# **1** Isolating the Impacts of Land Use and Climate Change on Streamflow

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12

## 13 Abstract

14 Quantifying the isolated and integrated impacts of land use and climate change on streamflow is 15 challenging as well as crucial to optimally manage water resources in the river basin. This paper 16 presents a simple hydrologic modelling based approach to segregate the impacts of land use and 17 climate change on streamflow of a river basin. The Upper Ganga Basin in India is selected as the 18 case study to carry out the analysis. Streamflow in the river basin is modelled using a calibrated 19 Variable Infiltration Capacity hydrologic model. The approach involves development of three 20 scenarios to understand the influence of land use and climate on streamflow. The first scenario 21 assesses the sensitivity of streamflow to land use changes under invariant climate. The second 22 scenario determines the change in streamflow due to change in climate assuming constant land 23 use. The third scenario estimates the combined effect of changing land use and climate over 24 streamflow of the basin. Based on the results obtained from the three scenarios, quantification of 25 isolated impacts of land use and climate change on streamflow is addressed. Future projections 26 of climate are obtained from dynamically downscaled simulations of six general circulation 27 models (GCMs) available from the Coordinated Regional Downscaling Experiment (CORDEX) 28 project. Uncertainties associated with the GCMs and emission scenarios are quantified in the 29 analysis. Results for the case study indicate that streamflow is highly sensitive to change in urban 30 area and moderately sensitive to change in crop land area. However, variations in streamflow 31 generally reproduce the variations in precipitation. Combined effect of land use and climate on 32 streamflow is observed to be more pronounced compared to their individual impacts in the basin. 33 It is observed from the isolated effects of land use and climate change that climate has a more 34 dominant impact on streamflow in the region. The approach proposed in this paper is applicable 35 to any river basin to isolate the impacts of land use change and climate change on the 36 streamflow.

#### 37 **1 Introduction**

38 Land use (LU) and climate are the drivers of hydrologic processes in a river basin (Vörösmarty 39 et al., 2000; Nijssen et al., 2001; Oki and Kanae, 2006; Wada et al., 2011). Change in LU is 40 observed to influence the hydrological cycle and the availability of water resources by altering 41 interception, infiltration rate, albedo and evapotranspiration (ET) (Rose and Peters, 2001; 42 Scanlon et al., 2007; Rientjes et al., 2011). Climate in contrast affects the basic components of 43 hydrologic cycle such as precipitation, soil moisture, evaporation and atmospheric water content 44 (Gleick, 1986; Wang et al., 2008). Therefore, understanding the hydrologic response of a river 45 basin to changes in LU and climate forms a critical step towards water resources planning and 46 management (Vörösmarty et al., 2000). Moreover, with increase in scarcity of water resources, 47 hydrologic impacts of LU and climate change has drawn significant attention from the 48 hydrologic community (Scanlon et al., 2007). In this regard, several studies have been carried out 49 that focus on understanding exclusive impacts of either of the two drivers (Hamlet and Lettenmaier, 1999; Christensen and Lettenmaier, 2007; Beyene et al. 2010; Wagner et al., 2013; 50 51 Islam et al., 2014). However, optimum management of water resources in a river basin needs an 52 in depth understanding of the isolated and integrated effects of LU and climate on streamflow. 53 Due to complex response of streamflow to combined effects of LU and climate change (Fu et al., 54 2007; Guo et al., 2008), very few studies have been carried out on this aspect (Mango et al., 55 2011; Guo et al., 2008; Cuo et al., 2013; Wang et al., 2013). Segregating the individual 56 contribution of LU and climate to streamflow has recently become the focus of scientific work 57 (Wang and Hejazi, 2011; Wang et al., 2013; Renner et al., 2012; Renner et al., 2014).

58 Methods used to assess the impacts of LU and climate on streamflow can be broadly classified 59 into four categories (i) experimental paired catchment approach; (ii) statistical techniques such as 60 Mann-Kendall test; (iii) empirical or conceptual models and (iv) distributed physically-based 61 hydrologic models. Among these techniques, the paired catchment approach is most difficult but 62 often considered as the best approach for smaller catchments. However, applicability of paired catchment approach over large catchments may not be possible (Lørup et al., 1998) since it 63 64 requires years of continuous monitoring to gather sufficient data for the analysis. Statistical trend detection tests have been proved to be very useful in qualitatively determining the presence of 65 66 significant trend in the time series along with direction and rate of change (Zhang et al., 2008; Li

67 et al., 2009). But these techniques cannot be used for quantifying the change and attributing it to 68 a particular cause due to lack of physical mechanism (Li et al., 2009). Empirical or conceptual 69 models are simple hydrologic models that require only a few parameters to simulate a catchment. 70 However, a major drawback with these models is that the parameters may not be directly related 71 to the physical conditions of the catchment and thus may lack the ability to correctly represent a 72 catchment. Therefore, one is left with the option of using distributed physically based hydrologic 73 models, which are by far the most appealing tools to carry out impact assessment studies (Ott 74 and Uhlenbrook, 2004; Mango et al., 2011; Wang et al., 2012). These models operate within a 75 distributed framework to take physical and meteorological conditions of the basin into account 76 (Refsgaard and Knudsen, 1996). Physically distributed models include both fully distributed and 77 semi-distributed models. Owing to their extensive parameterization, fully distributed models are 78 difficult to employ at this catchment scale which make comparatively less data intensive semi-79 distributed models a practical alternative. This paper presents a simple hydrologic modelling 80 based approach to isolate the impacts of land use and climate on streamflow. For this purpose, 81 physically-based macroscale Variable Infiltration Capacity (VIC) hydrologic model (Liang et al., 82 1994) has been employed for the analysis.

83 In the present paper, Ganga river basin in India is selected as the case study to perform the 84 analysis. Few studies have been reported in literature (Nijssen et al., 2001; Arora and Boer, 2001 85 and Nohara et al., 2006) wherein Ganga basin is studied alongside other major river basins of the 86 world (to assess the effect of changing climate on flow regime), however, there is dearth of 87 studies that comprehensively examine the effects of LU and climate change on streamflow 88 exclusively in this basin. Originating from the Himalayas, the river Ganga traverses a stretch of 2525 km covering a catchment area of around 800.000 km<sup>2</sup> which is approximately 26% of the 89 90 entire India's land mass making it the largest river basin in India. During its course, Ganga flows 91 through some of the major states of India harboring about 44% of country's population 92 (http://censusindia.gov.in/). Due to presence of alluvium, the basin is very fertile and forms close 93 to 30% of India's cultivable area (http://eands.dacnet.nic.in/LUS\_2001-11.htm). Thus there is a 94 clear consensus that the river is of great social and economic importance to India. In this study, 95 the area under investigation is the upstream reaches of the Ganga basin encompassing river's 96 originating place (Fig. 1). This region is referred as the Upper Ganga Basin (UGB) in the paper.

LU analysis carried out by Tsarouchi et al., (2014) on the UGB suggests that between 1984 to
2010 basin experienced increase in urban and crop land area and decrease in barren land area.

99 In order to obtain the isolated impacts of LU and climate change on streamflow, following 100 objectives are addressed in the current work: (i) assess sensitivity of the streamflow to changes in 101 different LU categories, (ii) examine impacts of climate change on the streamflow and (iii) 102 analyze integrated impacts of LU and climate change on the streamflow. The three objectives are 103 translated into three scenarios wherein first two scenarios quantify the independent effects of LU 104 and climate on streamflow under their invariant counterparts i.e., climate and LU respectively are 105 kept constant. The third scenario deals with concurrent changes in LU and climate. Results from 106 the three scenarios are further used to segregate the hydrologic impacts of LU and climate 107 change. The aforementioned objectives are investigated over the UGB as a case study by 108 employing a calibrated and validated VIC model to simulate streamflows. To assess the impact 109 of future climate on streamflow in the basin, dynamically downscaled climate simulations for six 110 GCMs obtained from the CORDEX project are used. Climate change related analyses are carried 111 out under the uncertainty framework to address two issues, one, climate models based 112 uncertainties, and two, emission scenarios based uncertainties.

#### 113 **2 Data and Methods**

#### 114 **2.1 Study Area**

The UGB, located within geographic coordinates of 25°30'N to 31°30'N latitude and 77°30'E to 115 80°E longitudes (Fig. 1), drains a catchment area of 95,593 km<sup>2</sup>. While most of the Ganga basin 116 117 comprises of agricultural areas with reasonably flat terrain, this region (UGB) is the only part of 118 the Ganga basin which is characterized by wide variation in topography with elevations ranging 119 from 21 m to 7796 m (Fig. 1), thus making it an interesting case study for investigation. In 120 addition, since the river Ganga originates in this region, any change in hydrologic response due 121 to LU and /or climate is likely to affect the entire flow regime downstream. Thus this region is 122 critical for assessing the impact of LU and climate change on the streamflow of the basin. In the 123 backdrop of recent flood event in July 2013 in the UGB, which has been attributed to climate 124 change (Singh et al., 2014), isolating the hydrologic impacts of changing LU and climate in this 125 basin has become much more important.

126 In this study, the UGB is divided into three regions, upstream, midstream and downstream 127 (Fig.1) based on altitude, topography and land use characteristics. The upstream region is highly 128 mountainous, characterized by glaciers and dense forests having elevations from 297 m to 7796 129 m. From upstream to midstream region, there is transition from hills to plains. Midstream region 130 is dominated by forests and crop lands with elevations ranging from 75 m to 3079 m. The 131 downstream region is mostly covered by crop lands having consistent elevations of around 100 132 m. In addition to the varying land use characteristics, these three regions have different 133 climatology as well. From 1971 to 2005, upstream, midstream and downstream regions recorded 134 an average annual precipitation of 1294, 1009 and 826 mm respectively. Most of the 135 precipitation is concentrated during the monsoon months from June to September (JJAS). 136 Average annual temperatures across the three regions during the same period were 20°C, 23°C 137 and 26°C respectively. Due to significant variation in the characteristics of these regions, they 138 are modelled separately in the paper. Details of data required to drive the hydrologic model are 139 presented in the following section.

## 140 **2.2 Input Data for the Hydrologic Model**

141 The current study employs physically based Variable Infiltration Capacity (VIC) hydrologic 142 model for the analysis. The VIC model is a semi-distributed soil-vegetation-atmosphere-transfer 143 model that solves coupled water and energy balance equations grid wise to calculate different 144 hydrologic components (Liang et al., 1994). Within a grid the VIC model considers sub-grid 145 heterogeneity by dividing each grid cell into number of tiles which in turn depend on different 146 land use types present in the grid. Each tile generates different response to the precipitation in the 147 form of infiltration, soil moisture storage, runoff and evaporation, owing to difference in land 148 surface properties. When VIC concludes the computation of energy and water balance 149 calculations for each grid within the watershed, streamflow routing model developed by 150 Lohmann et al., (1998) is activated that transports the surface runoff generated within a grid 151 along with the baseflow to the outlet of grid cell which is further routed through the river channel 152 to the watershed outlet.

Hydrologic models in general require topographic, soil, hydro-meteorological and LU data which can be procured from various sources. In the present work, topographic information is obtained from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)

156 DEM (Digital Elevation Model) available at 30 m spatial resolution. Digital soil map for the 157 region is procured from National Bureau of Soil Survey and Land Use Planning, India at a scale 158 of 1:250,000. Meteorological data (rainfall, maximum temperature, minimum temperature and 159 wind speed) for the period 1971-2005 at daily time scale is procured from two sources: Indian 160 Meteorological Department (IMD) (Rajeevan et al., 2006) and Princeton University (PU) 161 (Sheffield et al., 2006). Meteorological data from both the sources are brought to a common grid 162 resolution of 0.5° which also serves as the resolution for executing the VIC hydrologic model. 163 Observed streamflow data ( $Q_{obs}$ ) for two locations: Bhimgodha (1987-2011) and Ankinghat 164 (1977-2009) is obtained (at monthly scale) from Uttar Pradesh Irrigation Department and Central 165 Water Commission (CWC). Between Bhimgodha and Ankinghat stations, there are diversions 166 such as Upper Ganga Canal (UGC), Madhya Ganga Canal (MGC) and Lower Ganga Canal 167 (LGC) (Fig. 1) that divert the water from the main Ganga River. Therefore, along with  $Q_{obs}$ , data corresponding to various diversion channels is also procured from CWC and added to the 168 169 observed (regulated) flow thereby converting the observed streamflow to naturalized flow  $(Q_n)$ 170 <sub>obs</sub>). The flow data thus obtained  $(Q_{n-obs})$  is used for model calibration and validation.

For LU data, landsat imageries for the years 1973, 1980, 2000 and 2011 are selected and then classified to determine the LU change in the basin over four decades. Field study is carried out to collect the training sites for image classification. The accuracy of classified images is obtained to be 89%, 83%, 88% and 79% for 1973, 1980, 2000 & 2011 images respectively which is seen to be generally good. Thus the classified images can be used as LU maps of the UGB for the corresponding time periods. Results of classification and change in LU are presented in section 3.1.

178 To carry out hydrologic impact studies related to climate change, one needs data on future 179 climate variables such as rainfall (P), temperature (T) and wind speed (W) which in the current 180 study is procured from CORDEX South Asia group (http://cccr.tropmet.res.in/cordex/index.jsp) 181 at daily scale for six Coupled Model Intercomparison Project 5 (CMIP5) GCM simulations 182 (Table 1). Each model has a time series for all the requisite variables corresponding to the 183 twentieth century climate (historic run) and future climate using Representative Concentration 184 Pathway, RCP 4.5 and RCP 8.5 emission scenarios. All the GCM outputs are brought to a 185 consistent resolution of  $0.5^{\circ}$ .

186 It is now well known that large scale pattern of climate variables simulated by GCMs may be 187 realistic, but when downscaled to regional level, they may exhibit significant bias compared to 188 the observed data (Maurer and Hidalgo, 2008; Ghosh and Mujumdar, 2009). This can have 189 significant effect on hydrological impact studies which necessitates the need of performing bias 190 correction on the climate variables obtained. In the current work, climate variables obtained from 191 the GCMs are bias corrected with IMD gridded data (which is considered as observed data) at 192 daily scale using the technique developed by Wood et al., (2002). A distribution function is fit to 193 the observed daily data and individual GCM data.  $F_{GCM}(x)$  of a GCM simulation is identified for 194 a given x and the corresponding observed value x' is obtained from the observed CDF,  $F_{obs}(x')$ 195 such that  $F_{obs}(x') = F_{GCM}(x)$ . GCM value x is then replaced with the observed value x' on the 196 CDF of GCM.

197 Statistics of GCM simulated (post bias correction) and observed climate variables for upstream 198 region are presented in Taylor diagram (Fig. 2). It can be observed that all the models are 199 clustered together which could be due to the fact that all the GCM outputs are from the same 200 modelling center and, the clusters in case of  $T_{\text{max}}$  (maximum temperature) and  $T_{\text{min}}$  (minimum 201 temperature) [Fig. 2 (b) & (c) respectively] are closer to the observed data (represented by point 202 'a') which reflects a better quality of GCM outputs for T. In case of P [Fig. 2 (a)], it is observed 203 that the models' cluster is slightly far from point 'a', nevertheless, reasonably good correlation of 204 0.6-0.7 exists between GCM P and observed P. Similar inferences are drawn from the analyses 205 over midstream and downstream regions.

206 In addition to the correlation coefficient, climatology of variables for different GCMs is 207 compared with the climatology of the observed variable from 1971-2005 at monthly scale. These 208 results are presented in Fig. 3 for one of the grid cells within the UGB. The observed and GCM 209 climatology at monthly scale for time period 1971-2005 is represented following Wood et al. 210 (2002). It can be observed from Fig. 3 that the GCMs successfully reproduce the mean and 211 variance of the rainfall climatology for most of the months. However, for post-monsoon period 212 (i.e. October, November and December) GCMs overestimate the rainfall compared to the 213 observed rainfall. For  $T_{\text{max}}$  and  $T_{\text{min}}$ , (Fig. 3 B & C respectively) GCMs could successfully 214 reproduce the observed climatology across all the months. Other grids within the UGB were 215 found to demonstrate a similar pattern for both rainfall and temperature. Based on this analysis,

216 downscaled variables are considered to reasonably represent the climate of the region and are 217 further used to drive the VIC model.

In addition to the meteorological data and LU information, VIC requires explicit information about the vegetation type in the study region. In the study area, it is observed from the agricultural statistics (http://mospi.nic.in/Mospi\_New/site/India\_Statistics.aspx) that wheat is grown in abundance during the rabi season (October-March) while rice and millets are grown during the kharif season (July-October). Furthermore, sugarcane is also grown in the upstream region of the UGB. Therefore, vegetation parameters corresponding to these four crops are provided as input to the relevant grid cells within the UGB.

#### 225 **2.3 VIC Hydrologic Model:** Calibration and Validation

226 For the model calibration in the present work, three parameters as suggested by Lohmann et al., 227 (1998) are calibrated to obtain an optimum combination such that the error between observed 228 and simulated streamflow is minimum. The three parameters considered are (i) B - variable 229 infiltration curve parameter; (ii) Ds - fraction of maximum velocity of baseflow where nonlinear 230 baseflow begins; and (iii) Ws - fraction of maximum soil moisture where nonlinear baseflow 231 occurs. According to Liang et al., (1994) the parameter *B* has largest effect on runoff hydrograph 232 and Ds and Ws parameters are critical in influencing the baseflow. Calibration of these 233 parameters is necessary since their values vary with catchments. Moreover, these are the only 234 three parameters which are unknown in the present study. All the other parameters 235 (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/SoilParam.shtml) 236 are obtained from the soil map used in this study.

VIC model is established independently for upstream, midstream and downstream regions but model calibration became possible only for upstream and midstream regions since  $Q_{obs}$  is not available for the downstream region. To address this issue, utilizing the facts that the downstream region has soil type similar to that of midstream region (loam and sandy loam) and the three parameters are essentially influenced by soil, it is assumed that the calibrated parameters obtained for midstream will hold good for downstream region.

To perform model calibration, initially the sensitivity of the simulated discharge to each of the three parameters is tested and their rough estimate of range for both upstream and midstream 245 regions are obtained. Within this range, several candidate models for upstream and midstream 246 regions are created based on several plausible combinations of these three parameters. The VIC 247 model is executed for all the combinations and the one that has maximum predictive power in terms of coefficient of determination ( $R^2$ ), normalized root mean square error ( $E_{NRMSE}$ ), nash 248 249 sutcliffe efficiency ( $E_{NSE}$ ) and bias ( $\beta$ ) for monthly series of simulated streamflow ( $Q_{sim}$ ) during 250 calibration period is considered. Here, a negative value of  $\beta$  indicates that model overestimates 251 the simulated data and vice versa. It is to be noted that, though the VIC model is executed at 252 daily scale, daily  $Q_{\rm sim}$  values are aggregated to monthly values to carry out comparison between 253  $Q_{\text{sim}}$  and  $Q_{\text{n-obs}}$  since  $Q_{\text{n-obs}}$  is available only at monthly scale.

254 For the current work, periods of 1987-1999 and 1977-1995 in the upstream and midstream 255 regions respectively are considered for calibration. Figure 4 provides the plots of corresponding 256 observed and calibrated VIC simulated monthly streamflow series for the two regions. It can be 257 observed from Fig. 4 that simulations during the calibration period captured the observed pattern 258 and magnitude of hydrograph very well. In particular, rising and recession limbs of hydrographs 259 are simulated accurately for both the regions. Shortcomings in the VIC simulations for both the 260 regions include mismatch of peak flows which could be due to errors in modelling extreme 261 precipitation by the model. Since we are not dealing with extremes in the present case study, this 262 error is not of much concern. In addition, it may also be observed that at the end of each 263 recession limb, there is a sharp drop, which is below the level of  $Q_{n-obs}$ . It could be due to 264 inconsideration of baseflow contribution from the ground water in  $Q_{sim}$  which needs to be 265 included in Indian watersheds, wherein groundwater serves as major contributor to the 266 streamflow in the form of baseflow during the months of November to March. Also, in the 267 upstream region, some infrequent peaks are simulated by the model during low flow periods 268 which can be attributed to the overestimation of snow melt runoff by the snow module (which is 269 kept active) in the region. Pre and post monsoon rainfall events could also result in this kind of 270 behavior.

The calibrated models are validated from 2000-2005 and from 1996-2005 for the upstream and midstream regions respectively (presented in Fig. 5). Streamflow pattern and magnitude of runoff are well simulated during validation. Table 2 presents optimum set of parameters for the two regions along with their performance measures during calibration and validation. Based on 275 the performance measures it is seen that model is able to predict  $Q_{n-obs}$  reasonably well. Slight 276 negative  $\beta$  [which are evident from scatter plot of Fig. 4 (a)] is observed for upstream region 277 which could be due to overestimation of low flow values. Positive  $\beta$  for midstream region could 278 be due to lack of groundwater contribution to  $Q_{sim}$ . The rigorously calibrated and validated VIC 279 model is used to simulate the streamflow under different scenarios considered in the present 280 study.

#### 281 **2.4 GCM and Emission Scenario Uncertainty**

282 Despite strong correlation between the model simulated and observed climate variables (Fig. 2), 283 it is noticed that the magnitude of uncertainty across different models is quite large with respect 284 to observed P and T at annual scale. These uncertainties may get manifested in the hydrologic 285 response (Arnell, 2011) when the future projections are used to drive the VIC hydrologic model 286 for impact assessment. As a result it is essential to quantify the uncertainties associated with both 287 climate data and streamflow generated from the VIC model, which, in the present work, is 288 carried out over six GCMs and two emission scenarios. The uncertainty is quantified with Root 289 Mean Square Difference ( $\sigma$ ) metric given by Eq. (1) (Giorgi and Mearns, 2002; Ekström et al., 290 2007).

291 
$$\sigma = \left[\frac{1}{n}\sum_{i=1}^{n} (\Delta X_i - \overline{\Delta X})^2\right]^{\frac{1}{2}}$$
(1)

where, *n* is the number of GCMs for a given RCP; *X* is variable under study;  $\Delta X_i$  is the change in the *i*<sup>th</sup> model mean value from the mean of the baseline period of the variable *X*;  $\overline{\Delta X}$  is the ensemble average of change in mean given by Eq. (2)

$$295 \qquad \overline{\Delta X} = \frac{1}{n} \sum_{i=1}^{n} \Delta X_i \tag{2}$$

In the present work,  $\Delta X$  is considered as estimate of effect of climate change.  $\sigma$  quantifies the average deviation of change in individual model mean from ensemble average of change in mean. Higher the  $\sigma$ , more is the uncertainty associated with the  $\overline{\Delta X}$  and consequently less reliable are the results. Further, the ensemble mean of models is statistically analyzed with baseline period's mean to test for equality of means using two sampled t-test. The results of t-test are interpreted in terms of confidence levels for the change in future projections with respect tobaseline period.

In order to infer the confidence level in terms of climatology, classification considered by Maurer (2007) is used according to which, confidence level (i) >90% indicates a highly significant change;(ii) 67-90% indicates moderately significant change, and (iii) <67% indicates insignificant change. Furthermore, same test is used to estimate the confidence level with which it can be claimed that the two emission scenarios give statistically different ensemble means. Figure 6 presents the overview of the work.

#### 309 3 Results and Discussion

Sections 3.1 and 3.2 provide analysis pertaining to the quantification of changes observed in LU and climate. In section 3.3, these results are used to quantify streamflow variations within the uncertainty framework.

## 313 **3.1 Analysis of Land Use**

Classification of landsat imageries resulted in LU maps for the UGB which are presented in Fig. 7. It can be observed that the UGB exhibits wide variations in the LU wherein upstream parts are snow covered and downstream parts are crop land. The dominant LU type in the UGB is crop land which covers about 56% of the entire basin (45%, 53%, 64% and 66% for 1973, 1980, 2000 and 2011 respectively). Upon visual examination of figures, it is evident that from 1973 to 2011, area under forest in the upstream region has diminished significantly. Percentage of total basin area under different LU categories in the UGB for different time periods is provided in Table 3.

321 It should be noted that for the present study, detailed snow cover mapping is not performed. Thus 322 the percentage area observed under snow category in Table 3 should not be considered as a trend 323 in the snow cover of the region. Urban category is observed to occupy very less area in the basin (< 5%) across all the time periods. For dense forest area, a decline was observed from 1973 to 324 325 2000 followed by an increase. The reason could be attributed to better forest management 326 strategies that are introduced in the region after creation of Uttarakhand state in November 2000. 327 It is observed that there is slight increase in surface area of water which could be attributed to 328 development of structures such as Ramganga reservoir (Fig. 1) after 1973. Results reflect that 329 there has been a massive increase in the area under cultivation in the basin. The dynamics of LU

is heavily supported by rapid increase in population of the region (120% increase between 2001
and 2011 as per census of India, http://censusindia.gov.in/). The impact of changes in LU over
streamflow is assessed in section 3.3.1. The following section provides analysis of climate
change in the UGB.

## 334 **3.2 Analysis of Climate Variables**

335 Observed rainfall obtained from IMD and projections of rainfall (P) obtained from GCMs are 336 examined for long term trends using Mann Kendall test (Mann 1945; Kendall, 1938). It is 337 noticed that observed P did not show any trend during the period 1971-2005 for upstream, 338 midstream and downstream regions. However, projections of P exhibits a monotonic increase at 339 the annual scale during the period 2010-2099 for all the regions with large inter annual 340 variability. In order to determine the change in the climatology of the three regions, outputs from 341 GCMs for future time period are aggregated into five time slices T1 (2010-2020), T2 (2021-342 2040), T3 (2041-2060), T4 (2061-2080) and T5 (2081-2100). Further on, comparisons are made 343 between the means of the future time slices' and the baseline period (1971-2005). Figure 8 (top 344 panel) shows average change in annual P over all GCMs ("ensemble mean change") in future 345 time slices from the baseline period which is calculated using Eq. (2). Associated with the 346 ensemble mean change is uncertainty, obtained using Eq. (1), which is represented by error bars 347 in the figure. Uncertainty limits reflect the average deviation of change in the mean of individual 348 GCMs from the ensemble mean.

T2 in case of RCP 4.5 emission scenario is observed to exhibit maximum change for all the three regions along with high uncertainties. High confidence level associated with T2 imply probable impacts in hydrologic response associated with this time slice. RCP 8.5 emission scenario, for most of the time slices, exhibits moderately significant change which may result in less probable impacts.

Upon assessing the monthly variability in P, it is observed that it may decline significantly during monsoon months whereas there might be an increase during winter months (October, November, December, January) across the three regions. This may result in shift in seasonal pattern of P in the region. Furthermore, if analyzed longitudinally from upstream to downstream it is noticed that the variation in P in downstream region is much more severe. 359 On analyzing the trend in observed and projected annual mean  $T_{\rm max}$  and  $T_{\rm min}$ , it is noticed that 360 observed annual mean  $T_{\text{max}}$  did not show any trend during 1971-2005, while observed annual 361 mean  $T_{\min}$  depicted an increasing trend during the same period. However, projected annual mean  $T_{\rm max}$  and  $T_{\rm min}$ , are observed to show an increasing trend for future scenarios. Upon assessing the 362 363 monthly variability, mean  $T_{\text{max}}$  and  $T_{\text{min}}$  are observed to increase significantly during winter 364 months and they may decline during April to September in all the regions. Results corresponding 365 to ensemble change in mean annual  $T_{\text{max}}$  and  $T_{\text{min}}$  from the baseline are shown in Fig. 8, center and bottom panels respectively. Change in  $T_{\text{max}}$  and  $T_{\text{min}}$  can affect the hydrology by changing 366 367 rain to snow ratio, ET and consequently runoff (Christensen et al., 2004). Therefore, change in T 368 may affect the overall water availability in the basin. On assessing the change in T longitudinally 369 over UGB, it is observed that downstream region may experience maximum increase in the 370 annual mean  $T_{\text{max}}$  and  $T_{\text{min}}$  thus causing serious implication in this part of the UGB. Downstream 371 region, as mentioned earlier, may suffer from sporadic P along with significant increase in T, 372 resulting in severe water availability problem in this part of the UGB. This condition may prove 373 to be detrimental from agricultural point of view as this area is heavily under cultivation (86% of 374 total downstream area).

375 Upon evaluating the emission scenario based uncertainty, it is found that there is no significant 376 difference between the two scenarios RCP 4.5 and RCP 8.5 which indicates that the scenario 377 based uncertainty will be minimum. Impacts of changes in P and T on streamflow are presented 378 in section 3.3.2.

## 379 **3.3 Hydrologic Responses to Land Use and Climate Change**

380 To evaluate the effects of land use (LU) and climate change on the hydrology of the study area, 381 three scenarios are considered. The first two scenarios are based on the single factor approach (Li 382 et al., 2009), i.e., one driving factor is changed at an instant keeping the other constant. In the 383 first scenario, climate is considered invariant while LU is varied with time whereas in the second 384 scenario, LU is considered invariant while climate is varied with time. These two scenarios are 385 constructed to understand how streamflow would respond if only one of the driving forces is 386 changed with time thereby assisting in quantifying the influence of individual factors on 387 streamflow. In reality, both LU and climate change simultaneously with time and the hydrologic 388 response is generated based on their integrated effect which is addressed by the third scenario.

Finally from the integrated response, contributions of LU and climate on the streamflow variability is segregated using results from the other two scenarios. In depth analysis in the first two scenarios is carried out due to lack of detailed studies that examine the effects of LU and climate change on streamflow in the UGB.

## 393 **3.3.1 Impact of Land Use Change**

394 In order to investigate hydrological impacts of LU change, simulations are carried out keeping 395 climate fixed at 1971 while LU is changed progressively from 1971 to 2011. LU in any region changes gradually over a period of time and therefore starting and ending years may 396 397 satisfactorily represent the change that has occurred in each LU class. Considering this, LU of 398 the intermittent years can be obtained using rate of change in each LU class between the starting 399 and ending years. It is to be noted that to obtain LU information for 1971 and 1972, rate of 400 change between 1973 and 1980 is considered. LU obtained for each year is then used to drive the 401 VIC model to obtain simulations under LU effect with invariant climate. Although simulations 402 are carried out continuously from 1971 to 2011, for the sake of brevity, results corresponding to 403 the starting year (1971) and the ending year (2011) for all the three regions are presented in Fig. 404 9.

405 It can be observed from the Fig. 9 that from 1971 to 2011, there is an increase in the magnitude 406 of peak discharge for the upstream and midstream regions. This observation is consistent with 407 other studies reported in literature which state that LU change has pronounced effect on peak 408 flows due to alterations in the infiltration capacity of the surface (Fohrer et al., 2001; Naef et al., 409 2002; Tollan, 2002; McIntyre et al., 2014). No change in the discharge regime of the 410 downstream region is noticed. LU and topography of the region is observed to have a 411 conspicuous effect on the hydrologic response from the basin which is reflected in the 412 hydrograph patterns for the three regions. Rising limb of the upstream region [Fig. 9 (a)] begins 413 during April while for midstream and downstream [Fig. 9 (b) & (c) respectively] it occurs during 414 May-June. The early occurrence of rising limb in upstream region can be attributed to the 415 snowmelt runoff contribution to the streamflow. However, for midstream and downstream 416 regions, rising limb begins with the onset of monsoon. The recession limb of hydrograph for 417 upstream region falls quickly owing to the steep slope of the region. For midstream, a sharp drop 418 is observed up to a certain level during October indicating the termination of direct runoff 419 contribution to streamflow. Following this, the contribution is predominantly through baseflow 420 which in this case is observed to be higher than the baseflow before the monsoon months. The 421 higher baseflow during post monsoon period could be attributed to slow release of water stored 422 by forests (dense and scrub) in the region aided by low elevation of the terrain in the region. 423 Downstream region, though entirely a flat terrain, is dominated by crop land and urban areas that 424 lack the capacity of holding the water, therefore limiting the contribution of baseflow to 425 streamflow which leads to the observed sharp decline in recession limb. Furthermore, long term 426 impacts of LU change are more evident in annual streamflow which is observed to increase by 427 12 %, 17% and 1% from 1971 to 2011 for upstream, midstream and downstream regions 428 respectively.

429 Sensitivity of the region to different LU categories is assessed in separate simulations. In this 430 case, simulations considering each LU class are performed and change in streamflow under each 431 category is quantified. To quantify the magnitude of change in streamflow caused by change in 432 LU, ratio between streamflow and LU is computed. The ratio is referred to as Runoff-LU ratio 433 (RL) in the present study. The RL indicates the effect of 1% change in any LU category on 434 streamflow and aids in identifying the significance of a particular LU class in determining the 435 hydrologic response. Based on the ratios obtained, streamflow response (to a particular LU 436 category) is classified under three categories: (i) highly sensitive if RL is  $\geq 3$ . It indicates that a 437 change of 1% in LU category results in the change of hydrologic response by atleast three times; 438 (ii) moderately sensitive,  $(1 \le RL \le 2)$ ; and (iii) insensitive, (0 < RL < 1). Sign associated with the RL 439 indicates the direction of change.

440 It can be observed from Table 4 that in the upstream region, RL is maximum for the urban area 441 implying that the hydrologic response in this region is highly sensitive to the changes in urban 442 area. It can be inferred that 1% change in the urban area results in 4% increase in the streamflow 443 from the upstream region. The upstream region has significant portion of area under dense forest 444 that has shown minor increase in the last decade (2000 to 2011) (Table 3). The simulated 445 streamflow is observed to be moderately sensitive to this increase, though the observed impact is 446 in the opposite direction, i.e., increase in forest results in decrease in streamflow. Furthermore, 447 streamflow simulated from the upstream region is moderately sensitive to crop lands as well. 448 Midstream region has crop land as the dominant LU type covering 53% of the area during 1971

449 and 81% of the area in 2011, streamflow is observed to be moderately sensitive to it. It is also 450 observed that streamflow is moderately sensitive to urban area in this region. Though the 451 downstream region is predominantly cultivated land (approximately 85% of the area), hydrologic 452 response is observed to be moderately sensitive to changes in the urban area. High sensitivity of 453 streamflow from the regions to urban area can be attributed to the fact that increase in urban 454 sprawl could reduce the infiltration resulting in generation of higher surface runoff. In addition to 455 this, it can be observed that hydrologic response to change in forest area in the midstream and 456 downstream regions has a positive sign unlike in the upstream region, where the response has a 457 negative sign. This is due to the fact that midstream and downstream regions are dominated by 458 scrub forest, area under which has decreased over the time period, thereby increasing the 459 streamflow. Thus all the three regions of the UGB are observed to be moderately sensitive to 460 change in crop land area while moderately to highly sensitive to change in urban area.

#### 461 **3.3.2 Impact of Climate Change**

462 Streamflow observed at Bhimgodha (outlet for upstream region) and Ankinghat (outlet for the 463 midstreamregion) stations is examined for the presence of trend using Mann-Kendall test. It is 464 noticed that the observed streamflow for upstream (1987-2005) and midstream (1977-2005) regions do not show any trend. However, in order to investigate the individual impact of 465 466 changing climate on hydrology, simulations are carried out keeping LU fixed for 1971 and 467 altering climate continuously for the baseline period (1971-2005) and future emission scenarios 468 (2010-2100). The simulation results obtained are referred to as  $Q_{\text{clim}}$  hereafter. To quantify the 469 change in streamflow, the VIC model is driven using the downscaled, bias-corrected six GCM 470 outputs and the simulation results obtained are compared with the baseline simulation results. 471 Change in ensemble mean annual  $Q_{\text{clim}}$  for five future time slices from the baseline annual 472 streamflow for the three regions is presented in Fig. 10 with the associated uncertainties shown 473 as error bars.

From the Fig. 10, it can be observed that change in  $Q_{\text{clim}}$  has patterns similar to that of change in mean annual P (Fig. 8, top panel). Change in  $Q_{\text{clim}}$  for all the time slices is observed to be moderate to highly significant in most of the cases indicating probable impacts of climate change on hydrologic response of the basin. Uncertainty is observed to increase through the time slices and maximum uncertainty in projection results for all the three regions is observed in T5. 479 Although the two scenarios gave consistent results, to address the issue of scenario based 480 uncertainty, mean of ensemble annual  $Q_{clim}$  series of RCP 4.5 is compared with mean of 481 ensemble annual  $Q_{clim}$  series of RCP 8.5. The two means are found to be moderately different for 482 the midstream region, indicating the need to consider the two scenarios as separate cases.

483 Assessment of the monthly variations in the  $Q_{\text{clim}}$  across future time slices indicated that  $Q_{\text{clim}}$ 484 may decrease for JAS months for the three regions while it may increase during the months of 485 October, November and December (OND). The variations observed in  $Q_{\text{clim}}$  during JAS and 486 OND are found to be consistent with that of P. However, this is not true for all the months such 487 as June, where P is observed to decrease in future while  $Q_{\text{clim}}$  is observed to increase which can 488 be attributed to decrease in T that may reduce evaporation from the region resulting in higher 489 runoff. Similar kind of response of streamflow to P and T in a catchment is reported in literature 490 for a different case study by Fu et al. (2007). To further assess the sensitivity of  $Q_{\text{clim}}$  to changes 491 in P and T and quantify their effect, runoff ratio (RR) is computed using average annual runoff 492 and rainfall for each time slice. Results pertaining to the values of *RR* are presented in Table 5.

493 The RR is a simple index that reflects the relationship between P and  $Q_{\text{clim}}$  by determining the 494 proportion of P that gets converted to  $Q_{\text{clim}}$  (Zhang et al., 2011). RR is calculated by normalizing 495 the  $Q_{\text{clim}}$  with P within the same time scale. Analyzing RR over a period of time on the same 496 river basin (under same LU conditions) aids in understanding topographic response and effect of 497 climate on streamflow. In the present study, longitudinal variation in RR strikingly depicts the 498 catchment topography from upstream to downstream. RR is observed to be 60% for the upstream 499 region, 44% for the midstream region and 23% for the downstream region during the baseline 500 period. Upstream region is characterized by mountainous terrain and steep slopes thus most of 501 the P gets converted to  $Q_{\text{clim}}$  (high RR), whereas downstream region has very flat terrain thus 502 much of the P get evaporated or infiltrated into soil and little gets converted to  $Q_{\text{clim}}$  (low RR). 503 Analysis of *RR* over the different time slices for a particular region indicate that in general, when 504 P does not change significantly from the baseline period, increase in T results in reduced RR. 505 This is intuitive as increase in T leads to loss of water as evaporation which reduces  $Q_{\text{clim}}$  and 506 consequently lessens RR. The RR is observed to increase and approach towards baseline RR with 507 slight increase in P (irrespective of change in T). In such cases, temperature variations are seen to 508 be of less importance. In most of the cases it is observed that decrease in P results in decrease in

509 RR, but in few cases such as T4 and T5 (RCP 4.5 and RCP 8.5) for downstream region, P is 510 observed to reduce accompanied by an increase in T. In such a case, one might expect RR to 511 reduce significantly which is not observed. This anomaly could be attributed to occurrence of 512 short duration dense rainfall events in the region. Reduction in *RR* is observed in case when *P* is 513 observed to increase with no significant change in T. This kind of behavior could be due to shift 514 in seasonal pattern of P or due to increased inter-arrival time between the two P events. In 515 summary,  $Q_{\text{clim}}$  from the downstream region is observed to be very sensitive to the changes in P 516 whereas  $Q_{\text{clim}}$  is sensitive to P up to a certain threshold for midstream region, beyond which  $T_{\text{max}}$ 517 also starts playing a role. Owing to the complex topography and climatology of the upstream 518 region, it is difficult to interpret the sensitivity of  $Q_{\text{clim}}$  to different climate factors.

## 519 **3.3.3 Integrated Impacts of Land Use and Climate Change**

520 In a real world situation, change in LU and climate occurs simultaneously and the impact of both 521 these factors is reflected in the streamflow. To carry out analysis pertaining to this scenario, one 522 needs concurrent information on LU and climate. Under this notion, VIC model is driven for 523 1971-2005 (baseline period) across the three region in the UGB. It is to be noted that the process 524 of obtaining projections of future LU conditions in the basin does not come under the purview of 525 present work. Therefore, integrated impact of LU and climate change on future streamflow could 526 not be assessed. The results obtained from this analysis can be interpreted as the streamflow 527 simulations under simultaneous change in LU and climate conditions (hereafter referred to as 528  $Q_{\rm int}$ ). In order to assess decadal variations in streamflow of the UGB, baseline period is 529 aggregated to four time periods: P1 (1971-1980); P2 (1981-1990); P3 (1991-2000) and P4 (2001-530 2005), although, VIC model is executed for the entire duration. Results corresponding to  $Q_{int}$  for 531 upstream, midstream and downstream regions are presented in Table 6. It is observed that no 532 clear inference about the implication of LU and climate on streamflow can be achieved from the 533 obtained  $Q_{int}$  values due to large variability in the streamflow corresponding to the variability in 534 rainfall. Therefore a further analysis is necessary to isolate the impacts of LU and climate on 535 streamflow response which is presented in the following sub-section.

## 536 **3.3.4 Isolating the Impacts of Land Use and Climate**

537 In order to segregate the impacts of LU and climate, the proposed approach primarily requires 538 results of  $Q_{int}$  (obtained from the section 3.3.3), and  $Q_{clim}$  (obtained from the section 3.3.2) over

- the same time period. Herein  $Q_{int}$  and  $Q_{clim}$  are comparable based on the fact that the respective simulations are obtained under identical conditions of hydrologic model and climatology. This condition reflects that the only changing subject among the two scenarios is the land use input to the hydrologic model. Therefore, the residue of the two scenarios,  $Q_{int} - Q_{clim}$ , is considered to be the exclusive contribution of LU to streamflow (hereafter referred to as  $Q_{LU}$ ). To segregate the contribution of LU and climate from  $Q_{int}$ , a linear response of LU and climate to the streamflow is assumed.
- 546 In the present case study, simulations of  $Q_{int}$  and  $Q_{clim}$  are obtained for the time periods P1, P2, 547 P3 and P4 mentioned earlier for upstream, midstream and downstream regions.  $Q_{int}$  and  $Q_{clim}$  are
- 548 then used to estimate  $Q_{LU}$ . Alongside, the percentage contributions of LU and climate to  $Q_{int}$  are

stand also computed (
$$Q_{c \lim (LU)}$$
 (%) =  $\frac{Q_{c \lim (LU)}}{Q_{int}} \times 100$ ). Table 6 presents results pertaining to these.

550 Results from Table 6 suggest that climate is the dominant contributor to streamflow across all the 551 regions. Contribution of LU, on the other hand, is observed to be minimal. Further insight to the 552 influence of LU to streamflow is obtained from the inferences drawn from section 3.3.1. It is 553 observed from the analysis in section 3.3.1 that streamflow is highly sensitive to changes in 554 urban land in upstream and downstream regions while it is moderately sensitive to urban and 555 crop land areas in midstream region. The spatial extent of urban area is observed to be very less 556 in the upstream and downstream regions (less than 10%), which could have resulted in negligible 557 contribution of LU to streamflow. For the midstream region, despite ~70% of the area is under 558 crop land, contribution of LU to streamflow turned out to be less. This could be due to moderate 559 sensitivity of streamflow to the changes in crop land category. It is well understood that crop 560 lands contribute more to the ET than to the streamflow. Contribution of urban area to streamflow 561 is negligible due to its less spatial extent in the midstream region. When  $Q_{LU}$  (%) is assessed 562 across the time periods in the three regions, it is observed that there is gradual increase in the 563 contribution of LU to streamflow. This could be attributed to the fact that area under the 564 sensitive LU categories (urban area and crop land) is increasing with time in the regions.

565 Contribution of LU and climate on the streamflow response is isolated at the monthly scale as 566 well. It is observed that climate is major contributor to the streamflow across all the three regions 567 at monthly scale as well (Pl. see the attached supplement). 568 In the present study, the application of proposed methodology of isolating the hydrologic impacts 569 of LU and climate is limited only to the baseline period due to unavailability of future LU 570 information. However, this approach can be applied to the future time periods as well upon 571 obtaining future LU projections along with climate simulations. This is illustrated by conducting 572 the analysis on T1 (2010-2020) wherein  $Q_{int}$  is obtained by driving VIC model under LU 573 condition of 2011 (assuming that LU may not change significantly during this decade) and 574 climate simulations from six GCMs for the corresponding time period. Results for the T1 are 575 presented in Table 7.

576 From Table 7, it can be observed that the contribution of LU to streamflow from upstream region 577 has increased (compared to P4). This could be attributed to increase in area under urban land by 578 65% in T1 from P4 in the upstream region. No significant increase is observed in crop land and 579 urban land areas in T1 from P4 for midstream and downstream regions respectively (2% increase 580 in crop land in midstream region and 20% increase in urban area in downstream region) which 581 could have resulted in unvarying contribution of LU to streamflow from P4 (Table 6) to T1 582 (Table 7) in these regions.

583 From the analysis, it can be concluded that the proposed approach can be applied over a 584 catchment with a well calibrated and validated hydrologic model. Future work involves 585 generating LU projections for future time periods which can be corroborated with climate 586 projections described in section 3.3.2 to isolate the impacts of LU and climate on future 587 streamflow simulations. Although there is presence of snow covered region in the basin, 588 segregating the contribution of snow melt runoff from the total streamflow is not feasible at this 589 stage due to lack of observed data. This limits the assessment of impact of temperature changes 590 on snow melt and its consequences on the streamflow.

#### 591 **4** Conclusions

In the present paper a hydrologic modelling based methodology is presented to isolate the impacts of LU and climate on streamflow in a river basin. To achieve this, three objectives are considered (i) assessing the sensitivity of the streamflow to the changes in LU (ii) examining the impact of change in climate on the streamflow and (iii) integrated impact of LU and climate change on the streamflow of the UGB. These three objectives are translated to three scenarios and are used to segregate the influence of LU and climate change on the streamflow. Not many 598 studies conducted earlier have considered the combined effect of LU and climate on the 599 hydrology of the basin. The VIC hydrologic model is used to understand the impact of LU and 600 climate change on the streamflow. The VIC model, owing to its comprehensive ability to 601 simulate hydrological processes, has been used widely to perform impact assessment studies. 602 However, being a physically based distributed model, there are concerns associated with the 603 model structure and the number of calibration parameters. Furthermore, due to spatio-temporal 604 variability in the input variables, parameter set for the initial or reference time period may not be 605 suitable for future period (Viney et al., 2009). In the present study, these issues of concerns are 606 partially addressed by calibrating and validating the VIC model over the upstream, midstream 607 and downstream regions of the UGB.

LU change analysis of the study region indicated an increase in the areas of crop and urban land 608 609 categories to which streamflow is observed to be moderately to highly sensitive. From the 610 climate change analysis it is observed that rainfall may decrease during the monsoon months and 611 increase during the winter months which may result in shift in seasonal rainfall pattern. Annual 612 means of  $T_{\text{max}}$  and  $T_{\text{min}}$  are observed to increase in the future. Streamflow is observed to 613 reproduce the variations in rainfall. All the changes in rainfall,  $T_{\text{max}}$  and  $T_{\text{min}}$  pertaining to climate 614 change scenario are found to be statistically significant from the baseline period, indicating that 615 deviation in their magnitudes is likely to cause serious impacts on the hydrologic response. It 616 may be noted that the meteorological variables from only six GCMs are used for the analysis, 617 which is a limitation of the study. There is a need to consider more GCMs to address the issue of 618 model and scenario based uncertainty more comprehensively.

The integrated effect of LU and climate change on streamflow is observed to be more prominent in the study area. From the analysis of isolating the individual impacts of LU and climate from their integrative effects on streamflow, it is observed that climate contributes more to the simulated streamflow (>90%). In contrast, LU did not contribute significantly to the simulated streamflow which could be attributed to less spatial extent of sensitive LU categories in the region.

The proposed approach is generic and applicable to any river basin to isolate the relative impactsof LU and climate change on streamflow. However, the approach is based on the assumption of

627 linear response of LU and climate to the streamflow. The case study analysis indicates that the 628 change in climate may become a major concern in the UGB for water resources management.

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Table 1. GCMs from the CORDEX project used in the present study

Experiment Name (Abbreviation)	
Commonwealth ACCESS1.0 (ACC) CSIRO	
Scientific and CNRM-CM5 (CNR) Centre National de Recherches Meteore	ologiques
Industrial Research CCSM4 (CCS) National Center for Atmospheric Resea	arch
Organization, GFDL-CM3 (GFD) Geophysical Fluid Dynamics Laborator	ory
(CSIRO) Australia MPI-ESM-LR (MPI) Max Planck Institute for Meteorology (	(MPI-M)
CCAM NorESM1-M (NOR) Norwegian Climate Centre	

Regio n	No. of	Value of	Calibration				Validation			
	candidate models	optimum set of parameters	$R^2$	E <sub>NRMSE</sub>	$E_{NSE}$	β	$R^2$	E <sub>NRMSE</sub>	$E_{NSE}$	β
Upstre am	47	B=0.13; Ds=0.0005;Ws =0.76	0.77	0.23	0.77	-0.02	0.83	0.29	0.79	-0.18
Midstr eam	80	<i>B</i> =0.044; <i>Ds</i> =0.0004; <i>Ws</i> =0.62	0.88	0.14	0.86	0.12	0.71	0.47	0.53	-0.04

Table 2. Structure of VIC model obtained for the upstream and midstream region along with the
 performance measures during calibration and validation phase

	Area (% of total area of 95,593 km <sup>2</sup> )					
Category	1973	1980	2000	2011		
Snow	9.5	10.4	6.5	5.5		
Dense Forest	14.5	12.8	11.4	14.8		
Scrub Forest	23.6	14.8	13.9	9.0		
Crop Land	45.1	53.2	64.3	66.2		
Barren Land	5.0	6.4	0.6	0.2		
Urban Area	1.5	1.6	2.3	3.2		
Water	0.7	0.9	1.0	1.1		

Table 3. LU analysis of UGB for years 1973, 1980, 2000 and 2011

LU classes Region Crop Land Forest Urban Barren Upstream 2.05 4.02 -1.31 0.91 1.49 0.1 0.97 0.93 Midstream 1.17 2.69 0.63 0.9 Downstream

Table 4. Runoff-LU ratio for different LU categories for upstream, midstream and downstream
 regions

(10111	Time	Rainfal	l (mm)	Runof	f (mm)	Runoff Ratio		
Region	Period	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	
	Baseline	1294	1294	772	772	0.60	0.60	
	T1	1196+172	1210+46	697+84	683+32	0.58	0.56	
		(-8)	(-7)	(-10)	(-12)	(-2)	(-4)	
	Т2	1084±480	1257±43	619±287	715±30	0.57	0.57	
		(-16)	(-3)	(-20)	(-7)	(-3)	(-3)	
Upstream	T3	1377±171	1323±32	816±137	771±26	0.59	0.58	
-		(+6)	(+2)	(+6)	(0)	(-1)	(-2)	
	T4	1416±198	1357±42	845±163	800±38	0.60	0.59	
		(+9)	(+5)	(+9)	(+4)	(0)	(-1)	
	T5	$1424 \pm 182$	$1405 \pm 27$	$854 \pm 148$	842±26	0.60	0.60	
		(+10)	(+9)	(+11)	(+9)	(0)	(0)	
	Baseline	1009	1009	441	441	0.44	0.44	
	T1	$844 \pm 84$	871±63	323±31	328±56	0.38	0.38	
		(-16)	(-14)	(-27)	(-25)	(-12)	(-4)	
	T2	787±265	884±53	296±115	332±52	0.38	0.38	
		(-22)	(-12)	(-33)	(-25)	(-12)	(-12)	
Midstream	T3	1003±135	952±31	413±77	378±20	0.41	0.40	
		(-1)	(-6)	(-6)	(-14)	(-3)	(-4)	
	T4	1062±159	1016±28	462±101	427±23	0.44	0.42	
		(+5)	(+1)	(+5)	(-3)	(0)	(-2)	
	T5	$1071 \pm 160$	$1058 \pm 21$	471±121	452±21	0.44	0.43	
		(+6)	(+5)	(+7)	(+3)	(0)	(-1)	
	Baseline	826	826	192	192	0.23	0.23	
	T1	579±63	590±55	102±13	107±19	0.18	0.18	
		(-30)	(-29)	(-47)	(-44)	(-5)	(-5)	
Downstream	T2	557±183	$589 \pm 40$	89±43	104±13	0.16	0.18	
		(-32)	(-29)	(-54)	(-46)	(-7)	(-5)	
	Т3	721±108	663±38	141±34	127±13	0.20	0.19	
		(-13)	(-20)	(-27)	(-34)	(-3)	(-4)	
	T4	743±128	731±23	150±46	$148 \pm 7$	0.20	0.20	
		(-10)	(-11)	(-22)	(-23)	(-3)	(-3)	
	T5	785±101	771±37	173±36	167±16	0.22	0.21	
		(-5)	(-6)	(-10)	(-13)	(-1)	(-2)	

**Table 5.** Runoff Ratio across time slices for upstream, midstream and downstream regions (terms in parentheses indicate the percent change from the baseline values)

		D1 $D2$ $D2$ $D2$ $D2$				
Region	Streamflow	(1971-1980)	1981-1990)	(1991-2000)	(2001-2005)	
	$Q_{\rm int} ({ m m}^3{ m s}^{-1})$	775	772	859	823	
	$Q_{\rm clim}$ (m <sup>3</sup> s <sup>-1</sup> )	760	741	824	777	
Upstream	$Q_{ m clim}$ (%)	98	96	96	94	
	$Q_{\rm LU} ({ m m}^3{ m s}^{-1})$	15	31	35	46	
	$Q_{ m LU}(\%)$	2	4	4	6	
	$Q_{\rm int}$ (m <sup>3</sup> s <sup>-1</sup> )	1130	1183	1266	1195	
	$Q_{\rm clim}({ m m}^3{ m s}^{-1})$	1108	1110	1182	1107	
Midstream	$Q_{ m clim}$ (%)	98	94	93	93	
	$Q_{\rm LU} ({ m m}^3{ m s}^{-1})$	22	73	84	88	
	$Q_{ m LU}(\%)$	2	6	7	7	
	$Q_{\rm int}$ (m <sup>3</sup> s <sup>-1</sup> )	123	103	85	78	
Downstream	$Q_{\rm clim}({\rm m}^3{\rm s}^{-1})$	122	103	85	77	
	$Q_{ m clim}$ (%)	100	100	99	98	
	$Q_{\rm LU} ({\rm m}^3{\rm s}^{-1})$	1	0	1	1	
	$Q_{ m LU}(\%)$	0	0	1	2	

**Table 6.** Contribution of climate and LU to the streamflow for different time periods

Upstream Midstream Downstream Streamflow RCP 4.5 **RCP8.5** RCP 4.5 **RCP8.5** RCP 4.5 RCP8.5  $Q_{\rm int} \,({\rm m}^3{\rm s}^{-1})$ 56±11  $800 \pm 72$ 789±28 1008±110 971±138  $52\pm5$  $Q_{\rm clim}$  (m<sup>3</sup>s<sup>-1</sup>) 703±23  $938{\pm}132$ 903±123  $51\pm5$  $713\pm62$  $55\pm11$  $Q_{\text{clim}}(\%)$ 89 89 93 93 98 98  $Q_{LU}(m^3 s^{-1})$  $87 \pm 10$  $86\pm5$  $70\pm23$  $68 \pm 16$  $1\pm0$  $1\pm0$  $Q_{\rm LU}(\%)$ 11 11 7 7 2 2

Table 7. Contribution of LU and climate to streamflow during T1 (2010-2020) time slice under
 RCP 4.5 and RCP 8.5 emission scenarios



Figure 1. Location map and details of the UGB



Figure 2. Taylor diagram for (a) Rainfall (mm) (b)  $T_{max}$  (°C) and (c)  $T_{min}$  (°C) for upstream region



Figure 3.GCMs climatology compared with observed climatology for monthly (A) rainfall, (B)
 maximum temperature and (C) minimum temperature from 1971-2005 (represented from
 January-December as i-xii)



Figure 4. Calibration results of (a) Upstream and (b) Midstream region













Figure 8. Change in the ensemble mean of rainfall (top panel), T<sub>max</sub> (center panel) and T<sub>min</sub>
(bottom panel) from the baseline period for RCP 4.5 (first bar of a time slice) and RCP 8.5
scenarios (second bar of a time slice) at each time slice (T1: 2010-2020; T2:2021-2040; T3: 2041-2060; T4: 2061-2080 and T5: 2081-2100)





Figure 10. Change in ensemble mean of  $Q_{clim}$  from the baseline period for RCR 4.5 (first bar of every time slice of all the plots) and RCP 8.5 (second bar of every time slice of all the plots) scenarios at each time slice (T1: 2010-2020; T2:2021-2040; T3: 2041-2060; T4: 2061-2080 and T5: 2081-2100)