Original Research Article

Flow regime alteration due to anthropogenic and climatic changes in the Kangsabati River, India

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A R T I C L E   I N F O

Article history:
Received 15 September 2013
Received in revised form 27 May 2014
Accepted 2 June 2014
Available online 17 June 2014

Keywords:
Indicators of Hydrologic Alteration
Climate change
Anthropogenic intervention
SWAT

A B S T R A C T

According to the ‘natural flow paradigm’, any departure from the natural flow condition will alter the river ecosystem. Flow regimes have been modified by anthropogenic interventions and climate change is expected to cause additional impacts by altering precipitation extremes. This study aims to evaluate the observed hydrologic alteration caused by dam construction and simulate alteration due to expected climatic changes in a monsoon dominated mesoscale river basin in India. To analyze the natural flow regime, 15 years of observed streamflow (1950–1965) prior to dam construction is used. Future flow regime is simulated by a validated hydrological model Soil and Water Assessment Tool (SWAT), using four high resolution (~25 km) Regional Climate Model (RCM) outputs 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 Hydrologic Alteration (IHA) method which is based on the Range of Variability approach is used. This approach enables the assessment of ecologically sensitive streamflow parameters for the pre- and post-impact periods. Results of our analysis indicate that flow variability in the river has been significantly reduced due to dam construction with high flows being reduced and low flows during non-monsoon months considerably enhanced. Streamflow simulated based on projected climatic changes reveals reduced monsoonal flows with marginal changes in non-monsoon streamflow. The combined effect will reduce flow variability, potentially affecting the ecosystem. We conclude that in such modified basins, adaptive river basin management will be necessary to maintain such an extreme river flow regime for the long term viability of riverine ecosystems.

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1. Introduction

Amidst a growing understanding that sufficient water is essential for the sustainability of riverine ecosystems, significant stress has been placed on assessing important characteristics of the river flow regime needed to sustain ecosystem functions. Poff et al. (1997) have discussed how the ecological integrity of riverine ecosystems is a function of flow characteristics and their interactions with water quality, energy sources, physical habitat and biota. The
natural dynamism of a river is demonstrated by the flow variability across hourly, daily, seasonal, annual and longer time scales. Primarily, five flow components; magnitude, frequency, duration, timing and rate of change, which have a significant influence on the ecological dynamics of river systems, have to be ‘mimicked’ in order to maintain ecosystem diversity and the diversity of organisms therein (Poff et al., 1997; Gibson et al., 2005; Arthington et al., 2006; Laizé et al., 2013).

Several studies over the past decade have discussed changes in river flow regimes brought about by human intervention (Gibson et al., 2005; Sun and Feng, 2012; Yang et al., 2012; Poff and Matthews, 2013). Dams are known to alter natural flow regimes of rivers when compared to the pre-impoundment period and have been found to homogenize distinct river flow regimes across broad geographic scales (Poff et al., 2007). Simplistic and static rules for delineating environmental flow requirements may be detrimental to the critical ecological functions of river flow variability and sustenance of ecosystems (Arthington et al., 2006). Dammed seasonality and interannual flow variability of rivers due to dams alters the habitat dynamics which makes assessment of these impacts critical from the point of view of biodiversity conservation (Poff et al., 2007). In their global analysis, (Döll and Zhang, 2010) find that along with ecological impacts of water diversion by dams, climate change induced flow alterations can have a strong impact on freshwater ecosystems. However, a strong regional variation in dam impacts may be observed in such studies, and also might have been underestimated. For an improved ability to gauge potential implications for riverine ecosystems, which experience different types of flow regimes across different regions, observed changes at a basin scale need to be analyzed, along with flow alterations caused by future climate change.

In this study, we analyze long-term observed and simulated streamflow at a location which lies downstream of a large earthen dam on the Kangsabati river to evaluate dam and future climate change induced flow alterations. This river, located in the lower Ganges basin, has been damned to create the Kangsabati reservoir which provides flood/drought relief and diverts water for irrigation and domestic purposes in the command area. Flow regime changes due to dam construction could be exacerbated in the coming decades as future climate projections forecast a general decrease in precipitation, increase in temperature and an intensification of climatic extremes in the basin (Mittal et al., 2013). Use of hydrologic indicators for assessing environmental flow requirements. From the myriad hydrologic indicators available for assessing environmental flow requirements (Olden and Poff, 2003; Suen, 2010), we employ the Range of Variability Approach (RVA) (Richter et al., 1997) derived from aquatic ecology theory which involves a detailed assessment of the hydrological variability of river. This method is useful for detecting changes in the hydrological regime due to a known perturbation and for establishing flow-based river management targets (Chen, 2012) making it suitable for analyzing the impact of human intervention and climate change on the Kangsabati river basin.

2. Methodology

2.1. Study area

The Kangsabati river basin is located mostly within the Indian state of West Bengal, bounded by the 86° E and 87°30’ E longitudes and the 22°20’ N and 23°30’ N latitudes and having an approximate area of 5796 km². The Kangsabati river flow in a south-easterly direction before becoming the last contributing river to the Ganges river in India. The river basin is traditionally considered drought prone (Saxena, 2012), although it receives an average annual rainfall of 1200 mm. The high concentration of rainfall during monsoon (JJAS) months results in a skewed streamflow distribution with large differences in daily and monthly river flows within the natural flow regime. The Kangsabati river which originates in the uplands of the Chhota Nagpur plateau has caused highly eroded and gullied topography in the upper reaches where ephemeral 1st and 2nd order streams are dominant. This eroded landscape turns into undulating uplands towards the middle reaches and finally alluvial plains in the lower reaches. The Kangsabati reservoir project is located at the confluence of the Kangsabati river and its major tributary; the Kumari. This reservoir, built in two phases (1965 and 1973), receives inflow from both sub-basins. Along with the provision for irrigation and domestic water consumption needs the project also provides 246.7 million m³ storage for flood relief. Along with these benefits, drought mitigation, pisciculture and recreational facilities are also a part of the project (Saxena, 2012). Some of the storage capacity has diminished over the past 40 years due to siltation. As a result, the current reservoir storage capacity is about 1/3rd of the annual reservoir inflow (Bhave et al., 2013b). Previous studies in this basin (Bhave et al., 2013a,b; Mittal et al., 2013) have discussed stakeholder experiences of past climatic changes. Moreover, projected climatic changes in mid-21st century demonstrate an amplification of the impacts due to changing precipitation extremes, particularly, consecutive dry days (CDD), highest five day precipitation (RX5D) and number of days with precipitation greater than 50 mm (PD50).

2.2. Analytical approach

Availability of long duration river discharge data is an essential requirement for assessing ecologically important characteristics of the natural flow regime. Kennard et al. (2010) suggest that hydrologic metrics should be based on more than 15 years of discharge data to reduce bias and increase accuracy. Mohanpur, a discharge gauging station of the Irrigation & Waterways Department, Government of West Bengal, approximately 80 km downstream of the Kangsabati reservoir has recorded and made available daily discharge data from 1950 onwards. Natural river flow conditions existed for a 16-year period between 1950 and 1965. The period between 1965 and 1973 constitutes an intermediate period between the completion of the Phase I and II of the Kangsabati reservoir project. The 37-year period from 1974–2010 marks the post-dam period where
dam effects on flow regime are studied using Mohanpur as the reference location.

A calibrated SWAT model is used for simulating future runoff (Section 2.3). Kangsabati reservoir is not considered during the model setup, so as to isolate the climate change signal and analyze only the impact of climate change. Taking due notice of the oft-discussed uncertainty issues, it has been proposed that climate-induced changes in river flow regime can be best analyzed using multiple climate models (Döll and Schmied, 2012). Regionally relevant, comprehensive and state-of-the-art high resolution RCM climate simulations are therefore used here (Mathison et al., 2013; Mittal et al., 2013). SWAT simulations for the period 1970–1999 are based on historical simulations of climate models which represent the natural climatic variability in the basin, while SWAT simulations for the period 2021–2050 represent future hydrologic conditions under a climate change scenario.

Based on this understanding, observed and simulated flows are then analyzed with the help of the Indicators of Hydrologic Alteration (IHA) software of The Nature Conservancy (2009). Pre- and post-impact periods are compared in this approach to evaluate the degree of hydrologic alteration caused by the intervention. Moreover, recent addition of the Environmental Flow Components (EFCs) in the IHA software provide greater support for translating key flow characteristics into environmental flow management (Mathews and Richter, 2007). The entire range of hydrologic metrics available are compared to determine key alterations in the natural flow regime and their potential implications for the riverine ecosystem are discussed.

**Table 1**

<table>
<thead>
<tr>
<th>River discharge station</th>
<th>Calibration</th>
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<th></th>
<th>Validation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>P factor</td>
<td>R factor</td>
<td>NSE</td>
<td>$R^2$</td>
<td>P factor</td>
<td>R factor</td>
<td>NSE</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Simulia</td>
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<td>1.08</td>
<td>0.63</td>
<td>0.69</td>
<td>0.71</td>
<td>0.94</td>
<td>0.53</td>
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<td>Tusuma</td>
<td>0.78</td>
<td>0.75</td>
<td>0.72</td>
<td>0.86</td>
<td>0.76</td>
<td>0.65</td>
<td>0.76</td>
<td>0.79</td>
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<tr>
<td>Rangagora</td>
<td>0.68</td>
<td>1.1</td>
<td>0.74</td>
<td>0.66</td>
<td>0.62</td>
<td>1.02</td>
<td>0.67</td>
<td>0.66</td>
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<td>Kharidwar</td>
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<td>0.84</td>
<td>0.64</td>
<td>0.75</td>
<td>0.79</td>
<td>0.9</td>
<td>0.64</td>
<td>0.75</td>
</tr>
<tr>
<td>Mohanpur</td>
<td>0.4</td>
<td>0.59</td>
<td>0.68</td>
<td>0.87</td>
<td>0.63</td>
<td>0.72</td>
<td>0.49</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Fig. 1. Map of the Kangsabati basin showing land cover land use classes, location of hydro-meteorological stations and Kangsabati reservoir.
2.3. SWAT model and data

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 by subdividing the basin into multiple hydrological response units (HRUs). Each HRU represents a unique combination of soil, land cover and elevation. 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 are performed using the Arc-SWAT extension for ArcGIS 9.3. The Sequential Uncertainty Fitting algorithm (SUFI-2) (Abbaspour, 2007) is used to calibrate SWAT and to perform uncertainty analysis at five streamflow gauge stations in the Kangsabati Basin. Two optimization criteria are used to assess model performance: Nash-Sutcliffe efficiency (NSE) and the coefficient of determination ($R^2$). Both NSE and $R^2$ describe the goodness-of-fit between simulated and observed flow; and the model simulation would be considered best when their values approach one (Moriasi et al., 2007). SUFI-2 quantifies the 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 95% band, while the $R$ factor is derived by taking the ratio of the average width of the 95% band 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). Input data used for SWAT simulation includes a 90 m x 90 m resolution Shuttle Radar Topography Mission (SRTM) DEM and soil data from survey topsoehets of the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Govt. of India. Unsupervised land use classification of LandSat ETM and ETM+ images for the time periods 1990 and 2001 are used for the calibration (1991–2000) and validation (2001–2010) periods respectively, while 2011 land use information is used as reference for the future (2021–2050) period.

SWAT simulations are driven by four RCM simulations and their ensemble mean (referred as MME hereafter). RCM simulations are obtained by forcing two regional climate models REMO and HadRM3 with two CMIP3 GCMs ECHAM5 (Roekner, 2003) and HadCM3 (Gordon et al., 2000), under the SRES A1B scenario. The resulting four simulations are REMO-ECHAM5, HadRM3-ECHAM5, HadRM3-HadCM3 and REMO-HadCM3. This is the only and the most comprehensive set of high resolution (~25 km) future climatic projections available for the Kangsabati river basin developed under the EU project HighNoon (http://www.eu-highnoon.org/). 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

Fig. 2. Changes in annual (a) minimum and (b) maximum streamflow from 1950 to 2010.
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 study also evaluates the applicability of these simulations for the Kangsabati basin, while the high spatial resolution of these simulations have been found to be useful for hydrological assessments (Bhave et al., 2013a,b; Bhave et al., 2014). Two sets of RCM simulations are used for the analysis; (i) historical simulations (20c3 m) for the period 1970–1999 (ii) future simulations for the period 2021–2050 based on the A1B SRES emission scenario.

2.4. Indicators of Hydrologic Alteration

The IHA methodology, which is conceptually based on the Range of Variability Approach (RVA), is used to assess degree of departure from the natural flow regime due to dam and projected climate change (Richter et al., 1996, 1997). IHA, originally designed to analyze hydrologic effects of dams by comparing streamflow in pre- and post-impact periods, assumes that natural flow alteration alters the ecosystem. It is useful to compare flow parameters under different scenarios (observed and future period in this study) and particularly for assessing key flow regime characteristics, such as magnitude, timing, frequency and duration (Pradhanang et al., 2013). To analyze the degree of hydrologic alteration in ecologically relevant statistics, the IHA estimates 67 hydrologic parameters derived from daily flow statistics. These are subdivided into two categories: 33 IHA parameters and 34 Environmental Flow Components (EFC). Most widely used IHA parameters consist of five major categories: (i) magnitude of monthly streamflows; (ii) magnitude of and duration of annual extreme flows; (iii) timing of annual extreme flows; (iv) frequency and duration of high and low pulses and (v) rate and frequency of flow changes. The five flow components which describe the ways in which an organism experiences river flow variability include: (i) extreme low flows; (ii) low flows; (iii) high-flow pulses; (iv) small floods and (v) large floods (Mathews and Richter, 2007). The IHA covers most flow components and is useful for analysing high information and non-redundant indices. However, the choice of relevant indices has to be assessed on a case-to-case basis (Olden and Poff, 2003). In this study, only those results which depict significant changes in flow regime are presented and discussed to increase their relevance.

3. Results and discussion

3.1. SWAT model calibration and validation

Results of the model performance and degree to which it accounts for uncertainty are evaluated in terms of P factor, R factor, NSE and $R^2$ for both calibration and

![Fig. 3. Flow duration curves of seasonal streamflow for reference months February, May, August and November for pre-dam (1950–1965) and post-dam (1974–2010) periods.](image_url)
validation periods (Table 1). The P factor indicates that data for majority of the stations are well bracketed in predicting the uncertainty of the model, whereas the R factors are mostly below or around 1. The small values for P and larger values for R factor in case of Mohanpur gauge station indicate higher prediction uncertainties. NSE and $R^2$ values for all stations reveal that discharge simulation is satisfactory based on the criteria given by Moriasi et al. (2007). NSE values lie between 0.6 and 0.8 whereas $R^2$ values vary from 0.6 to 0.9 for majority of the stations except for Mohanpur. In general, in the downstream of Kangsabati dam, the model prediction has larger uncertainties. The poor calibration and validation results in case of managed downstream flow has also been observed in other studies (Faramarzi et al., 2010; Vaghefi et al., 2013) (Fig. 1).

3.2. Flow regime alterations due to dam

Natural flow variability is essential to maintain channel and floodplain habitats, which support aquatic and riparian species (Poff et al., 1997). Alterations due to dam (Figs. 2, 3 and 4a) reveal a marked reduction in peak flows, increase in low flows and because of water diversion for irrigation and a reduction in total annual discharge. In Fig. 4(a), middle, low and high alterations correspond to changes in the median, 25th percentile and 75th percentile flows. Dam construction modifies the natural flow regime directly by storing high flows and maintaining certain minimum flows during the non-monsoon months (Fig. 4a). Absorbing high flows, which cause downstream floods, is an important function of the dam, while providing water for domestic consumption and irrigation in downstream sections necessitates regular dam releases during non-monsoon months. Such alterations have been known to cause geomorphic simplification, floodplain disconnection and disruption of lateral and longitudinal connectivity, thereby affecting habitat dynamics and making it difficult for native biota to adapt (Bunn and Arthington, 2002; Poff et al., 2007). From pre-dam to post-dam period, the 1-day through 7-day minimum flows remain almost the same,

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**Fig. 4.** Monthly median river flow rates and hydrologic alterations for (a) pre-dam (1950–1964) and post-dam (1974–2010) and (b) control (1970–1999) and future climate change (2021–2050) periods at the Mohanpur gauging station.
whereas there is a marked increase in 30-day minimum of about 127% (Table 2). There is a statistically significant difference (Mann–Whitney U-test) in the maximum flows during the post-dam period. As shown in Fig. 2, the 30 and 90-day minimum flows increase dramatically after completion of dam construction. Such an effect is part of the regularly observed dampening effect of dams (Poff et al., 1997; Bunn and Arthington, 2002; Poff et al., 2007). Conversely 1-day through 90-day maximum flows have reduced significantly because the dam absorbs and stores

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<tr>
<td>1-day minimum</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.117</td>
</tr>
<tr>
<td>3-day minimum</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.094</td>
</tr>
<tr>
<td>7-day minimum</td>
<td>0.0</td>
<td>0.6</td>
<td>0.0</td>
<td>0.777</td>
</tr>
<tr>
<td>30-day minimum</td>
<td>1.1</td>
<td>2.5</td>
<td>127.3</td>
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</tr>
<tr>
<td>90-day minimum</td>
<td>4.3</td>
<td>4.5</td>
<td>4.7</td>
<td>0.642</td>
</tr>
<tr>
<td>1-day maximum</td>
<td>2240.0</td>
<td>1105.0</td>
<td>−50.7</td>
<td>0.007</td>
</tr>
<tr>
<td>3-day maximum</td>
<td>1647.0</td>
<td>774.7</td>
<td>−53.0</td>
<td>0.014</td>
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<tr>
<td>7-day maximum</td>
<td>1024.0</td>
<td>474.3</td>
<td>−53.7</td>
<td>0.040</td>
</tr>
<tr>
<td>30-day maximum</td>
<td>476.1</td>
<td>253.2</td>
<td>−46.8</td>
<td>0.051</td>
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<td>90-day maximum</td>
<td>254.1</td>
<td>190.5</td>
<td>−25.0</td>
<td>0.077</td>
</tr>
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</table>

**Table 2**
Changes in annual mean, minimum and maximum flows between pre- and post-dam periods. p-values from Mann–Whitney U-test at 10% significance level.

[Fig. 5. Timing, frequency and duration of ecologically important extreme low flows and high flow pulses for the control (1970–1999) and future climate change (2021–2050) periods.]
high flows generated by isolated precipitation events along with the monsoon high flows (Fig. 3).

Fig. 3 and Table 2 provide an estimate of flow duration curves, which depict the percentage of time a specified discharge has been equaled or exceeded during the pre- and post-dam period, for four months (February, May, August and November) representative of four seasons (DJF, MAM, JJAS and ON) respectively. In the post-dam period, there is an overall increase in the flow rate in February, while the zero-flow duration has significantly reduced. Summer rice (Boro rice) water demand in the reservoir command area during summer months may be associated with significant reduction of high flows during May. There is also a reduction in flow rate especially for low flows in August and November while high flows in November remain consistent. Due to dam construction, the frequency of occurrence of small floods (defined as having a return interval between a 2 and 10 years) has reduced significantly. The dam has eliminated the large floods (defined as having a return interval greater than 10 years). Siluroid fishes, especially species such as Bagarius bagarius and Mystus gulio, which are found in the Kangsabati River, are highly sensitive to reduction in high flows. Benthic siluroid fishes are very good indicators of environmental degradation (Wootton et al., 1996) and changes in the timing of extreme low flows and high flow pulses 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). Channel bed sedimentation brought about by reduction in floods also causes degradation of their habitat (Lisle, 1989; Mishra et al., 2009). The observed decline in these two species since 1960 and the consequent absence by 2002 near Mohanpur station (Mishra et al., 2009) may be associated with the hydrologic changes brought about by Kangsabati dam. Overall, it is observed that while low flows are enhanced, the high flows are reduced by the dam leading to a dampening of the extreme seasonality of river flows.

3.3. Flow regime alterations due to climate change

The isolated impact of climate change on runoff, based on MME climate projections (2021–2050), is simulated without considering the effect of the Kangsabati dam using SWAT. The results show an increase in monthly median streamflow for winter months, with the maximum increase during December (Fig. 4b) as compared to control period (1970–1999). Analysis of IHA and EFC parameters shows that there is an overall reduction in median flows during monsoon season with maximum reduction observed during August. As shown in Fig. 5, the median timing of the extreme low flows and high flow pulses comes later in the year. However, whereas there is an

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**Fig. 6.** Flow duration curves of seasonal streamflow for reference months February, May, August and November for the control (1970–1999) and future climate change (2021–2050) periods.
increase in variability of timing of extreme low flows, for high flows there is a decrease. There is a slight reduction in the frequency of both, extreme low flows and high flow pulses, which affects the overall flow variability. Compared to the control period, the duration of low flows has increased by approximately 11% while for high flow pulses there is a change in the 25th–75th percentile range without any change in the median duration. There is a marked difference between the flow duration curves for control and future period for months May, August and November (Fig. 6). For May and August high flows are intensified which may be associated with the increase in Rx5D and PD50 precipitation extremes (Mittal et al., 2013). For February, results show a slight increase in streamflow for the extreme low flows, which always remain above the 1 m$^3$/s flow rate. The medium flows from approximately 80 m$^3$/s to about 1 m$^3$/s show a significant decrease during May. On the other hand, high flows during the post-monsoon November month shows are reduced from approximately 1050 m$^3$/s to 850 m$^3$/s. An increase in the duration of extreme low flows has been known to decrease species richness of macroinvertebrate assemblages and increase the macrophyte biomass (Suren and Riis, 2010). On the other hand, floods of different sizes are essential for maintaining diversity of riparian plant species and aquatic habitat (Caruso et al., 2013). Therefore the projected changes due to climate change may have an impact on the aquatic habitat of the Kansabati river thereby affecting the riparian plant species and aquatic biota.

4. Conclusions

This study provides a detailed basin scale assessment of ecologically relevant flow alterations in a monsoon-dominated river basin. 67 flow alteration parameters are calculated using IHA and are compared to pre-impact natural flow conditions for analyzing the impact of dam construction and future climate change by mid-21st century. 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. Such changes impact aquatic and riparian habitat and will adversely affect key species. 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 may be exacerbated by climate change. On the other hand, the effects of existing dam operations may nullify some impacts of climate change. Moreover, future dam operations may not be similar to current and may be useful for managing the impacts of climate change. Reduction in precipitation and higher temperature induced increase in evapotranspiration when combined with expected increase in human water demand will reduce water availability for the sustenance of riverine ecosystems. Lack of sufficient long term ecological data, a limitation in the assessment of habitat changes, necessitate long-term integrated and interdisciplinary assessments, for addressing this gap in understanding. Other changes such as sediment yield, water temperature, nutrient influx and water quality parameters also need to be monitored for better understanding of ecosystem impacts which will inform the method of river restoration. Integrated assessments in the future may aid much needed adaptive river basin management, in such a modified river basin, to maintain the naturally extreme river flow regime.

Conflict of interest

None declared.

Financial disclosure

None declared.

Acknowledgement

This work has been supported by the HighNoon project (www.eu-highnoon.org), funded by the European Commission Framework Programme 7 under Grant No. 227087.

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