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Impact of human intervention and climate change on natural flow regime

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Abstract

According to the 'natural flow paradigm', any departure from the natural flow condition will alter the river ecosystem. River flow regimes have been modified by anthropogenic interventions and climate change is further expected to affect the biotic interactions and the distribution of stream biota by altering streamflow. This study aims to evaluate the hydrologic alteration caused by dam construction and climatic changes in a mesoscale river basin, which is prone to both droughts and monsoonal floods. To analyse the natural flow regime, 15 years of observed streamflow (1950-1965) prior to dam construction is used. Future flow regime is simulated by a calibrated hydrological model Soil and Water Assessment Tool (SWAT), using ensemble of four high resolution (~25 km) Regional Climate Model (RCM) simulations for the near future (2021-2050) based on the SRES A1B scenario. Finally, to quantify the hydrological alterations of different flow characteristics, the Indicators of Hydrological Alteration (IHA) program based on the Range of Variability Approach (RVA) is used. This approach enables the assessment of ecologically sensitive streamflow parameters for the pre- and post-impact periods in the regions where availability of long-term ecological data is a limiting factor. Results indicate that flow variability has been significantly reduced due to dam construction with high flows being absorbed and pre-monsoon low flows being enhanced by the reservoir. Climate change alone may reduce high peak flows while a combination of dam and climate change may significantly reduce variability by affecting both high and low flows, thereby further disrupting the functioning of riverine ecosystems. We find that, in the Kangsabati River basin, influence of dam is greater than that of the climate change, thereby emphasizing the significance of direct human intervention.

Keywords: Anthropogenic impact, climate change, flow alteration, IHA, RCM, SWAT

1 Introduction

Flow regime alteration of important seasonal flow components, such as high flows and low flows, by anthropogenic activities, especially large dams, has generated immense scientific interest with regards to implications for riverine ecosystems, biodiversity conservation and invasion by non-native species (Bunn and Arthington, 2002; Lytle and Poff, 2004; Meijer et al. 2014). Degradation of ecological health is now associated with the downstream section of dams (Poff and Zimmermann 2010; Suen 2011). Carlisle et al. (2010) reported that across regions and anthropogenic conditions, biological impairment is directly related to the magnitude of streamflow reduction. Moreover, regulation of river flow and alteration of flood and drought timing is expected to favour species that spawn during certain times (Freeman et al. 2001).

Along with direct anthropogenic impacts, human-induced climate change is also expected to affect the hydrologic cycles and thereby alter natural flow characteristics. Increasing temperatures will directly increase evaporation and alter plant transpiration rates, thereby reducing runoff (Bates et al. 2008). Doll and Zhang (2010) have shown that by mid-21st century, climate change effect on flow regimes may be greater than that caused by dams and water withdrawals. Global analysis of potential changes in runoff regimes shows that by the year 2050, most regions will experience significant changes in hydrological regime (Arnell and Gosling 2013). Changes brought about by climate change will interact with existing anthropogenic factors and thus cause additional stress to riverine ecosystems (Fung et al. 2013; Ravazzani et al. 2015).

Much needed interaction between scientists from hydrological, ecological and geomorphological foci over the past 20 years has increased our understanding of riverine dynamics, which is an essential prerequisite for gauging future implications of human actions. Such studies typically require long-term monitoring and assessment of baseline conditions to benchmark the effect of changes (Wagener et al. 2010). However, increasingly, resources for developing such quantitative understanding and data are declining (Mishra and Coulibaly 2009). Shifting baseline conditions due to human intervention has added to the existing issue of insufficient ecological information (Wagener et al. 2010). Historically, insufficient resources for regular survey and assessment of ecological conditions of riverine systems have been a significant limitation for carrying out change detection studies in developing countries.

In this study of the Kangsabati River basin, we address two important research gaps related to natural flow regime alteration; (i) effect of anthropogenic activity (damming) and future climate change for a mesoscale river basin with a strong monsoonal influence on hydrology and (ii) usage of sparse and scattered ecological data to derive inferences regarding potential impacts of damming and climate change on riverine ecosystem. We quantify observed alterations in the flow regime due to damming and then model the ramifications of climate change using the conventional ‘top-down’ hydrological modelling approach forced by (Regional Climate Model) RCM simulations for the mid-21st century period. The study approach makes three novel contributions to the existing body of knowledge.

- Few gauging stations in the developing world have long-term and accessible observed discharge data which can be used for determining impact of a dam constructed 50 years ago. This study is valuable because it extends our understanding of observed changes in river flow regime in a developing country context.
- A methodological innovation in the modelling approach is that we examine the potential impact of climate change alone by isolating the climate change signal. We also compare potential future climate change impacts with combined impact of dam and climate change.
- For a mesoscale river basin, GCM outputs are not useful because they do not provide the necessary spatial variability, which RCM simulations provide. The four RCM simulations used here represent the most comprehensive set of high resolution future climate simulations available for this region, which make them useful for assessing potential scenarios of future climate change impact on the river flow regime.

1.1 Description of the study area

The Kangsabati River (basin area: 5,796 km^2) originates in the Chotanagpur plateau of central India, flows in a southeasterly direction to merge with the Ganges River in India, as its last contributing river (Figure 1). Upper reaches have hardpan sub-surface geology while the middle reaches consist of transitional undulating terrain, which levels out into the alluvial plains of the lower reaches. The geology of this lateritic region and the excessively drained topography cause high monsoon runoff coupled with low flow conditions during the dry months. Therefore, despite a high average annual rainfall (western part, 1300 mm and eastern part, 1600 mm), the basin has been traditionally considered drought prone due to low water holding capacity of the lateritic soil, high summer temperatures and high evapotranspiration rates (Mishra and Desai, 2005; Saxena, 2012).

The Kangsabati reservoir is located at the confluence of the Kangsabati River and a major tributary, Kumari. A dam constructed in 1965 on the Kangsabati River was followed by a second connected dam over Kumari River in 1973. In the intermediate period, partial regulation of the total flow took place. Since 1974 inflow to the Kangsabati reservoir comprises of the combined streamflow of Kangsabati and Kumari sub-basins. The diverted water is primarily used for irrigation in the reservoir command, the area of which is approximately 5,568 km^2. The dam also provides flood water storage to mitigate the flooding problems in the lower reaches. High water demand in the command area has also led to over-exploitation of groundwater resources and consequently affected the river flow.

Figure 1

This river sustains the natural ecosystems which provides locals with their staple food; fish. It also has the most diverse macrophytic riverine vegetation in the region with up to 80 species found across the pre-monsoon, monsoon and post-monsoon seasons (Pradhan et al. 2005). Most siluroid fishes in the region are commercially important and the lower reaches of the Kangsabati River possess the greatest variety of fishes in the region. However, these fishes are highly vulnerable to environmental degradation, particularly habitat destruction (Giri et al. 2008). The studies performed in this region, being sporadic and short term, do not allow for a coherent long-term ecosystem analysis of river discharge and ecological health.

Figure 2 presents the observed discharge at Mohanpur gauging station for the period 1950-2010, where the 1950-1965 represents the natural flow regime, 1965-1973 represents partial effect of dam, while dam altered flow regime prevails from 1974-2010. Barring the 1978 floods, the dam has effectively kept peak flood levels below the 4000 m^3/s mark. The dampening effect of the dam is also clearly visible with larger bases of the flood peaks after 1985. Beyond existing anthropogenic interventions, impending climate change is expected to alter the hydrological characteristics of the region by reducing the frequency of extreme precipitation events and lengthening dry spells (Mittal et al. 2013).

Figure 2

1.2 Study design

Assessment of ecologically important natural flow regime characteristics necessitates long-term data, especially for the period prior to the onset of an impact event or change. The gauging station at Mohanpur, about 80 km downstream of the reservoir has pre-dam discharge data for the period 1950-1965, which may be considered enough for a bias-free and appropriate assessment (Kennard et al. 2010). After the intermediate period of 9 years (1966-1973), where the influence of damming is partial and therefore difficult to understand in terms of impact, a total of 37 years of post-dam discharge information is available (1974-2010). This constitutes the observed data and forms the basis for the pre- and post-dam analysis at Mohanpur. Variability in regulated rivers is highly influenced by water use, while climatic forcing at different time scales also brings about hydrological changes. Therefore, it is crucial to separate flow regime changes caused by climate change from dam effects, so that a better knowledge of ecosystem impacts and potential restoration may be developed (Zolezzi et al. 2009). Based on this understanding, analysis of impact of dam and climate change on streamflow has been carried out in three parts; (i) effect of dam (ii) impact of future climate change (climate change signal) and (iii) impact of both dam and climate change in the future. Hydrologic alteration of biologically relevant flow regimes expected to be caused by dam construction and climate change are assessed using Indicators of Hydrologic Alteration (IHA) (The Nature Conservancy 2009).

2. Methods and Data

2.1 SWAT hydrologic model

SWAT 2009 (Neitsch et al. 2009) is used to simulate river discharges for observed and future period. SWAT typically operates on a daily time step and accounts for spatial heterogeneities of soil, land cover and elevation, by subdividing basin into multiple hydrological response units (HRUs). The rainfall-runoff model simulates the discharge from each sub basin and routes the streamflow to the watershed outlet (Neitsch et al. 2009). Preprocessing and model setup were performed using the Arc-SWAT extension for ArcGIS 9.3. The Sequential Uncertainty Fitting algorithm (SUFI-2) (Abbaspour et al. 2007) is used to calibrate SWAT and quantifies uncertainty using *P* factor and *R* factor statistics. The *P* factor, which varies from 0 to 1, represents the fraction of observed discharge which falls within the 95PPU band, while the *R* factor is derived by taking the ratio of the average width of the 95PPU and the standard deviation of the observed discharge. While a value of less than 1 is considered desirable for *R* factor, the ideal value for *P* factor is 1 (100% values within the band) (Vaghefi et al. 2013). 95PPU is 95 Percent Prediction Uncertainty, calculated at the 2.5% and 97.5% levels of an output variable, disallowing 5% of the bad simulations. Three evaluation criteria are used to assess model performance: Percent bias (PBIAS), Nash-Sutcliffe efficiency (NSE) and coefficient of determination (R^2). PBIAS, NSE and R^2 describe the goodness-of-fit between simulated and observed flow; and the model simulation would be considered satisfactory when PBIAS values are < 25% and best when their values approach one in case of NSE and R^2 (Moriasi et al. 2007).

2.2 Assessment of hydrologic alteration

IHA methodology based on Range of Variability Approach (RVA) is applied to assess the degree of departure from natural flow regime that has already occurred due to dam construction and is expected in the future due to climate change (Richter et al. 1997). RVA is the most widely used approach for quantifying hydrologic alterations in order to set appropriate environmental flow targets (Zolezzi et al. 2009). To analyse the degree of hydrologic alteration in ecologically relevant statistics, a subset of indices is used, as there exists redundancy among the indices representing different flow components (Olden and Poff 2003).

For RVA analysis, the pre-impact streamflow data is divided into three different categories; values upto 33rd percentile (lower category), 34th to 67th percentile (middle category) and values greater than 67th percentile (high category). A Hydrologic Alteration factor is calculated for each of the three categories as: (observed frequency – expected frequency) / expected frequency. A positive Hydrologic Alteration (HA) value indicates an increase in frequency of values in the category while negative indicates a reduction. In the absence of specific ecological information, the range between the 34th and the 67th percentile, i.e. the middle category is identified as the targeted range of variability for the post-impact period.

2.3 Observed input data

SWAT model required input for topography, soil and land use/land cover which are compiled from Global Land Cover Facility (GLCF) website, National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), unsupervised classification of digital remote sensing images of LandSat 5 Thematic Mapper (TM) for year 1990 (dated 07/11/1990 and 21/11/1990) and Landsat 7 Enhanced Thematic Mapper (ETM+) for year 2001 (dated 26/10/2001 and 02/11/2001) respectively. Observed climate data including precipitation, maximum air temperature and minimum air temperature from 1991 to 2010 for five weather stations (Figure 1) are gathered from India Meteorological Department (IMD) and Agro-Meteorology Department, Government of West Bengal. Observed discharge data from river gauging stations, Simulia, Tusuma, Rangagora, Kharidwar and Mohanpur are collected from the Central Water Commission (CWC) and Irrigation and Water Ways Department (IWWD), Government of West Bengal. The Kangsabati reservoir is included with reservoir operational information starting from 1974, when the second phase of Kangsabati dam completed. Reservoir management information includes measured monthly outflow to calculate reservoir outflow, reservoir surface area when reservoir is filled to emergency (12498 ha) and principal spillway (11101 ha), volume of water needed to fill the reservoir to the emergency (123500 m^3) and principal spillway (98186 m^3).

2.4. Future climate data

Daily precipitation, maximum and minimum temperature from four RCM simulations and their ensemble mean are used to drive calibrated SWAT. The historical (control) simulations for the period 1970-1999 and A1B SRES emission scenario based future climate simulations for the period 2021-2050 from four RCM simulations, REMO-ECHAM5, REMO-HadCM3, HadRM3-ECHAM5 and HadRM3-HadCM3; are obtained by the forcing from two CMIP3 GCMs namely ECHAM5-MPIOM and HadCM3 and two RCMs; REMO and HadRM3. The performance of these RCMs for the Kangsabati basin has been validated by comparing 20 year model simulations for the period 1989–2008, driven by lateral boundary forcings from ERAInterim reanalysis data (Simmons et al. 2007), with the observational datasets; Climate Research Unit (CRU) for temperature and Asian Precipitation Highly Resolved Observational Data (APHRODITE) for precipitation. Both the RCMs have demonstrated an adequate ability to capture the seasonal characteristics and interannual variability (IAV) of temperature and precipitation (Mittal et al. 2013). The ensemble mean of four RCM simulations are used to simulate future streamflow, due to which the use of bias correction is considered unnecessary (Maurer and Pierce 2014). The use of ensemble reduces the uncertainties in climate projection and provides more quantitative information for subsequent hydrologic impacts research (Jung et al. 2012).

3. Results and Discussion

3.1 SWAT model parameter sensitivity analysis

SWAT model was calibrated for the Kangsabati river basin using monthly observed streamflow at the five gauging station, during for the period 1991 to 2000. Due to the unavailability of observed weather data for the pre-dam period from 1950 to 1965, SWAT calibration was carried out using the post-dam period data. Initially, wide but meaningful ranges are assigned to sensitive parameters and with further simulations final ranges of model parameters were determined. The parameters with highest sensitivity are used to calibrate and validate the model. Table 1 shows the sensitive parameters included in the final calibration, their initial ranges, initial and final values and their t and p values. Eleven parameters representing the surface runoff, groundwater and soil properties are found to be sensitive in the estimation of streamflow. t-statistics provides a measure of sensitivity (larger in absolute values are more sensitive) and p-values determined the significance of the sensitivity with a values close to zero having more significance. Having high t-statistics and low p-value; Curve Number (CN2), alpha baseflow (ALPHA BF) and groundwater delay (GW DELAY) parameters are found to be the most sensitive to streamflow.

Table 1

3.2 SWAT model calibration, validation and uncertainty analysis

The statistical comparison between observed and SWAT simulated streamflow at different gauging stations during calibration period from 1991 to 2000 shows PBIAS values ranging from -12.4 to 7.9%, higher values of R^2 (ranging from 0.66–0.87) and NSE (ranging from 0.63–0.74) for all the gauging stations (Table 2). This suggests that model simulation can be judged as satisfactory as PBIAS values range between the ± 25% limits, R^2 is greater than 0.6 and NSE is greater than 0.5 (Moriasi et al. 2007), although NSE values for Simulia and Kharidwar are below

0.65, considered to be an acceptable value (Ritter et al. 2013). The *P* factor indicates that for all stations, more than 72% of the data are bracketed in the prediction uncertainty of the model, whereas the *R* factors are mostly around 1 except Mohanpur gauging station where the *P* factor is 40% and *R* factor is 0.59.

For validation for the period 2001 to 2010, PBIAS, R^2 and NSE validation values ranges from -4.8 to 11.8%, 0.66 to 0.85 and 0.53 to 0.76 respectively, indicating a good relationship between observed and simulated streamflow values except for Simulia, Kharidwar and Mohanpur station with low NSE values of 0.53, 0.64 and 0.49 which are unsatisfactory according to Ritter et al. (2013). The *P* factor indicates that for all stations, more than 62% of the data are bracketed in the prediction uncertainty of the model, whereas the *R* factors are mostly around or below 1 except Tusuma gauging station where the *R* factor is 0.65. In general, in the downstream of Kangsabati dam, the model prediction has larger uncertainties. Poor calibration and validation results in case of managed streamflow have also been observed before (Faramarzi et al. 2010; Vaghefi et al. 2013).

Table 2

3.3 SWAT model simulation

The calibrated model is used to simulate streamflow for two time periods, 1970-1999 (control) and 2021-2050 (future), based on ensemble mean of four RCM simulations for the SRES A1B scenario. To analyse the impact of climate change and the combined effect of dam and climate change, two separate simulations are carried out.

Simulation 1 (impact of climate change) - SWAT model streamflow simulations for these control period simulations without the inclusion of the Kangsabati dam represent the natural flow regime of the basin. Comparison of this flow regime with SWAT simulated flow regime for the future period (2021-2050) is used to isolate the impact of climate change.

Simulation 2 (impact of dam and climate change) - SWAT model is run for the future period (2021-2050) based on the RCM simulations and their ensemble. Kangsabati dam is included in this simulation to analyse the streamflow conditions due to both, dam and climate change. Comparison of future period simulations with observed streamflow for pre-dam period (natural flow regime - 1950-1965) is used to assess the combined impact of dam and climate change on the natural flow regime.

3.4 Impact of dam on flow regime

The primary function of the Kangsabati dam is to divert water for irrigation and to mitigate the impacts of monsoon floods. The IHA based analysis is described from the perspective of pre-monsoon, monsoon and post-monsoon periods. Seasonal variations in flow of the river after dam construction are much relevant to the physiological and life cycle stages of various freshwater fishes. In this case, *Bagarius bagarius*, the largest freshwater migratory siluroid fish (catfish), which is abundantly present in rivers flowing through West Bengal, is found to be absent in the downstream section of the Kangsabati dam ((Hamilton, 1822, Mishra and Coulibaly 2009). It is categorized threatened by the International Union for Conservation of Nature (IUCN 2013), primarily due to its decline as a result of dam construction which prevents their upstream migration for spawning (Lakra et al. 2011). The effect of Kangsabati dam on the observed flow regime is depicted in Figure 3, through monthly average flows, monthly low flows and Flow Duration Curves (FDCs) for the representative months of April (pre-monsoon), July (monsoon) and November (post-monsoon). During pre-monsoon, the middle value for monthly average and monthly low flows is higher in the post dam period, largely due to periodic dam releases during the otherwise dry period characterized by natural minimum flows. Post-impact period is also characterized by greater flow variability, with more frequent high flow events. The corresponding FDC clearly corroborates this assessment, by depicting persistent higher flow rates for more than 80% of the time period as well as significantly lower flow rates for the remaining 20% of the time. Whereas in the monsoon season, the dam dampens the monthly average and low flows by absorbing high flow pulses and maintaining a more consistent flow rate. The FDC clearly demonstrates the overall effect, where the difference between the area under the curves for the pre-dam and post-dam periods corresponds to the amount of water diverted for irrigation purpose. Irrigation requirements for the Rabi (winter season) crop further reduce the discharge downstream of the dam during the post-monsoon month of November. A fraction of the high flows is diverted for this purpose, thereby reducing the monthly average flows.

Figure 3

3.5 Effect of climate change on flow regime

Figure 4 (a) show the effect of climate change on simulated flow regime through FDC, EFCs and hydrologic alteration graphs based on the output of SWAT "S*imulation 1*- impact of climate change" for the time period 2021-2050. The comparative analysis of FDCs in Figure 4 reveals the effect of the climate change vis-à-vis the combined effect of dam and climate change. In this case, as the FDC demonstrates, climate change reduces flows, but the area under the curve is affected to a lesser degree than for the impact of dam alone (Section 3.4).

Figure 4 (b) demonstrates the deviation factor of coefficients of dispersion (CD), which represents the change in flow variability as represented by EFCs during the mid-21st century compared to control period. Climate change causes deviation in both extreme low flow and high flow components. Deviation for high flow peak and frequency is higher (>0.6), but the deviation for extreme low flow peak, duration, timing and frequency is lower (<0.6). A slight change in the timing of high flow pulses affects the benthic siluroid fishes which are very good indicators of habitat degradation (Wootton et al. 1996). The change in flow timings affects their life cycle by disrupting various stages such as spawning, egg hatching, rearing, movement onto the floodplains for feeding and reproduction or migration upstream and downstream (Poff et al. 1997).

Figure 4 (c) shows the extent of Hydrologic Alteration (HA) in monthly flows during the mid-21st century. A high HA (>0.5) for the high and low category is projected for the monsoon months (JJAS) while rest of the months show less hydrologic alteration in both the categories. Months of May and September shows high alteration in both the middle and high category, whereas less alteration is observed in all three categories during post-monsoon (ON) and winter months (DJF). This reduction may significantly affect the connectivity with the flood plains by potentially reducing the magnitude and areal spread of floods. Such drastic changes will affect the yolk-sac-larva of threatened species of siluroid fish *Mystus gulio*, which develops in floodplain freshwater (IUCN, 2013; Termvidchakorn and Hortle, 2013). Along with decrease in the number of high flow events, reduction of high flow duration and changes in their timing will add additional physiological stress to the fish species (Sharma and Shrestha, 2001). As of now, Mishra and Coulibaly (2009) reported a decline of 27.8% in *Mystus gulio* catch across southwestern Bengal. Observed reduction may be due to a combination of stressors such as overfishing, flow alteration and habitat loss, but in the absence of biological information and temporal monitoring of stressors, the influence of individual factors cannot be determined (Sarkar and Bain, 2007).

Figure 4

3.6 Effect of dam and climate change on flow regime

The output of SWAT "simulation 2 – dam and climate change" is used to analyse the combined impact of dam and climate change on hydrologic indicators in the Kangsabati basin during the mid-21st century (2021-2050) compared to pre-dam period (1950-1965). The combined effect of dam and climatic changes, depicted in Figures 4 indicates significant reduction in the magnitude, frequency and duration of extreme high and medium flow rates in the simulated flow, whereas, a small increase in low flows is observed in comparison with sole effect of climate change.

The FDC shows how extreme high flows above 2000 m^3/s are eliminated in this scenario. The natural flow regime shows a consistent temporal distribution with ~ 75% flows lying in the range from 200 m^3/s to 10 m^3/s (Figure 4 (a)). However, in the altered future condition, this percentage reduces significantly to ~10%. Similarly, the combined effect of dam and climate change shows significantly greater alteration in EFCs compared to only climate change.

Figure 4 (b) represents the deviation factor in CD of EFCs during future (2021-2050) period in comparison with natural flow (1950-1965). In case of combined impact of dam and climate change, deviation of >0.5 is observed for CD of all extreme low flow and high flow characteristics, as compared to the individual impact of climate change. There is also a moderate increase in deviation in high flow frequency and duration due to the combined effect of dam and climate change. Significant changes in timing, frequency and duration of extreme low and high flows implies that the life cycle of many aquatic species may get disrupted during various stages such as spawning, egg hatching, rearing and their movement onto the floodplains for feeding and reproduction (Suren and Riis 2010). Benthic siluroid fishes found commonly in the Kangsabati River, which have declined since the 1960's (Mishra and Coulibaly 2009), are highly sensitive to reduction in high flows which cause habitat degradation through channel bed sedimentation (Lisle 1989).

Figure 4 (c) shows the extent of HA in monthly flows due to the combined effect of dam and climate change. Unlike previous two scenarios, individual impact of dam and climate change; high hydrologic alteration in either of high, middle or low alteration category is distributed throughout the year except for the month of October, where HA is comparatively less. Positive HA (>0.5) in the high category is projected for June, August, September and November months while negative HA (> -0.5) is observed in January, February, March, April, July and December. Low flows in the month of January, February, March and April are projected to increase due to the increase in HA in the low category in these months whereas conversely shows reduction during May, June and November months.

Previous global analysis has indicated that the impact of climate change on flow regime is larger than the effect of dams and water withdrawals (Doll and Zhang 2010). However, this may be on account of two factors; the likely underestimation of dam impacts (Doll and Zhang 2010) and the high degree of spatial variation and basin specific impacts. An important factor which needs consideration is that the Kangsabati reservoir storage represents about one-third of the total annual discharge and is, therefore, a major factor in altering the flow regime of this basin. Future climate change will, therefore, put additional stress leading to greater risk of ecological change in a riverine ecosystem already affected by anthropogenic interference.

4. Conclusions

This study provides a detailed basin scale assessment of ecologically relevant flow alterations in a monsoon dominated, drought prone river basin. IHA and EFC parameters describing changes in long-term monthly average, timing, duration and frequency of extreme flow conditions show a significant change from the natural flow regime during the observed period. Dampening effect of dams on hydrological variability and the extreme seasonality of river flows is highly pronounced. Significant overall flow reduction by the dam for provision of irrigation and domestic water demands will be exacerbated by climate change. The combined effect of dam and climate change is found to be significantly greater than the individual impact of dam or climate change. However, lack of sufficient long-term ecological data is a limitation in the assessment of habitat changes in the Kangsabati basin. We find that the ecologically sensitive IHA parameters and the associated inferences that may be drawn regarding the impacts on aquatic species are useful in cases where availability of long-term ecological data is a drawback. There is an urgent need to correlate real time ecological, bio-geochemical and morphological characteristics with observed hydrological changes to better assess the vulnerability of aquatic ecosystems to future changes. A better understanding of ecosystem impacts will be useful to inform the method of river restoration and ecosystem management programmes in the future.

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Tables

Table 1 Sensitive SWAT parameters included in the final calibration, their initial ranges, final values and their t and p values

Parameter name[1]	**Definition**	**t-statistics[2]**	**p-value[2]**	**Initial value**	**Range of values in SWAT-CUP**	**Final value**
v__ALPHA_BF.gw	Base-flow alpha factor (days)	4.29	0.00	0.048	0.0-0.7	0.54
v__GW_DELAY.gw	Groundwater delay (days)	-7.65	0.00	31	0.0-250.0	80.75
v__GWQMN.gw	Threshold depth of water for return flow	-1.53	0.13	0	0.0-1.2	0.81
v__GW_REVAP.gw	Groundwater revap (water in the shallow aquifer returning to root zone) coefficient	1.43	0.15	0.02	0.0-0.2	0.10
v__ESCO.hru	Soil evaporation compensation factor	1.06	0.29	0.95	0.75-0.95	0.78
v__CH_N2.rte	Manning's N value for the main channels	-0.11	0.91	0.014	0.12-0.4	0.35
v__CH_K2.rte	Effective hydraulic conductivity in main channel	-1.42	0.16	0	0.0-74.0	33.37

Parameter name[1]	**Definition**	**t-statistics[2]**	**p-value[2]**	**Initial value**	**Initial range of multiplier in SWAT-CUP**	**Final value of the multiplier**
r__CN2.mgt	SCS runoff curve number for moisture condition II	11.31	0.00	75-98	-0.4-0.004	-0.18
r__SOL_AWC.sol	Available water capacity of first soil layer (mm/mm)	0.35	0.72	0.06	0.0-0.4	0.39
r__SOL_K (1).sol	Saturated hydraulic conductivity of first soil layer (mm/h)	1.42	0.16	500	0.0-1.6	0.22
r__SOL_BD (1).sol	Moist bulk density of first soil layer (mg/m^{3})	0.98	0.33	1	0.0-0.7	0.61

[1] The qualifier (v_) refers to the substitution of a parameter by a value from the given range, while (r__) refers to a relative change in the parameter where the current values is multiplied by 1 plus a factor in the given range.

[2] The t-statistics and p-values are results from 500 runs of SUFI2 simulations; the larger t-statistics and smaller p-value, shows more sensitive parameter.

Table 2 SWAT Model performance of five calibrated subbasins in the Kangsabati basin.

River discharge station	Calibration (1991-2000)					Validation (2001-2010)				
	P factor	*R* factor	PBIAS	NSE	R^2	*P* factor	*R* factor	PBIAS	NSE	R^2
Simulia	0.74	1.08	7.9	0.63	0.69	0.71	0.94	11.8	0.53	0.69
Tusuma	0.78	0.75	-6.1	0.72	0.86	0.76	0.65	5.3	0.76	0.79
Rangagora	0.68	1.10	-12.4	0.74	0.66	0.62	1.02	-4.8	0.67	0.66
Kharidwar	0.72	0.84	5.8	0.64	0.75	0.79	0.90	8.3	0.64	0.75
Mohanpur	0.40	0.59	5.4	0.68	0.87	0.63	0.72	6.2	0.49	0.85

Figures

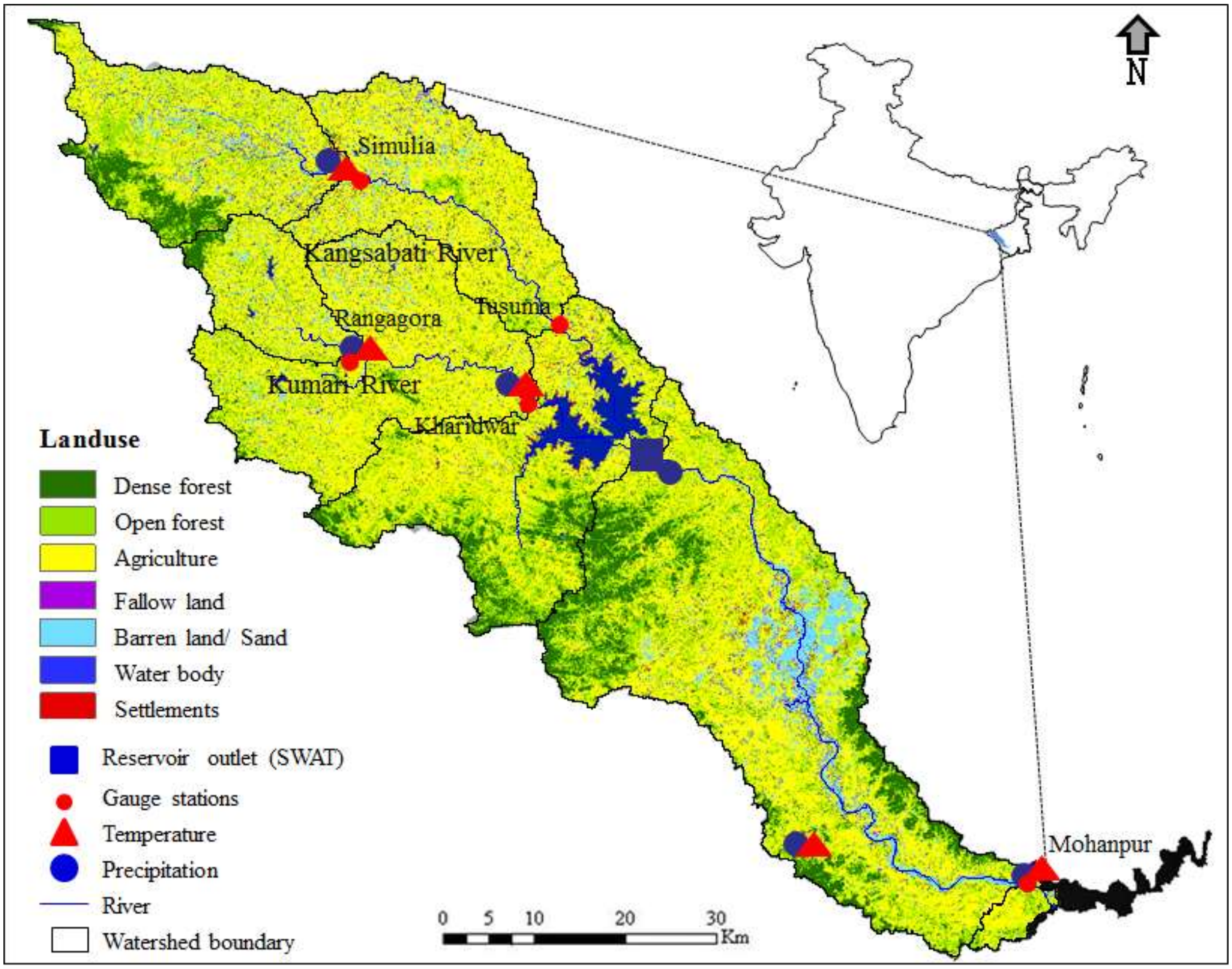
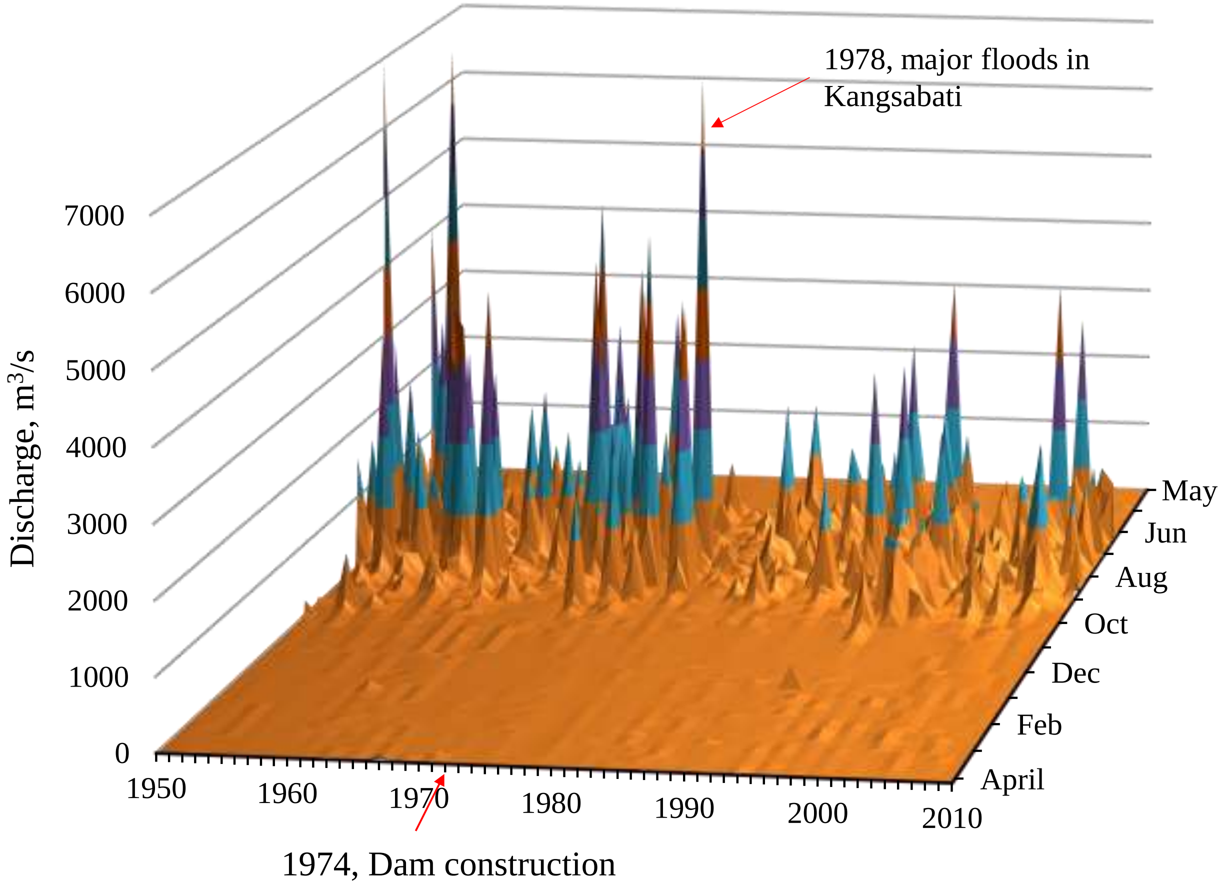
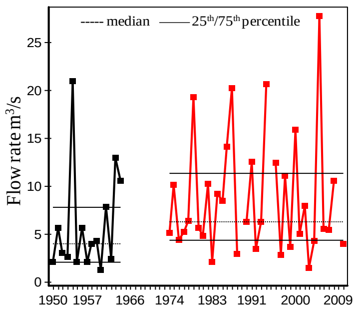
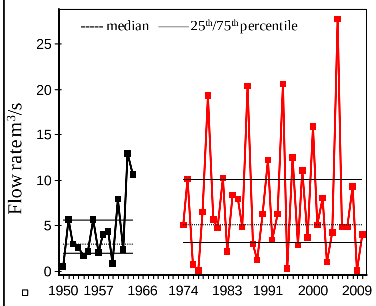
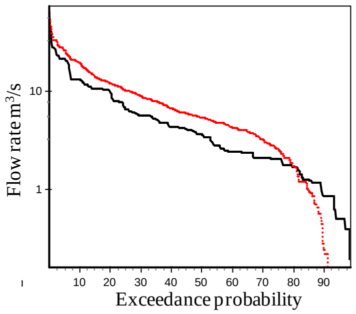
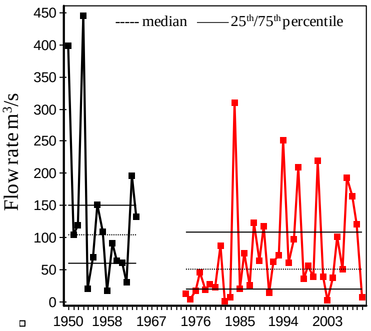
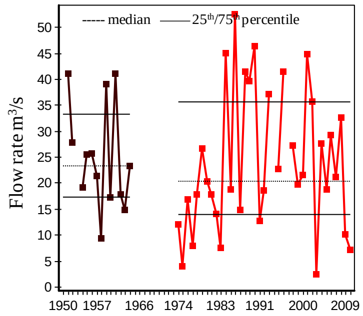
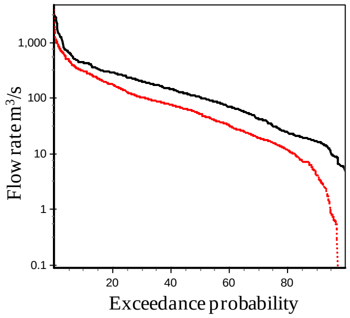
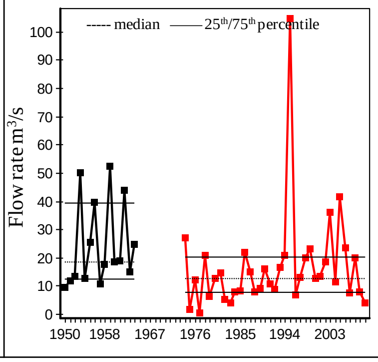
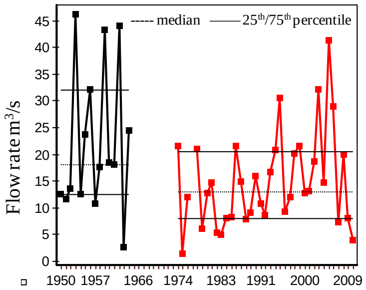
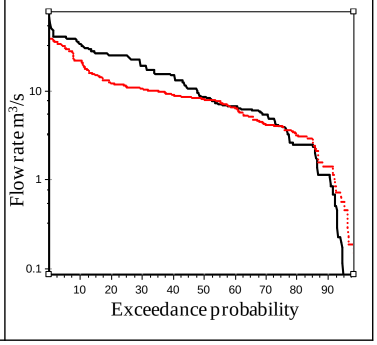


Figure 1



1978, major floods in Kangsabati
Discharge, m³/s
7000
6000
5000
4000
3000
2000
1000
0
1950
1960
1970
1980
1990
2000
2010
May
Jun
Aug
Oct
Dec
Feb
April
1974, Dam construction

Figure 2

Period	Monthly flows	Monthly low flows	Flow Duration Curve (FDC)
Pre-monsoon			
Monsoon			
Post-monsoon			

— Pre-dam — Post-dam

Figure 3

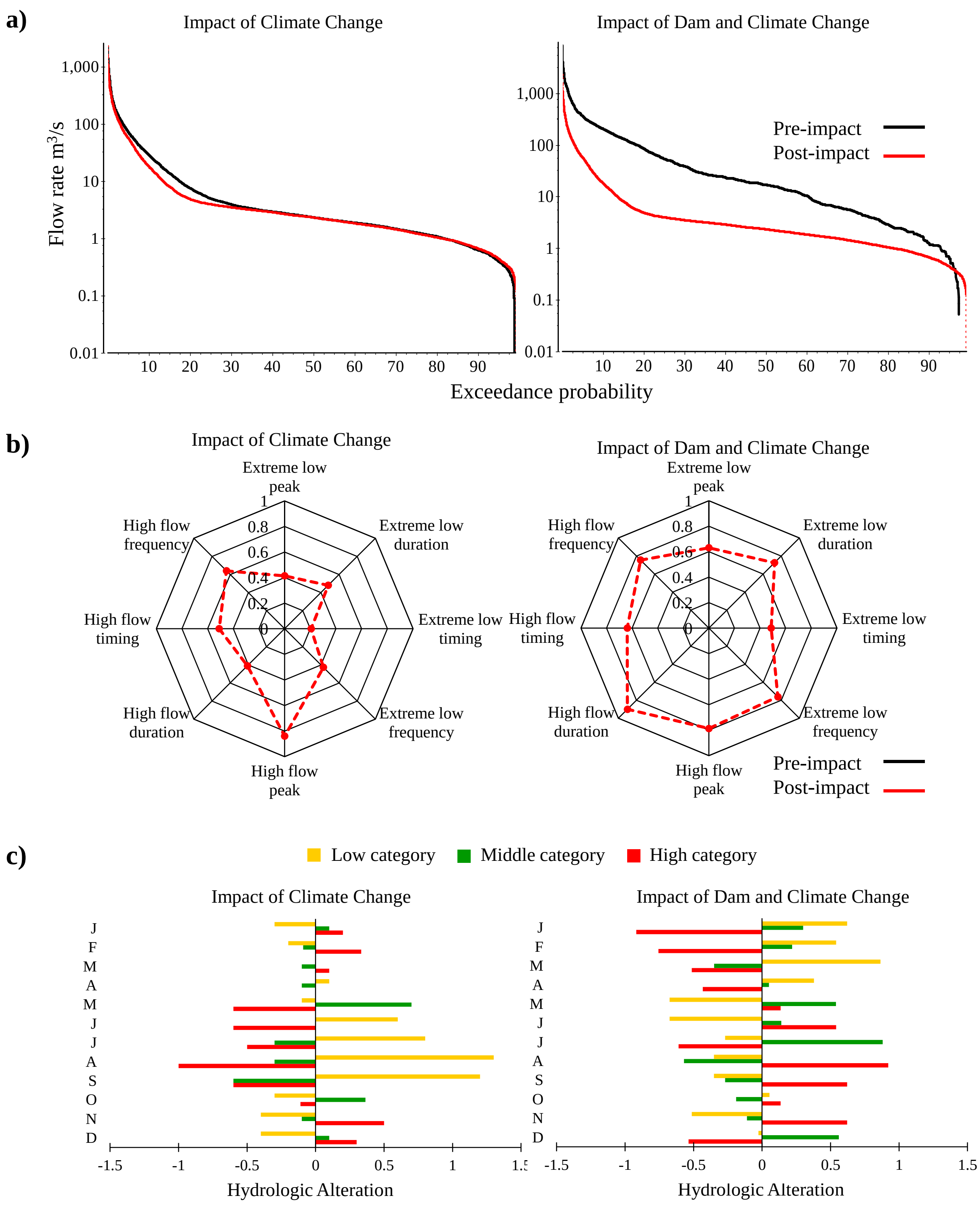

a)
Impact of Climate Change
Impact of Dam and Climate Change
Flow rate m^3/s
1,000
100
10
1
0.1
0.01
10
20
30
40
50
60
70
80
90
Exceedance probability
Pre-impact
Post-impact
b)
Impact of Climate Change
Impact of Dam and Climate Change
Extreme low peak
Extreme low duration
Extreme low timing
Extreme low frequency
High flow peak
High flow duration
High flow timing
High flow frequency
1
0.8
0.6
0.4
0.2
0
Pre-impact
Post-impact
c)
Low category
Middle category
High category
Impact of Climate Change
Impact of Dam and Climate Change
J
F
M
A
M
J
J
A
S
O
N
D
-1.5
-1
-0.5
0
0.5
1
1.5
Hydrologic Alteration

Figure 4