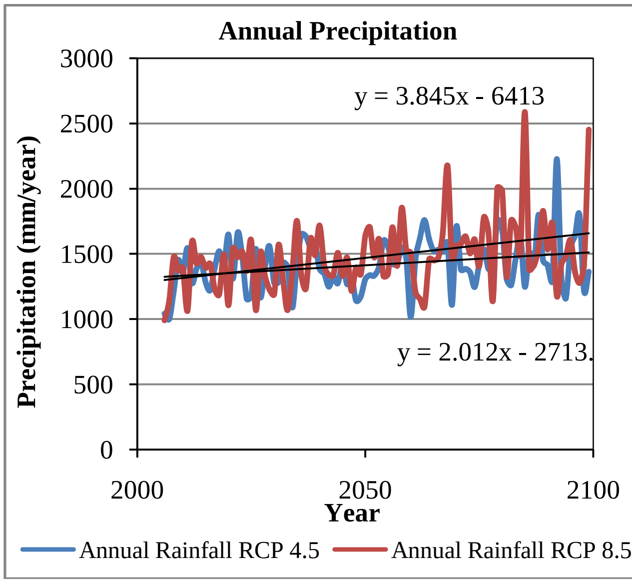
(a) (b)

Figure 5: Validation of VIC discharge and observed discharge at Vijayawada a) Scatterplot, b) Hydrograph

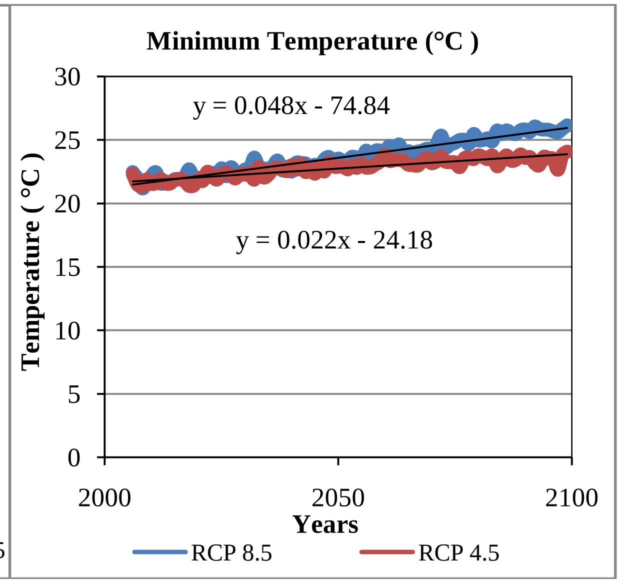
5.2 Analysis of Future Climatic Data (2006 – 2100)

Assessment of future climate change impacts on water resources commonly involves climate variables (i.e., precipitation, temperature) from global climate models (GCMs) in combination with hydrological models (Pechlivanidis et al., 2011). The World Climate Research Programme (WCRP) has recently launched a framework, called COordinated Regional climate Downscaling EXperiment (CORDEX), to generate and evaluate fine-scale ensembles of regional climate projections for all continents globally (Giorgi et al., 2009). To understand the impact of climate change over the basin, it is necessary to analyse the long-term average (2006 -2100) of the climatic variables, which is extracted from CORDEX south Asia data. The climatic variables precipitation, wind speed, maximum and minimum temperature were extracted over the region of Krishna basin and the long term spatial average of entire basin for future (2006 – 2100) using the RCP 4.5 and RCP 8.5 are analyzed.

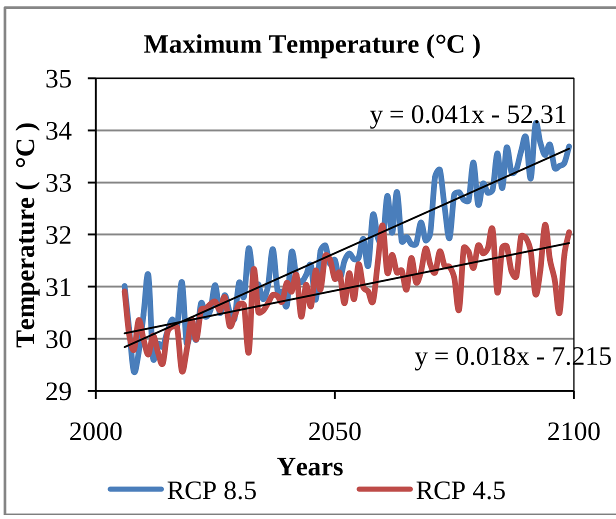
Figures 6a represents the positive trend in precipitation, maximum temperature, minimum temperature and wind speed during entire century. The analysis of future meteorological inputs indicates increasing trend of 2.012 mm/year, 0.019°C/year, 0.023°C/year in annual precipitation, annual average maximum and minimum temperature, respectively for RCP 4.5 and 3.845 mm/year, 0.041°C/year and 0.048°C/year in annual precipitation, annual average maximum and minimum temperature for RCP 8.5, respectively.



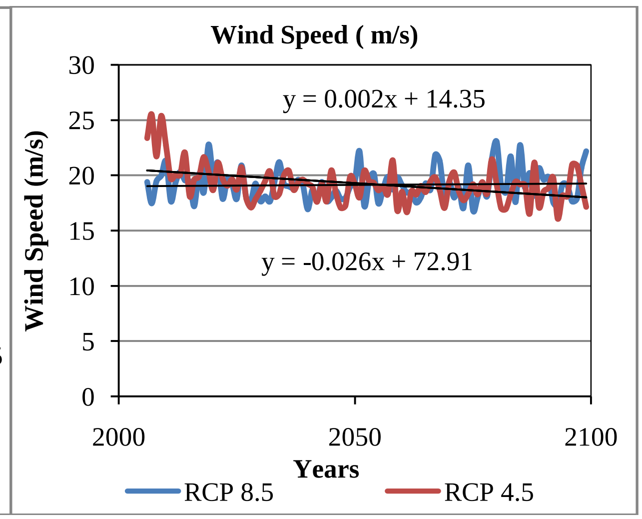
a) Annual Mean Precipitation



b) Annual Mean Minimum Temperature



c) Annual Mean Maximum Temperature



d) Annual Mean Wind Speed

Figure 6: Trend in Future Climatic Variables a) Annual Mean Precipitation, b)Annual Mean Minimum Temperature, c) Annual Mean Maximum Temperature, and d)Annual Mean Wind Speed

The annual average values of future climatic parameters averaged for time span of 20 years (e.g.2021 – 2040, 2041 - 2060, 2061 – 2080, 2081- 2100) indicate a gradually increasing trend in minimum and maximum temperature in both the RCP scenario (RPC 4.5 and RCP 8.5). Precipitation in RCP 4.5 exhibits decreasing trend up to 2040, however in RCP 8.5 continuous increasing trend has been observed. In case of wind speed decreasing trend has been observed during entire century in RPC 4.5 predictions, RCP 8.5 predictions also follow same trend till mid-century (till 2040), however sudden increase has been observed in wind speed after mid-century in RCP 8.5 predictions. These climatic variables are used as metrological inputs for VIC model to simulate future (2006-2100) hydrological response of Krishna basin.

5.3 Hydrological Response of the Basin towards Future Climatic

The hydrological simulation of the Krishna basin under future climatic scenario has been carried out using VIC model at 25 × 25 km grid. All the inputs except meteorological forcing remain unchanged from calibration-validation stage, the meteorological forcings for time period 2006-2100, generated using RCP4.5 and RCP8.5 scenarios, are used in the present study. By simulating the VIC model with water balance mode for the period of 2006 - 2100 using the downscaled meteorological datasets of RCP 4.5 and RCP 8.5 the water balance scenario of the basin have been generated. As the analysis of climatic parameter indicate increasing trend in precipitation, similarly the hydrological simulation also indicates increase in runoff with time from the basin. Figures 7shows the constant increasing trend in runoff. The analysis of future hydrological scenario indicates an increasing trend of 1.780mm/year and 4.130mm/year in annual runoff under RCP 4.5 and RCP 8.5, respectively.

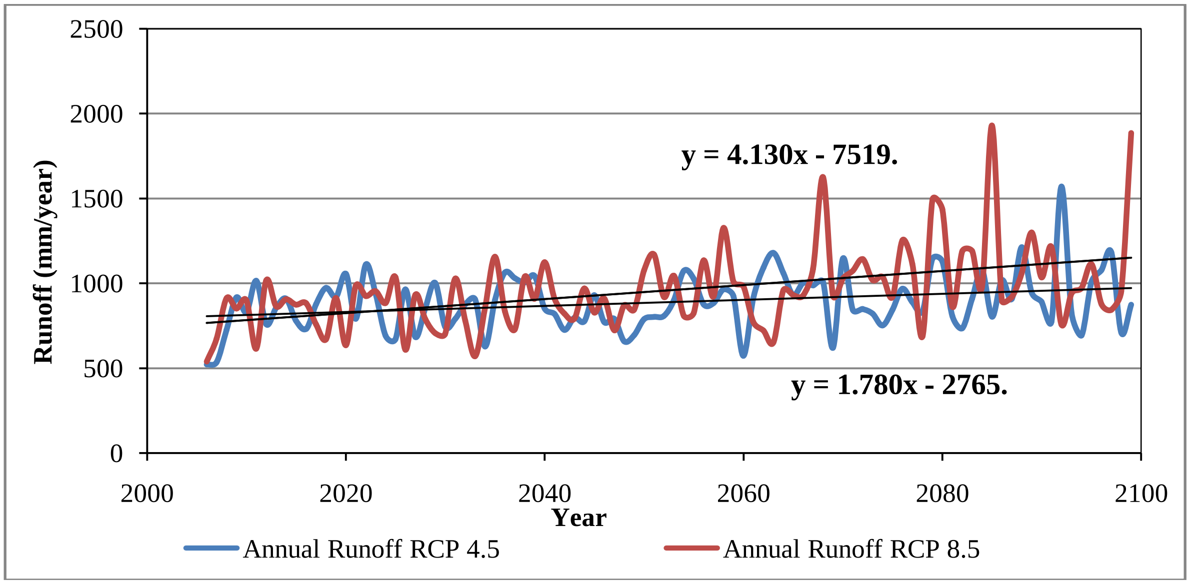


Figure 7: Long-term Trend in Average Runoff (Simulated)

5.4 Impact of Climatic Change on River Discharge

The VIC model can also be used to evaluate impact of climate change on long-term trend in discharge, actual usable water resources, from the basin. The VIC model simulated hydrological fluxes (surface runoff) of each grid are routed to Vijayawada station of Krishna basin and the results are analyzed here to highlight the impact of future climatic parameters on the water availability of the basin. In general increasing trend in discharge at Vijayawada during entire century is observed under RCP 4.5 and RCP 8.5 scenarios. Additionally, a change in the flow distribution is observed between RCP 8.5, RCP 4.5 and historical data. This change is due to the increase in precipitation and runoff over the basin as per results of VIC simulations. This means more water will be available in the water stress basin in coming times. However, one has to understand that runoff and discharge from basin not only depends on climatic parameters but also on land surface parameter, of which LULC in dominant one. In present study a static LULC (of year 2005) scenario has been used to simulate the basin hydrology of Krishna River, however, it is highly unlikely to have static LULC scenario throughout the coming century, especially with fast growing economy like India. Hence, the result highlighted in the present study regarding increase or decrease in natural water availability or loss can’t be taken as is for actual planning, however, they can be used as indicator scenario if underline assumptions used to setup the VIC model are going to be true.

The trend in future annual (2006 – 2100) discharge at Vijayawada station under both the climate change scenario (RCP 4.5 and RCP 8.5) is shown in Figure8. The continuously increasing trend of the order 13.76cumec/year and 27.83cumec/year is observed in annual discharge at Vijayawada station under RCP 4.5 and RCP 8.5 scenario, respectively. This increase in annual discharge in future (2006 – 2100) highlights the impact of climate change over Krishna basin. It is evident from Figure8 that inter-annual variability in discharge at Vijayawada increases as the time progress from the base line period (2006) indicating the presence of years with “extreme” climatic conditions.

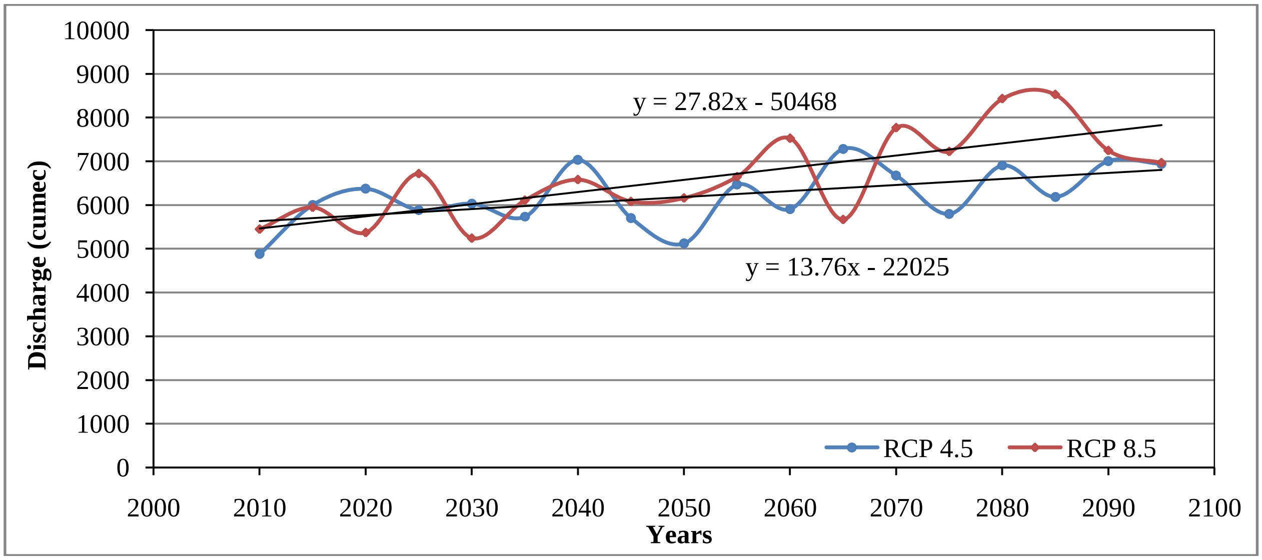


Figure8: Trends of Average Annual Simulated Discharge at Vijayawada under RCP 4.5 and RCP 8.5 (2006 – 2100)

5.5 Analysis of Hydrological Extremes

High and low flows and associated floods droughts are extreme hydrological phenomena caused by meteorological anomalies and modified by various catchment processes and human activities. As discussed earlier the probability of extreme hydrological events is more under future climatic scenario RPC 4.5 and RCP 8.5 as compared to past records. The high flow event (daily) at Vijayawada station during past 20 years were analyzed to decide the quantitative threshold for identifying high flow event which can be called as hydrological extremes. The discharge having 1% occurrence probability in entire observed records is selected as high flow event. The flow/discharge events having value equal to or greater than the threshold are marked as hydrological extreme event at Vijayawada. The count of such hydrological extreme events and the magnitude of highest flow event for the duration partitioned for every 20 year time interval, are analysed. The change in counts of hydrological extreme events compounded for every 20 years duration is shown in Figure9, whereas the magnitude of highest event expected to occur in that duration is presented in Figure10.

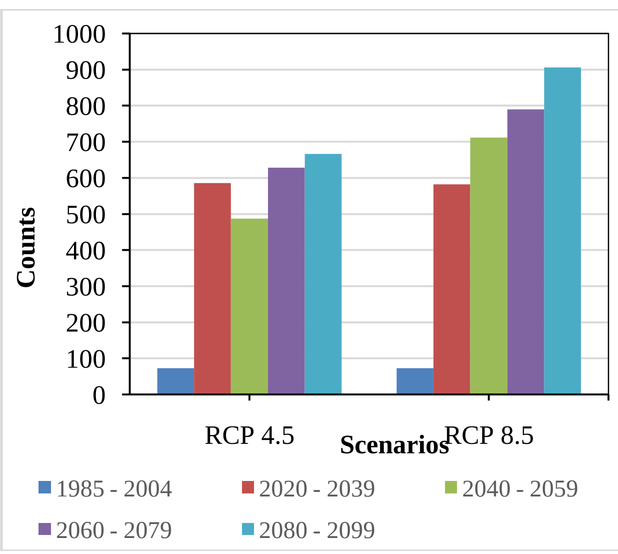


Figure 9: Counts of Probable Hydrological Extreme at Vijayawada

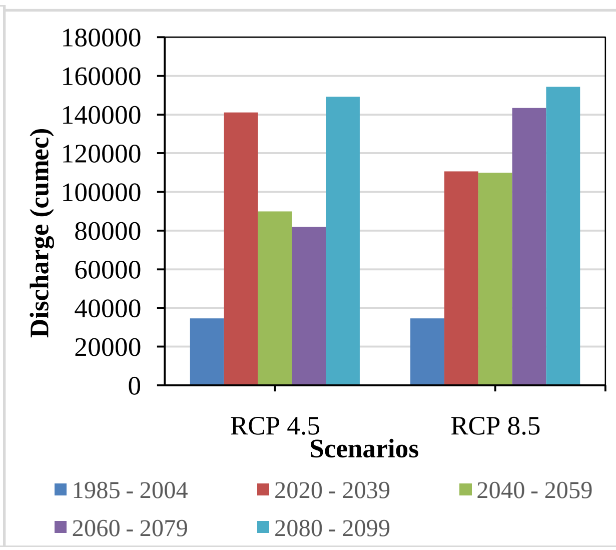


Figure 10: Magnitude of Highest Probable Hydrological Extreme Event at Vijayawada

It is evident from this analysis that not only frequency of hydrological extremes will increase in future time period but their magnitude as well. The percentage increasing in magnitude of extern flows as compared with present records will be of the order 57.67% - 76.78% and 68.48% – 77.53% under RCP 4.5 and RCP 8.5 scenario, respectively. The annual flow, number of hydrological extreme events and their magnitude are expected to increase under future changing climatic scenarios. Even with most optimistic RCP 4.5 scenario the Krishna basin will experience increase from 73 to 666 in hydrological extreme flow events and the magnitude of these events will be 58 to 77 % higher than what the basin has experienced in past. The scenario will be even more daunting if the climate change follows RCP 8.5 path. The analysis done here can be of use to water resources managers to prepare adaptation and utilization plans for increased extreme and mean annual flow at different reaches of the river.

6. CONCLUSION

In the present study, hydrological response of Krishna basin under different climate change scenarios has been analysed using Variable Infiltration Capacity (VIC) model. Initially, the VIC model was set-up, simulated, calibrated and validated using Land Use Land Cover (year 2005) generated under ISRO- GBP LULC project. The model was calibrated using observed monthly discharge data of Huvinhedgi station. The calibrated model was then validated (R^2 = 0.82) using observed data of 20 years from Vijayawada station. All model parameters of calibrated model stage were kept changed except for simulating future hydrological scenarios of the basin. The meteorological forcings consisting future downscaled climatic inputs for the entire century (2006-2100) were extracted from RCP 4.5 and RCP 8.5 scenarios of IITMRegCM4-4 predictions provided by The Indian Institute of Tropical Meteorology (IITM) Pune. These meteorological forcings were used to simulate the hydrological response of Krishna basin.
The analysis of future meteorological inputs highlights the increasing trend in annual precipitation, minimum temperature and maximum temperature throughout the century. The increasing trend in all the meteorological parameters is higher in RCP 8.5 scenarios compared to RCP 4.5 scenario. The increase in annual precipitation results in increase in annual runoff from Krishna basin throughout the century. Overall increasing trend of 1.780 mm/year and 4.130 mm/year was observed in average annual runoff from the basin under RCP 4.5 and RCP 8.5 scenarios, respectively.

The surface runoff fluxes from each model grid of the basin were routed to different outlets. The future discharge at Vijayawada station was analysed to quantify the status of future water availability and hydrological extremes. The routed future discharge at Vijayawada station shows increasing trend of 13.76 cumec/year and 27.83 cumec/year under RCP 4.5 and RCP 8.5 scenarios, respectively. This increase in annual discharge along with increasing trend in average annual runoff indicates increased water availability in the Krishna basin under future climate change scenarios. The peak discharge having occurrence frequency of 1% in the observed daily discharge data of Vijayawada station was identified and considered as threshold for hydrological extreme event. The daily discharge events from future simulated discharge at Vijayawada were analysed for span of every twenty years and the count of probable hydrological extreme events, highest of these events and the date of occurrence of this highest were recorded. The analysis indicates increase of 57.67 % -76.78 % and 68.48 % - 77.53 % in the magnitude of peak discharge using coming century under RCP 4.5 and RCP 8.5 scenario. The numbers of extreme events are also likely increase in coming century.

Therefore, it may be concluded that though future climate change scenarios (RCP 4.5 and RCP 8.5) may enhance overall water availability in the Krishna basin, however, the magnitude and count of hydrological extreme events is also going to increase in the basin.

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