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# A combined bottom-up and top-down approach for assessment of climate change adaptation options

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SUMMARY

Focus of recent scientific research in the water sector has shifted from analysis of climate change impacts to assessment of climate change adaptation options. However, limited attention has been given to integration of bottom-up and top-down methods for assessment of adaptation options. The integrated approach used in this study uses hydrological modelling to assess the effect of stakeholder prioritized adaptation options for the Kangsabati river catchment in India. A series of 14 multi-level stakeholder consultations are used to ascertain locally relevant no-regret adaptation options using Multi-Criteria Analysis (MCA) and scenario analysis methods. A validated Water Evaluation And Planning (WEAP) model is then used to project the effect of three options; option 1 check dams (CD), option 2 increasing forest cover (IFC) and option 3 combined CD and IFC, on future (2021–2050) streamflow. High resolution ($\sim$25 km) climatic projections from four Regional Climate Models (RCMs) and their ensemble based on the SRES A1B scenario for the mid-21st century period are used to force the WEAP model. Results indicate that although all three adaptation options reduce streamflow, in comparison with scenario without adaptation, their magnitude, temporal pattern and effect on high and low streamflows are different. Options 2 and 3 reduce streamflow percentage by an order of magnitude greater than option 1. These characteristics affect their ability to address key adaptation requirements and therefore, we find that IFC emerges as a hydrologically suitable adaptation option for the study area. Based on study results we also conclude that such an integrated approach is advantageous and is a valuable tool for locally relevant climate change adaptation policymaking.



## 1. Introduction

Historically, greater attention has been paid to analysis of climate change impacts compared to climate change adaptation. However, in recent years the scientific community has focused on climate change adaptation issues due to the increased understanding that inertia in the climate system due to previous green house gas emissions will necessitate adaptation in the long term (Bormann et al., 2012; Mathison et al., 2012). Although, analysis of climate change impact on water resources is frequently encountered in scientific literature, analysis of adaptation requirements, feasible adaptation options for specific geographical contexts and effectiveness of adaptation options is the need of the hour (Arnell, 2010). Adaptation in water resources is especially important due to anticipated scale and extent of climate change impacts and consequences for humans in the face of changing non-climatic factors such as population and land use (Smit and Pilifosova, 2001; Arnell, 2010).

Conventional options for planned adaptation in the water sector, including policies, technologies, structural measures, risk reduction, landuse change and capacity building measures have been prescribed before (Bates et al., 2008). However, location specific characteristics, adaptation requirements and the extent of change required limit the usefulness of generic adaptation options (Smit and Pilifosova, 2001). Suitability also varies with the chosen boundary for analysis, level of exposure and chosen time frame of adaptation response. Therefore, it is essential to determine locally suitable adaptation options which are acceptable to stakeholders and which adequately address adaptation requirements. Due to their experiential understanding of local biophysical and socio-economic systems, stakeholders are valuable knowledge bearers of potential adaptation options (Bhave et al., 2013). Moreover, stakeholder preferences play a significant role in regional scale adaptation planning and implementation (Bormann et al., 2012). Due to the combined biophysical and socio-ecological impacts of adaptation options an evaluation of any adaptation option should involve both qualitative and quantitative approaches.

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Two distinct approaches, top-down and bottom-up, characterize methods to determine climate change impacts and evaluate adaptation options (Burton et al., 2005; Füssel, 2007). Top-down approach, typically involves quantitative assessment of expected climatic changes which drive impact models. Measures to alleviate these impacts are then modeled and their efficacy is compared. Bottom-up approach first qualitatively characterizes social vulnerability, followed by which, adaptation options are identified and evaluated using participatory processes. While the top-down approach neglects human factors, it may be useful in characterizing uncertainty issues when multiple climate change projections are used. On the other hand, bottom-up approach gives insufficient importance to physical factors, but provides legitimacy through stakeholder involvement (Dessai and Hulme, 2004; Bormann et al., 2012). Therefore, integration of these approaches and appropriate sequencing of activities is important for determination of holistic, relevant and implementable adaptation options (Burton et al., 2005).

Such an integrated approach is derived and followed in this study based on the adaptation planning approach suggested by Wilby and Dessai (2010). It provides a roadmap to identify, prioritize and assess adaptation options using both bottom-up and top-down methods. Schematic shown in Fig. 1 depicts the manner in which integration and sequencing of the bottom-up and top-down methods are applied for a river catchment in India. This study is a part of the research carried out for the Ganges basin under the HighNoon project (www.eu-highnoon.org). In this study, we carry out hydrological assessment of stakeholder prioritized climate change adaptation options using Water Evaluation And Planning (WEAP) model forced by multiple Regional Climate Model (RCM) simulations.

## 2. Materials and methods

### 2.1. Study area – Kangsabati river catchment

The Kangsabati river catchment (3494 km$^2$), located mostly within the state of West Bengal (Fig. 2) has been selected as a study region. The Kangsabati river is the last contributing river to the Ganges river in India and was therefore chosen to represent the lower Ganges basin in the project Highnoon. The river originates in the Chhota Nagpur plateau and makes a south-eastward journey towards the Bay of Bengal. The Kangsabati reservoir marks the outlet of the Kangsabati river catchment. The Kangsabati river catchment is traditionally a drought prone region with frequent floods due to the heavy monsoon rainfall during July to September (JJAS) along with dry summer months (MAM). The average annual rainfall in the Kangsabati catchment is about 1400 mm while the annual mean temperature is 25.9 °C. The consequent high monsoon runoff in this lateritic region has resulted in highly gullied topography and eroded residual hills incised by first or second order ephemeral streams. The catchment is excessively drained and almost a third of non-forested land is degraded (UNDP, 2004). Along with little agricultural activity during dry season, crop productivity during monsoon is also affected by erratic spatio-temporal distribution of rainfall. In essence, due to the strong seasonality of the rainfall, the region faces intra-annual hydrological extremes of monsoon floods and intermittent droughts resulting in inconsistent water availability and soil degradation, which strongly influences the biophysical vulnerability of the people.

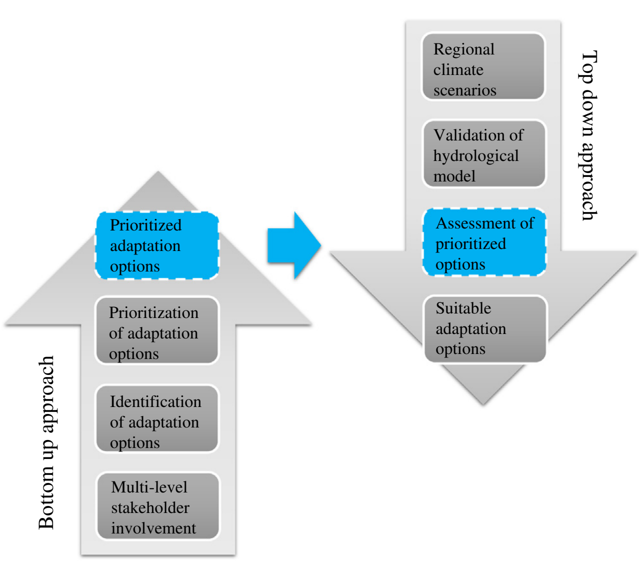



**Fig. 1.** Schematic representing integration and sequencing of bottom-up and top-down approaches.

Although governmental initiatives have focused on delaying monsoon runoff and storing water to provide water during the lean season, due to the steep slopes and high runoff, irrigation facilities are not well developed. Therefore, most farmers practice rain-fed agriculture as evidenced by a cropping intensity of 105% (West Bengal State Marketing Board, 2012). About 93% of the farming community consists of small and marginal farmers, who own small fragmented land portions in the absence of land consolidation. With 0.57 ha cultivatable land per agricultural worker and with 43.65% of the population below poverty line, this region is one of the most economically under-developed regions in India (UNDP, 2004). A changing climate is expected to increase the vulnerability of traditionally marginalized people in the region who practice rainfed agriculture and are heavily dependent on the consistent functioning of natural systems (Bhave et al., 2013; Mittal et al., 2013).

The Kangsabati reservoir is located at the confluence of the Kangsabati river and a major tributary, Kumari. The reservoir was constructed in two phases, with an earthen dam on the Kangsabati river in 1965 followed by a connected dam on the Kumari river in 1973, which together form the Kangsabati Reservoir Project. Two river gauge stations, Simulia and Tusuma, are located on the main river Kangsabati while, stations Rangagora and Kharidwar are located on the river Kumari (Table 1). An ungauged tributary of the Kumari feeds the reservoir after flowing from the southern part of the catchment. Inflow to the Kangsabati reservoir comprises of the combined streamflow of Kangsabati and Kumari sub-basins.

### 2.2. Multi-level stakeholder approach

As a part of the HighNoon project, stakeholder consultation was formulated to identify and prioritize locally relevant climate change adaptation options. Stakeholder knowledge and preferences are strongly contextual and location specific, which means that inclusion of a broad spectrum of stakeholder backgrounds is necessary for regional scale analysis. Therefore, a multi-level stakeholder approach was followed to gather such a diverse set of opinions, experiences and preferences. A total of 14 stakeholder consultation workshops; seven for identification and seven for prioritization exercises were organized at three levels. Consultation with 278 participants, including 46 women stakeholders was carried out through two state level workshops, six at district and six at community level (Table 2). State level stakeholders included policy makers, academicians, scientists, bankers and representatives from non-governmental and farmer organizations. Scientists from the district level agricultural organization Krishi Vigyan Kendra

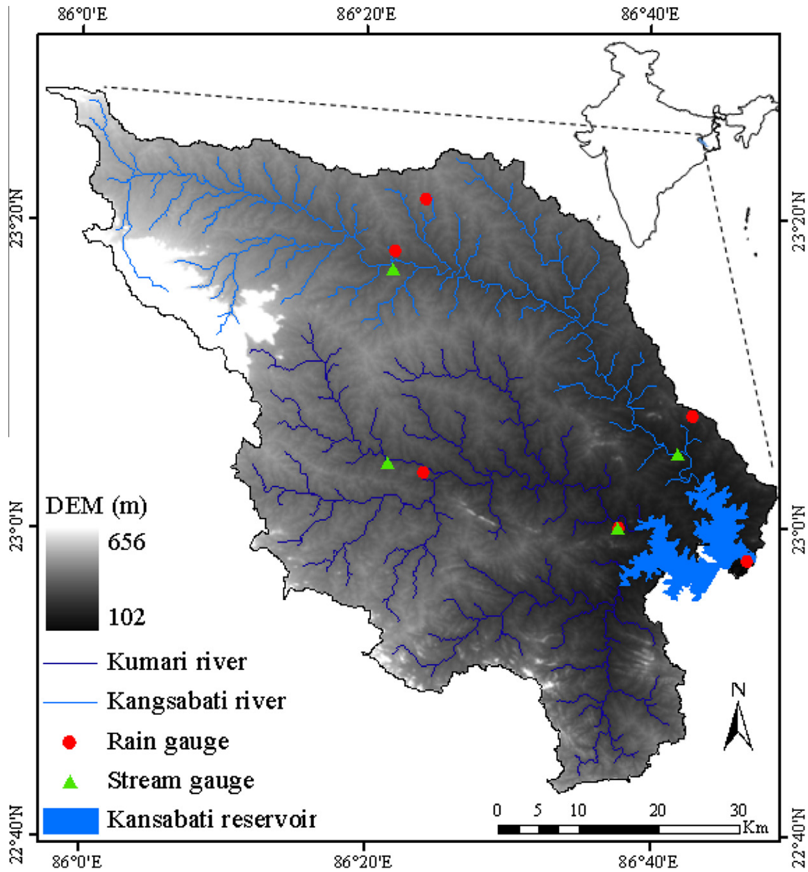



**Fig. 2.** Map of the study area: Kangsabati catchment.

**Table 1**
List of meteorological and discharge stations in the Kangsabati catchment.

| Sub-basin | Station | Variable | Elevation (m) | Latitude | Longitude |
|---|---|---|---|---|---|
| Kangsabati | Hatwara | Precipitation | 255.4 | 23°21′0″N | 86°24′0″E |
| | Simulia | Precipitation, Discharge | 220.9 | 23°18′0″N | 86°21′36″E |
| | Tusuma | Precipitation, Discharge | 163.3 | 23°7′48″N | 86°42′36″E |
| Kumari | Rangagora | Precipitation, Discharge | 197.8 | 23°3′36″N | 86°24′0″E |
| | Kharidwar | Precipitation, Discharge | 152.4 | 23°0′0″N | 86°37′48″E |
| | Kangsabati Dam | Precipitation | 135 | 22°57′36″N | 86°46′48″E |

**Table 2**
Details of multi-level stakeholder approach used for identifying and prioritizing climate change adaptation options.

| Stakeholders' workshop | Multi-level stakeholders | Number of stakeholders |
|---|---|---|
| Identification of climate change adaptation options | Community | 29 |
| | Community | 28 |
| | Community | 24 |
| | District | 15 |
| | District | 9 |
| | District | 6 |
| | State | 29 |
| Prioritization of climate change adaptation options | Community | 32 |
| | Community | 31 |
| | Community | 27 |
| | District | 8 |
| | District | 8 |
| | District | 7 |
| | State | 25 |

(KVK), which provides agricultural extension services to farmers comprised of district level participants, while individual farmers participated in the community level workshops. The stakeholders were given a brief idea regarding the type of expected climate change impacts in the region based on climatic studies. A participatory tool, problem web-solution web, was used for the identification of adaptation options while identified options were prioritized using two MCA tools; multi-criteria analysis and pairwise comparison along with scenario analysis for determining no-regret adaptation options.

*2.2.1. Identification of adaptation options*

A brainstorming tool; problem web-solution web, which is based on theoretical considerations of brainstorming (Shih et al., 2009) and vulnerability assessment (Downing and Patwardhan, 2004) was formulated to elicit stakeholder perceptions of key vulnerabilities, experiences of climate change impacts and relevant adaptation options. This process was mildly moderated to guide stakeholder discussion and interaction on specific issues. After mapping of key vulnerabilities, interrelationships between them were established by the stakeholders resulting in an interconnected network of problems. From this 'problem web' stakeholders select target problems for which 'solutions' in the form of adaptation options were to be elicited. To identify adaptation options the concept was framed as "*what would you do/recommend in a climate change scenario to nullify its impacts or to tide over the problems?*" Consequently, a network of solutions was obtained which included measures implemented previously, currently being implemented, based on experiences of the stakeholders and which targeted current climatic variability and expected future climate change in the region (for further information refer Bhave et al., 2013).

*2.2.2. Prioritization of adaptation options*

Pairwise comparison is an often used MCA tool which has been found to be useful in participatory processes (Hajkowicz and Collins 2007). This matrix based method involves one-to-one comparison between each pair of adaptation options (Fig. 3). A preferred option is chosen by the stakeholders and criteria used by them for making a choice are determined. After deriving stakeholder preferred adaptation options, criteria determined during the exercise are taken up for pair-wise comparison. Accordingly, a list of preferred criteria is obtained which provides an understanding of the adaptation requirements as determined by the stakeholders. A separate analysis conducted using the commercial MCA software D-sight, is carried out with state level stakeholders only. This analysis involved two types of criteria, criteria based on previous studies and criteria preferred by stakeholders. Here, a score on the scale of 1–10, is provided by the stakeholders based on their perception of the performance, with 10 representing the best performance, of each identified adaptation option. Weighted summation, which is probably the most commonly used MCA technique, is used for the analysing the performance evaluation provided by the stakeholders.

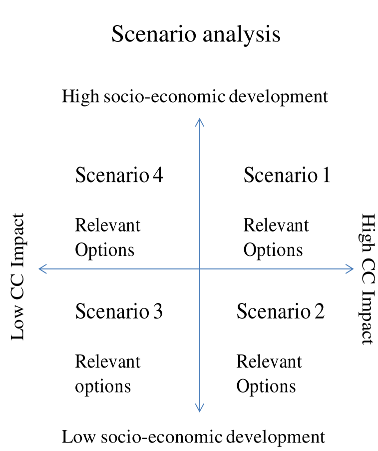
Scenario analysis is a frequently used method for determining robust options in the natural resources management problems where changes in interlinked biophysical and socio-ecological systems needs to be considered (Lempert et al., 2006). It involves analysis of possible future conditions for a region based on uncertain development of inherently uncontrollable factors such as socio-economic development, climatic changes, natural calamities and socio-political factors (Coreau et al., 2009). In this study, to identify no-regret options, an approach developed by van't Klooster and van Asselt (2006) is used to create a scenario space of four plausible futures represented by four quadrants (Fig. 3). No-regret adaptations are defined based on their characteristic of suitability in all four plausible futures defined by a combination of the level of socio-economic development and the level of climate change impacts. Based on their perception or experience, stakeholders discussed the applicability of each adaptation option for each quadrant. The analysis therefore revealed a set of adaptation options which are suitable for application in the region irrespective of the level of socio-economic development and climate change impacts.

*2.3. Climate scenarios*

Multiple projections of plausible future climate changes in comparison with single model outputs have been found to be better for dealing with climate change uncertainty issues (Mathison et al., 2012). To generate such a set of modeled future conditions for this study, four RCM simulations for the mid-21st century, with a horizontal resolution of ~25 km, are used. These simulations are obtained by forcing two regional models REMO and HadRM3 with two GCMs ECHAM5 (Roeckner, 2003) and HadCM3 (Gordon et al., 2000), under the SRES A1B scenario. This results in four RCM simulations, REMO-ECHAM5, HadRM3-ECHAM5, HadRM3-HadCM3, REMO-HadCM3. These high resolution model outputs represent the most comprehensive set of future climatic projections which are available for this region (Mathison et al., 2012). Moreover the applicability of these outputs for the Kangsabati river basin has been validated previously (Mittal et al., 2013). In addition to available modeled climatic conditions, use of ensemble mean conditions for hydrological modelling provides valuable input for adaptation planning. Therefore, for this study along with the individual model projections, Multi-Model Ensemble (MME) projections are also used to force the hydrological model WEAP. Consequently, five future climatic projections for the 30 year period, 2021–2050, are used.

*2.4. WEAP model and data*

WEAP, originally developed by the Stockholm Environment Institute, is a climate driven integrated water resources management model which includes a dynamically integrated rainfall-runoff hydrology module (Yates et al., 2005a,b). The spatially continuous hydrology module of WEAP is based on the principle of water balance accounting across multiple sub-catchments of a river basin and is capable of simulating all terrestrial components of the hydrologic cycle (Purkey et al., 2008). In WEAP the various water balance components; precipitation, evapotranspiration, runoff and groundwater contribution, are balanced on a monthly basis at each node and link in the system. This model provides an advantage in analysing concurrent scenarios related to hydrological change because it integrates hydrological modelling with a decision support system (Harma et al., 2012). The modelling framework can incorporate expected changes in climatic factors such




Pair-wise comparison

| | Option 1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|
| Option 1 | 1 | 1 v/s 2 Criteria | 1 v/s 3 Criteria | 1 v/s 4 Criteria |
| Option 2 | x | 1 | 2 v/s 3 Criteria | 2 v/s 4 Criteria |
| Option 3 | x | x | 1 | 3 v/s 4 Criteria |
| Option 4 | x | x | x | 1 |

**Fig. 3.** Scenario analysis method (left) used for analysis of no-regret options (where CC is climate change) and pair-wise comparison method used for prioritization of adaptation options.

as wind, humidity and temperature and resultant changes in evapotranspiration. Consequently, this model has proven useful for analysing hydrological characteristics of a basin for varying scenarios of future climate, land use and water demand (Joyce et al., 2011; Vicuña et al., 2011; Mehta et al., 2013). The Food and Agriculture Organization (FAO) rainfall runoff method available in the WEAP hydrology module is used to simulate the hydrological processes including runoff and infiltration.

In this study historical data for raingauge and river gauge stations is available for varying lengths of time, from 1982 to 2012 from various authorities in the Kangsabati catchment, including the India Meteorological Department (IMD), Central Water Commission (CWC) and the Irrigation and Waterways Department, Govt. of West Bengal (Table 1). Limited and scattered historical groundwater information is available from the Kangsabati Project Evaluation Report of the Govt. of West Bengal (2003) and from the groundwater monitoring stations of the Central Ground Water Board (CGWB). A common period from 1991 to 2010 is used for model calibration and validation. For analysis of changing land use patterns over the observed period, unsupervised land use classification of LandSat TM and ETM images for the years 1972, 1990 and 2001 are used. For future climate change scenarios, unsupervised land use classification of LandSat ETM + image for the year 2011 is used as a reference.

## 3. Results and discussion

### 3.1. Outcome of participatory approach

A comprehensive list of stakeholder identified adaptation options for the Kangsabati river basin have been provided by Bhave et al. (2013). These options include conventional soil and water conservation measures, such as check dams, increasing forest cover and village ponds. Measures to improve agricultural productivity such as integrated farming, organic farming, short duration varieties and crop diversification were also suggested. In addition water and agricultural management options, infrastructural measures such as increasing last mile connectivity, dissemination of weather forecast information, land consolidation and improving access to credit were also suggested by the stakeholders. Using three prioritization exercises; pair-wise comparison, scenario analysis and MCA, stakeholders prioritized the adaptation options identified by them. After compiling results for all analysis, common options across the analysis were determined. Commonality indicates high preference for an option which has no-regret characteristics. Criteria prioritization using pair-wise comparison revealed runoff reduction to be a preferred criterion. Amongst the common adaptation options, options which cause runoff reduction include Check Dams (CD) and Increasing Forest Cover (IFC). These options address stakeholder concerns, especially of individual farmers; about further runoff induced soil erosion of this eroded upland area and the resultant loss in soil fertility. Moreover, farmers in the Kangsabati river catchment have observed increasing soil moisture content as a result of social forestry of local tree species *Terminalia arjuna* and *Shorea robusta* (Bhave et al., 2013). Their experiences with such interventions reinforced their belief in introducing soil and water conservation measures for reducing runoff. State level stakeholders being concerned about reservoir siltation, were interested in delaying the high monsoon runoff, which is a large factor affecting the sedimentation rate. According to the Govt. of West Bengal (2003), live storage projections for the Kangsabati reservoir indicate a future reduction of 17.3% in 2050 with respect to 2012 storage levels. This means that approximately 30% of the original live storage capacity will be lost due to siltation by 2050. Moreover, state government officials were concerned about the rising scale of economic losses caused by monsoon flash floods. A recent case cited by the government officials occurred in 2007, when large reservoir releases caused damage to flood plain crops, property and even river discharge gauging stations at Mohanpur and Shahdoria in the downstream areas. Whilst reducing monsoon flows is important, the stakeholders also emphasized the need to maintain dry season low flows entering the reservoir to facilitate consistent irrigation supply in the command area. Avoidance of these stakeholder observed problems along with augmentation of local water availability is necessary in this region, for which well known soil and water conservation measures CD and IFC were preferred by the stakeholders. To analyse the potential of these prioritized adaptation options in influencing streamflow under climate change scenario, hydrological analysis using WEAP was carried out.

### 3.2. Prioritized options and WEAP scenarios

Before incorporating CD and IFC into WEAP, an assessment of suitable number and location of check dams as well as locally relevant increase in forest cover is necessary. For identification of suitable check dam locations, a runoff potential map is prepared using the extensively used Soil Conservation Service (SCS) curve number method and slope characteristics (De Winnaar et al., 2007). Here higher curve number values and slope < 15% indicate the amount of runoff which is considered appropriate for identifying check dam locations (Ramakrishnan et al., 2009). The determined locations are then prioritized in a Geographical Information Systems (GIS) environment using key morphometric characteristics including drainage network, basin geometry, drainage texture and relief (Table 3) and land use characteristics (Table 4). Such physical characteristics have been used before as criteria for prioritizing basin specific check dam locations (Ramakrishnan et al., 2009). Although 1st order streams are considered appropriate for locating check dams, in the study region, 1st order streams are mainly rain-fed and drain water only during monsoon. Therefore, only 2nd order perennial streams are considered suitable for preliminary analysis for check dam locationing. Although numerous potential check dam locations are determined through the morphometric analysis, in practice, land availability concerns play an important role in the actual implementation. To address

**Table 3**
Morphometric parameters used for determining suitable check dam locations.

| Morphometric parameter | Formula |
|---|---|
| *Drainage network* | |
| Bifurcation ratio ($R_b$) | $N_u/N_{u+1}$ |
| Rho coefficient | $L_u/R_b$ |
| *Basin geometry* | |
| Texture ratio ($T$) | $N_1/P$ |
| Circularity ratio ($R_C$) | $P/(4\Pi A)^{0.5}$ |
| Form factor ($R_f$) | $A/L_b^2$ |
| Elongation ratio ($R_e$) | $2/L_u\ (A/\Pi)^{0.5}$ |
| Shape factor ($B_s$) | $1/(R_f)$ |
| Compactness coefficient | $0.2841(P/A^{0.5})$ |
| *Drainage texture analysis* | |
| Drainage density ($D_d$) | $L_u/A$ |
| Length of overland flow ($L_o$) | $1/2\ D_d$ |
| Stream frequency ($F_s$) | $N_u/A$ |
| *Relief characteristics* | |
| Relief ratio ($R_h$) | $\Delta H/L_b$ |
| Ruggedness no. ($N$) | $D \cdot \Delta H$ |

Basin area ($A$), basin perimeter ($P$), total stream length of all orders ($L_u$), number of streams of order u ($N_u$), total number of streams of 1st order ($N_1$), basin length, km ($L_b$), the elevation of the highest point in the basin ($H_{max}$), The elevation of the lowest point in the basin ($H_{min}$).

**Table 4**
Historical land use (%) changes in the Kangsabati catchment from 1972 to 2011.

| Landuse (%) | 1972 | 1990 | 2001 | 2011 |
|---|---|---|---|---|
| Dense forest | 9.6 | 7.4 | 7.6 | 4.9 |
| Open forest | 10.3 | 14.5 | 8.5 | 11.9 |
| Agriculture | 60.1 | 59.9 | 47.0 | 61.1 |
| Fallow land | 12.4 | 6.4 | 14.8 | 1.9 |
| Barren land/sand | 3.4 | 5.4 | 16.5 | 15.2 |
| Water body | 3.1 | 5.1 | 4.3 | 3.5 |
| Settlements | 1.1 | 1.3 | 1.4 | 1.4 |

this issue, check dam locations on agricultural land, near forests and settlements are considered unsuitable. Based on above criteria, nine suitable check dam locations, three in Kangsabati and six in Kumari sub-basin, with a total catchment area of 845 $km^2$ are identified and used for hydrological analysis. Check dams located on the prioritized locations, are characterized by a constant storage capacity of 0.05 $Mm^3$ which is an appropriate size for 2nd order stream check dams with no buffer storage and uncontrolled spillage. These characteristics are based on government guidelines for the implementation of check dams in this region (CGWB, 2013). Other than evaporation losses from the check dam, runoff intercepted by check dams also contributes to groundwater recharge.

In order to quantify land use changes in the catchment, unsupervised classification of LandSat images into seven classes of land use; dense forest, open forest, agriculture, fallow land, barren land/sand, water body and settlements, is carried out using image processing software. The major changes observed over the time period 1972–2011, indicates reduction in dense forest cover (defined as canopy cover >40%), increasing area under agriculture and increased degradation of land (Table 4). Based on this analysis and stakeholder preference for IFC as an adaptation option, we followed an approach of converting existing open forest into dense forest and existing barren land into open forest for formulating future land use. This is in accordance with the guidelines issued by the National Green India Mission under the National Action Plan on Climate Change (NAPCC) (Govt. of India, 2008), where reforestation of degraded lands and intensification of forest cover are included under the mission objectives.

For analysing future streamflow, WEAP scenarios are obtained for each of the five climatic projections derived from four RCMs and their ensemble. The four WEAP scenarios include a base scenario without adaptation, a scenario with CD, a scenario with IFC and another with both CD and IFC. Fig. 4 shows the WEAP schematic as formulated for the Kangsabati catchment. A mid-21st century time-frame (2021–2050) is chosen for analysing adaptation strategies as it is often considered to be an appropriate timeframe, given that the inertia in the climate system due to past emissions will lead to visible changes by 2050 (Mathison et al., 2012). Moreover stakeholders in the Kangsabati basin have shown a preference for long term adaptation strategies addressing adaptation requirements in the mid-21st century (Bhave et al., 2013).

### 3.3. WEAP calibration and validation

The WEAP model is calibrated and validated at the four streamflow gauging stations located in the catchment (Fig. 2, Table 1) which represent the natural streamflow of the region due in the absence of irrigated agriculture. A monthly time step has been used for calibration, validation and future scenario analyses in this study so as to cover the residence time of the study area, during which all flows are assumed to occur (Purkey et al., 2008). Observed monthly discharge for 20 year period are used for the calibration (1991–2000) and validation (2001–2010) of the WEAP model. Monthly evapotranspiration values for the period are calculated using the Penman–Monteith method supported by the DSS_ET model (Bandyopadhyay et al., 2012). Parametric Estimation Tool (PEST) embedded within WEAP is used to calibrate parameters using an iterative approach to achieve good agreement between observed and simulated streamflow. Crop coefficient (Kc) parameter is calibrated using ranges provided by the Food and Agriculture Organization (FAO) (Allen et al., 1998). Monthly effective precipitation is

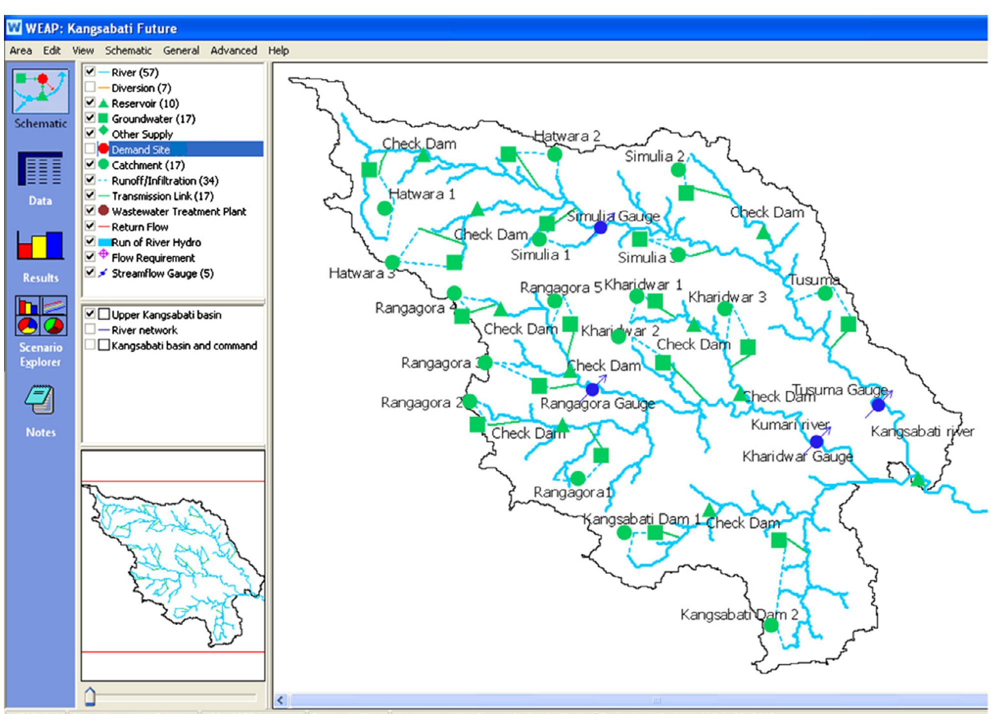



**Fig. 4.** Schematic of the Kangsabati catchment in Water Evaluation and Planning model (WEAP).

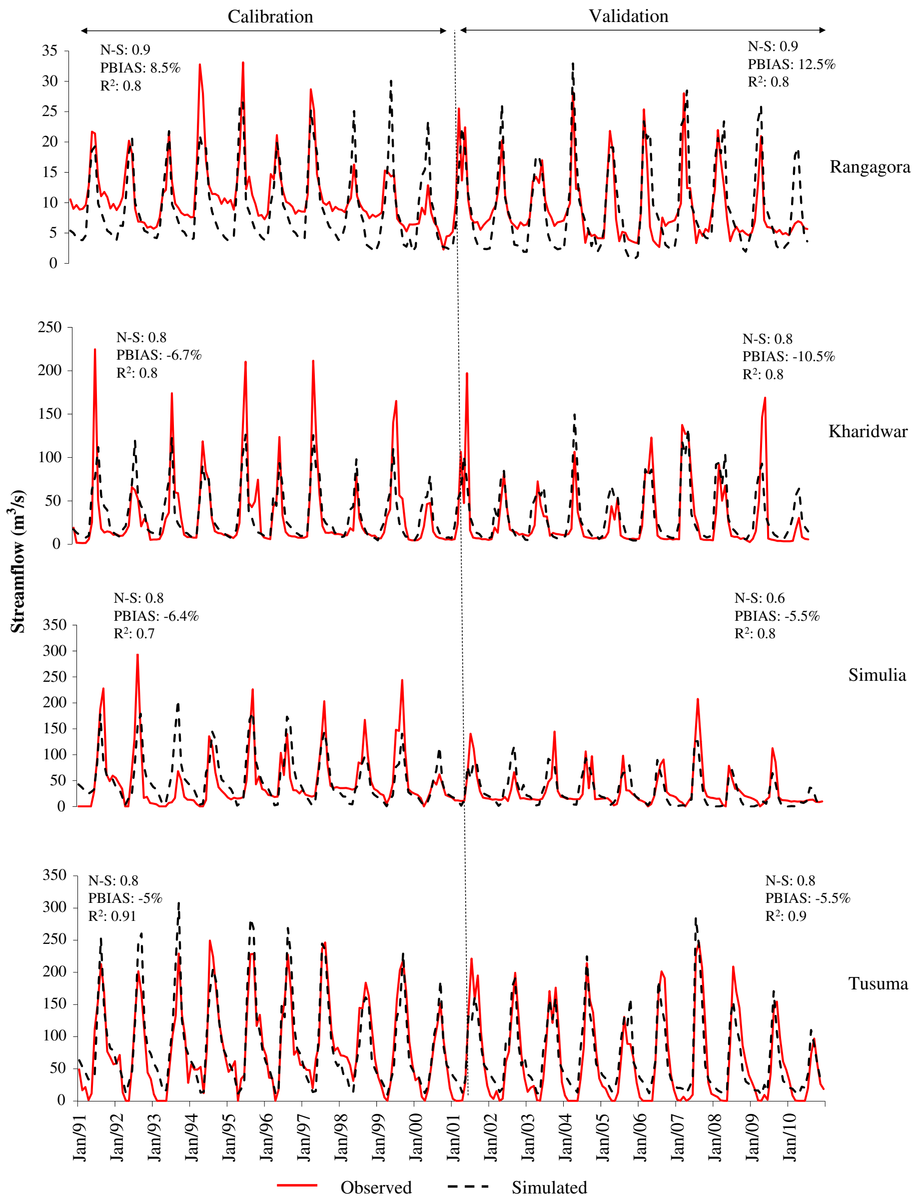



**Fig. 5.** Observed (line) and WEAP-simulated (dotted) monthly streamflow time series for the calibration and validation period at four stations in the Kangsabati catchment with respective values of three goodness-of-fit statistics (Nash–Sutcliffe Efficiency, $R^2$ and PBIAS).

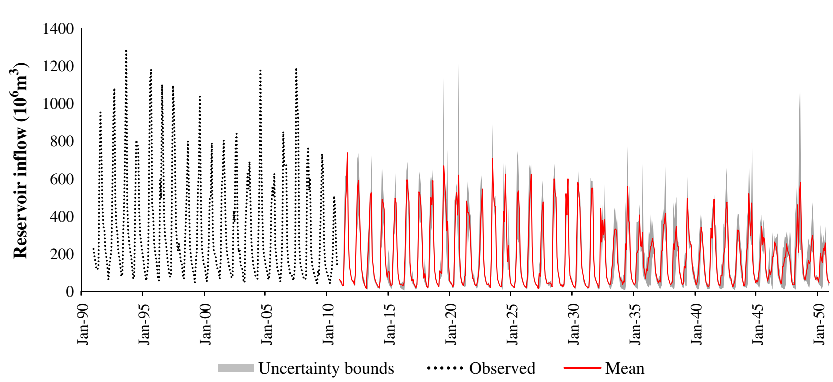



**Fig. 6.** Observed (dotted) and MME projected (line) reservoir inflow. Shaded area (grey) depicts range of reservoir inflow projected for the four RCM climate projections under A1B emission scenario.

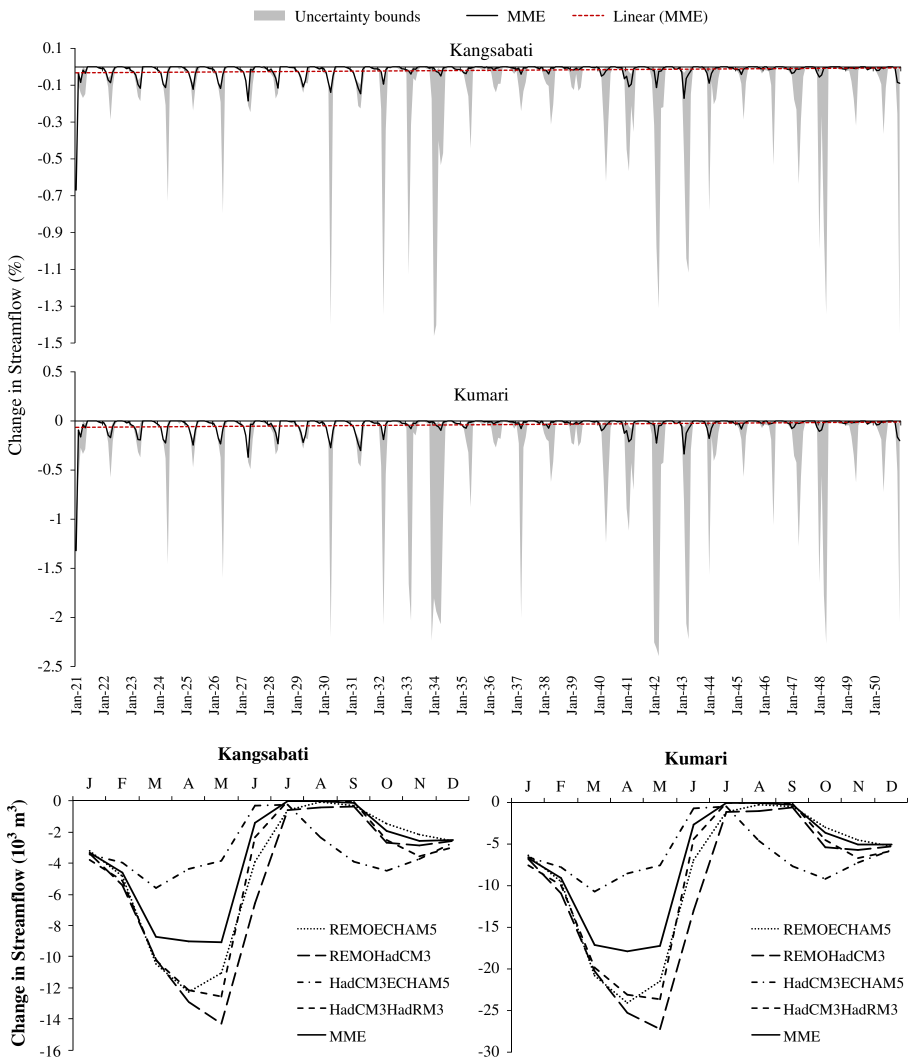



**Fig. 7.** Effect of check dams on streamflow for the period 2021–2050 compared to scenario without adaptation as projected by MME (bold line) and uncertainty bounds of four RCMs (grey shaded area) for the Kangsabati and Kumari sub basins with mean monthly change in streamflow for the individual RCMs and their MME.

calibrated based on land use specific runoff coefficients and basin-wide average values provided by the Govt. of West Bengal (2003).

Goodness of fit statistics, Nash–Sutcliffe Efficiency (NSE) criterion, the coefficient of determination ($R^2$) and the percent bias (PBIAS) are used to assess model accuracy in simulating observed streamflow at each of the four stations (Fig. 5). While $R^2$ values are a measure of the relationship between observed and simulated values, NSE indicates model performance and PBIAS is the deviation of the modeled streamflow from the observed expressed as a percentage (Moriasi et al., 2007). Results indicate reasonable ability of the model in simulating long term monthly time series of streamflow for the 20 year period. Calibration period NSE (0.8–0.9) and $R^2$ values (0.7–0.9) indicate model ability to adequately represent hydrological conditions in the basin. For the 10 year validation period model satisfactorily simulates observed streamflow for climatic conditions which are different from the calibration period supported by NSE (0.6–0.9) and $R^2$ values (0.8–0.9). Despite the simplified representation of groundwater contribution and the challenges of simulating streamflow characteristics of heavy precipitation months (JJAS), the model adequately reproduces observed streamflow pattern. Percentage bias results for the gauging stations ranged from −10.5 to 12.5 and indicate water balance errors, but falls within the ±15% range which suggest good model performance (Moriasi et al., 2007). Overall, since the statistical results are satisfactory, we consider the validated model suitable for Kangsabati catchment and may be used for exploring potential changes in streamflow due to climate change and to evaluate the effect of adaptation strategies.

### *3.4. Projected hydrological change*

The performance validation of the RCMs, REMO and HadRM3 driven by lateral boundary forcings from ERAInterim reanalysis data for 20 year period (1989–2008) for simulating temperature and precipitation patterns for this region provide confidence in the ability of the RCMs in generating reliable projections (Mittal et al., 2013). All future model simulations indicate an increasing annual mean temperature over the study period, with ensemble mean projections predicting an increase of 1.3 °C by 2050. This increase may have significant impact on evapotranspiration, affecting the surface hydrological budget (Im et al., 2010). On the other hand, a slight decrease in annual precipitation is projected by the ensemble mean over the 30 year period. Streamflow is strongly affected by temperature and precipitation and is consequently altered as a consequence of changing characteristics of climatic factors in the future. Projections from climate models do not predict actual climatic conditions, but provide useful information on uncertainty ranges (Miller et al., 2003). Forced by the five

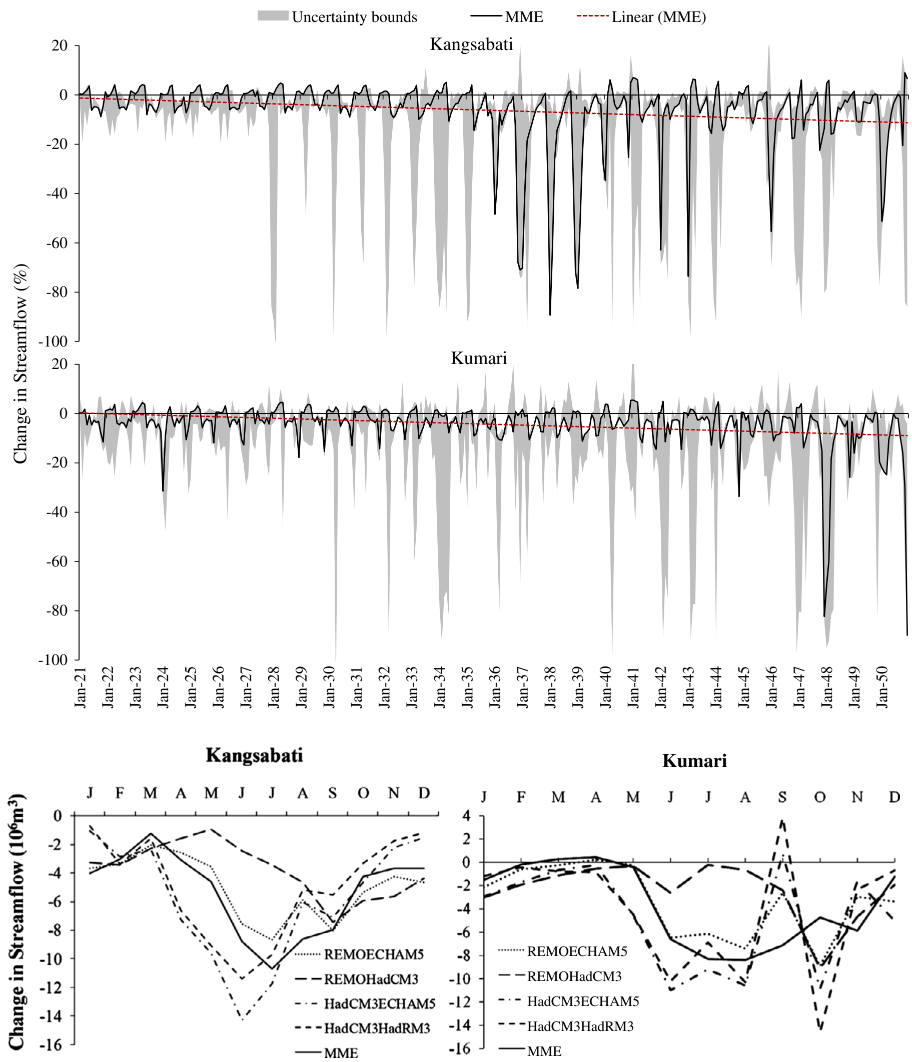



**Fig. 8.** Effect of increasing forest cover for the period 2021–2050 compared to scenario without adaptation as projected by MME (bold line) and uncertainty bounds of four RCMs (grey shaded area) for the Kangsabati and Kumari sub basins with mean monthly change in streamflow for the individual RCMs and their MME.

climatic model projections WEAP simulated monthly streamflows show a wide range of potential streamflow for the future. WEAP simulations of reservoir inflows till 2050 demonstrate a decreasing trend where annual inflows for the MME indicate a reduction of about 23% over the 30 year period, which amounts to about 0.45 billion $m^3$ (Fig. 6). However, dam ability to provide irrigation water supply in command areas should not affected significantly by the reduction in inflow because a corresponding degree of loss of reservoir capacity is projected in the future. Moreover the storage capacity as of 2012 is only about 1/3rd of the annual reservoir inflow, which is concentrated in the monsoon months (JJAS). In the monsoon season because of low irrigation water demand in the reservoir command area, excess water has to be released to the river. Therefore, the range of predicted reservoir inflow provides a reasonable set of upper and lower bounds of hydrological response of the Kangsabati catchment to climate change and demonstrates its value by providing decision-makers with potential changes in water availability.

### 3.5. Simulated hydrological effect of adaptation options

#### 3.5.1. Check dams

Changes in future flow regimes will have significant impacts on water availability in the catchment. The level of suitability of adaptation strategies will depend on their ability to influence the flow regime. Fig. 7 shows the inter-annual and monthly variability in projected changes in streamflow at outlets of Kangsabati and Kumari sub-basins due to check dams. Integration of nine check dams in WEAP modelling results in neglible change (<0.4%) in stream flow under MME projected scenario. Greater reduction is predicted in the Kumari sub-basin, which has 6 check dams compared to the Kangsabati sub-basin which has 3 check dams. It follows that a greater number of check dams results in a greater effect on streamflow. However, magnitude of this effect on streamflow decreases during the 30 year period as indicated by the linear trend for the MME. Although, the range of projected monthly mean streamflow is wide, a temporal pattern of streamflow reduction due to check dams is observed. Greater streamflow reduction during the dry season (MAM) contrasts with a minor reduction in monsoon (JJAS) streamflow (Fig. 7).

#### 3.5.2. Increasing forest cover

The effect of increasing the overall dense forest cover and converting barren land into open forest on runoff and consequently on streamflow in the two sub-basins is shown in Fig. 8. The reduction in MME projected streamflow,compared to a scenario without adaptation, occurs primarily during JJAS monsoon months for both sub-basins. This reduced runoff results due to increased

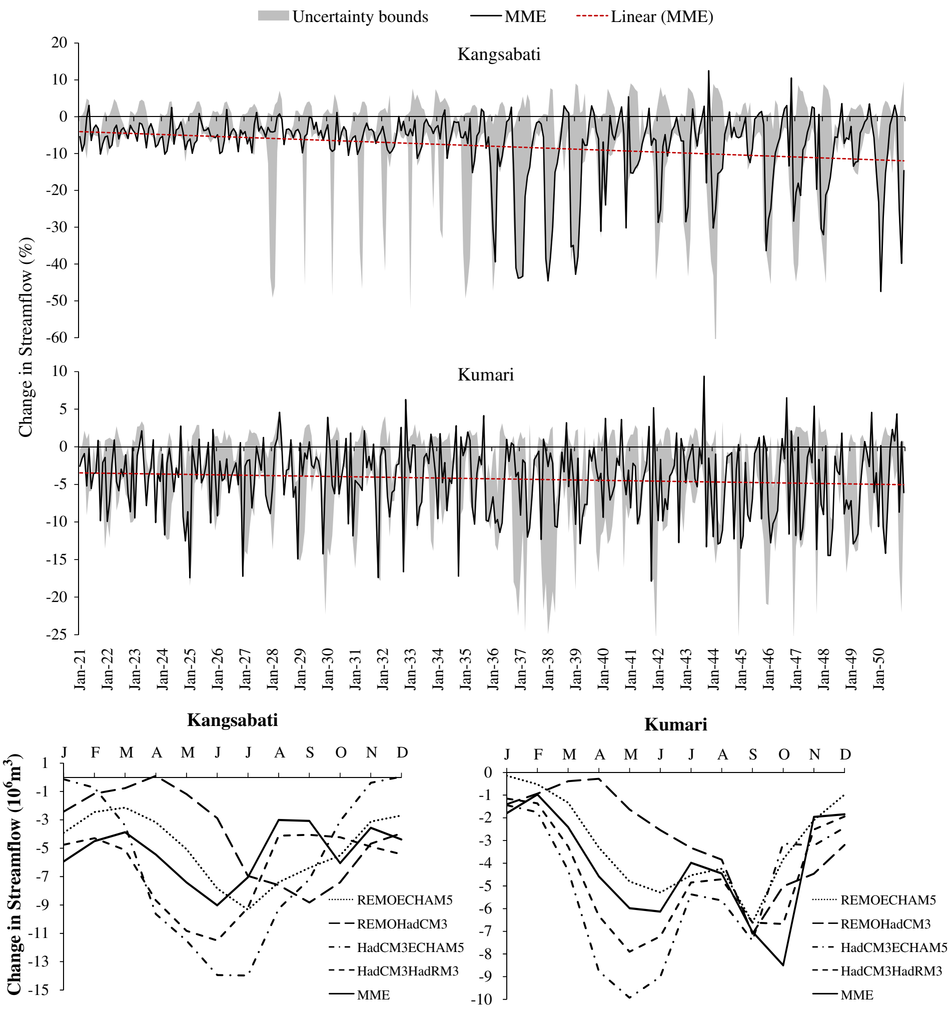



**Fig. 9.** Effect of combined check dams and increasing forest cover for the period 2021–2050 compared to scenario without adaptation as projected by MME (bold line) and uncertainty bounds of four RCMs (grey shaded area) for the Kangsabati and Kumari sub basins with mean monthly change in streamflow for the individual RCMs and their MME.

groundwater recharge as well as evapotranspiration. The modeled hydrologic response corresponds well with the groundwater recharge versus evapotranspiration tradeoff examined by Krishnaswamy et al. (2013). This feature when applied as an adaptation strategy for future climatic projections produces a significant effect on streamflow in the basin. Monthly mean projections demonstrate a pattern of greater monsoon (JJAS) streamflow reduction compared to the post-monsoon (OND) and dry season (MAM) periods. Wide range of projected streamflow in the future may be attributed to the RCM simulations of temperature and precipitation. As indicated by the linear trend, despite a general decrease in precipitation in the catchment, the overall effect of the changed land use on streamflow increases over the study period.

### 3.5.3. Combined effect of check dams and increase in forest cover

When used in combination, CD and IFC have an effect on streamflow of the same order of magnitude as IFC for both the sub-basins (Fig. 9). While a single trough during the MJJ months characterizes streamflow reduction in Kangsabati, a double trough is observed for Kumari sub-basin for MAM and ASO months (Fig. 9). As the linear trend demonstrates the effect of a combination of CD and IFC on streamflow reduction increases over the study period. There is adifference in streamflow response over time in the two sub-basins. While the magnitude of streamflow reduction caused by this adaptation option in the Kangsabati sub-basin increaseswhereas, only a slight change is observed in the Kumari sub-basin.

### 3.5.4. Percent exceedance of streamflow

The relationship between magnitude and frequency of streamflow, provided by percent exceedance curves, is a key aspect of the streamflow regime which is related to adaptation requirement. Adaptation requirement in terms of streamflow magnitude is of major consequence in a monsoon dominated region where high monsoon (JJAS) streamflow is followed by low magnitude streamflow conditions during the dry season (MAM). Fig. 10 demonstrates the effect of the three adaptation options on the percent exceedance of future MME streamflow as compared to the MME base scenario without adaptation. Positive values indicate reduction in streamflow, while negative values indicate increase in streamflow. As far as reservoir inflow is concerned decreasing the intensity of high flows may assist in reducing monsoon floods in downstream sections, while maintaining inflows during the lean period which is important for reliable irrigation and municipal water supply in the reservoir command area. Analysis confirms the lesser order of impact due to CD as compared to IFC and combined effect of CD and IFC. WEAP predicted that CD increases high magnitude streamflow for both Kangsabati and Kumari sub-basins. This effect is more prominent in the Kumari sub-basin due to presence of greater number of check dams where monsoon high flows are

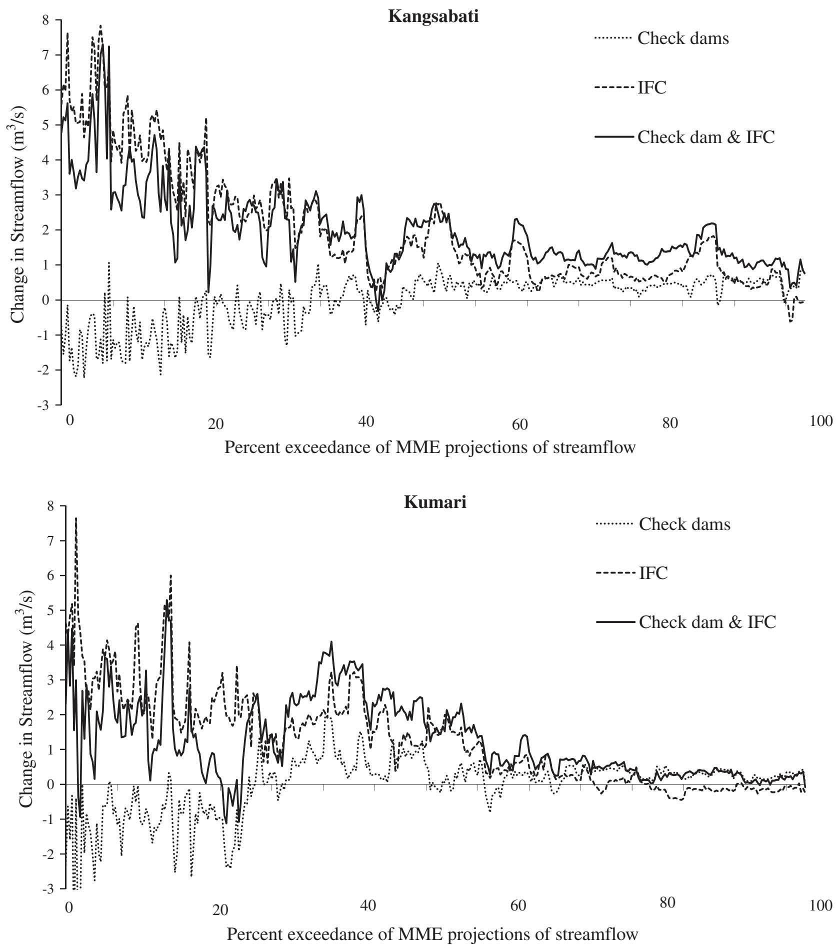



**Fig. 10.** Change in percent exceedance of of streamflow between adaptation (check dams, increasing forest cover and their combination) and without adaptation, estimated using MME projections for the 2021–2050 period.

enhanced by up to 5 $m^3$/s. Low flows on the other hand, which correspond to about 40% of the total flow period, are reduced by $\sim$1 $m^3$/s consistently, leading to an overall reduction in streamflow.

Adaptation options IFC and combined CD and IFC have similar scale and pattern of impacts on the streamflows, but are of different magnitude. Both options reduce high magnitude streamflow, of the order of 3–8 $m^3$/s, and they demonstrate better ability to reduce streamflow as compared to only CD. Application of these two options (IFC and combined CD and IFC) in the Kumari sub-basin does not change low flows while they reduce low flows in the Kangsabati sub-basin. Overall, WEAP predicts similar results for changes caused by IFC and combined CD and IFC ($-0.5$ to 8.0 $m^3$/s) for both sub-basins. Out of these two options, IFC shows greater ability to meet the adaptation requirement, especially for the Kumari sub-basin by reducing high flows by up to 8 $m^3$/s and increasing reservoir inflow by up to 0.5 $m^3$/s during the lean season. Fig. 8 also shows this lean season increase in reservoir inflow for the months of March and April for the Kumari river basin.

## 4. Conclusion

In this study, a combined bottom-up and top-down approach is used to identify, prioritize and evaluate the performance of locally relevant adaptation options in conjunction with stakeholder prioritized criteria. While the bottom-up approach comprised multi-level stakeholder workshops, the top-down approach involved hydrological assessment using the integrated water resources management model WEAP driven by high resolution climatic projections for the mid-21st century. Prioritized adaptation options and their combination are evaluated against the stakeholder prioritized criterion of runoff reduction in the Kangsabati catchment. Analysis of magnitude and temporal pattern of streamflow reduction reveals that IFC and combined CD and IFC are more effective in addressing adaptation requirements compared to CD. Moreover, IFC also has a greater potential to reduce high flows during monsoon and sustain low flows during dry season in comparison with combined CD and IFC. Such an option satisfies stakeholder criterion of runoff reduction in a manner that corresponds to the reasoning provided by them.

An important limitation of the approach used in this study is that the influence of non-climatic factors on streamflow, such as future land use change, population change and demand characteristics, are not accounted for. Better representation of expected changes in these factors will further improve the reliability of the analysis. Beyond the applicability of this study approach and its findings for the Kangsabati catchment, this work demonstrates a reliable approach to combine bottom-up participatory process and top-down modelling tools for identifying, prioritizing and evaluating locally relevant climate change adaptation options. A step further in this research will include a similar analysis of stakeholder prioritized adaptation options for the Kangsabati reservoir command area. This will be followed by stakeholder consultations to discuss the ability of analysed options to meet their requirements. We conclude that such a combined approach is valuable for policy makers as it provides a hydrologically relevant assessment of adaptation options in the face of uncertain future climatic conditions whilst maintaining much needed legitimacy through stakeholder involvement.

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