

Evaluation of hydrological effect of stakeholder prioritized climate change adaptation options based on multi-model regional climate projections

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Abstract An integrated process involving participatory and modelling approaches for prioritizing and evaluating climate change adaptation options for the Kangsabati reservoir catchment is presented here. We assess the potential effects of climate change on water resources and evaluate the ability of stakeholder prioritized adaptation options to address adaptation requirements using the Water Evaluation And Planning (WEAP) model. Two adaptation options, check dams and increasing forest cover, are prioritized using pair-wise comparison and scenario analysis. Future streamflow projections are generated for the mid-21st century period (2021–2050) using four high resolution (~25 km) Regional Climate Models and their ensemble mean for SRES A1B scenario. WEAP simulations indicate that, compared to a base scenario without adaptation, both adaptation options reduce streamflow. In comparison to check dams, increasing forest cover shows greater ability to address adaptation requirements as demonstrated by the temporal pattern and magnitude of streamflow reduction. Additionally, over the 30 year period, effectiveness of check dams in reducing streamflow decreases by up to 40 %, while that of forest cover increases by up to 47 %. Our study highlights the merits of a comparative assessment of adaptation options and we conclude that a combined approach involving stakeholders, scenario analysis, modelling techniques and multi-model projections may support climate change adaptation decision-making in the face of uncertainty.

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1 Introduction

Vulnerable populations practicing subsistence rain-fed agriculture in eastern India are dependent on the consistent functioning of natural cycles. Climate change will affect key components of the hydrological cycle by altering temperature and precipitation patterns (Refsgaard et al. 2013). Moreover, increasing population and changing land use patterns will also affect water availability and demand. Inertia in the climatic system due to previous greenhouse gas emissions and resultant climate change necessitates long-term adaptation from a water resources perspective (Moors et al. 2011; Immerzeel and Bierkens 2012; Mathison et al. 2012). Suitable options addressing location specific adaptation requirements need to be identified, prioritized and evaluated (Arnell 2010). For successful adaptation, options must suit local physiographic and hydroclimatic conditions, socio-economic development and stakeholder acceptability (Adger et al. 2005). No-regret options, the proverbial low-hanging fruit, are considered advantageous for addressing uncertainty because of their robustness and ability to provide benefit irrespective of the severity of climate change impact (Refsgaard et al. 2013). Adaptation options with such characteristics may be effectively identified by involving stakeholders and prioritized using Multi Criteria Analysis (MCA) (de Bruin et al. 2009; Bhave et al. 2013). Equally important is analysis of their effectiveness under multiple future scenarios. Future hydrologic patterns may be different from observed patterns, and should be derived using high resolution future climate simulations (Purkey et al. 2008). Dynamically downscaled Regional Climate Model (RCM) simulations provide an opportunity for hydrological assessment at higher spatial resolutions and provide better rainfall patterns by incorporating finer orographic details (Mathison et al. 2012). Further, multi-model projections allow consideration of uncertainty by providing a range of possible future runoff changes (Refsgaard et al. 2013).

This paper presents an integrated approach to prioritize and evaluate climate change adaptation options based on the framework developed through the HighNoon project (www.eu-highnoon.org) for the Kangsabati reservoir catchment. The overall objective of this paper is to outline a process for assessing regional suitability of adaptation options using modelling approaches, whilst preserving the legitimacy of the approach by incorporating stakeholder knowledge and preferences. Key research questions addressing the objective are:

- Can no-regret adaptation options in the water sector be prioritized using MCA and scenario analysis through multi-level stakeholder processes?
- Can water resources modelling be useful to compare the regional suitability of stakeholder prioritized options for multiple plausible future climate conditions?

A participatory approach, involving multi-level stakeholders, yields prioritized adaptation options with no-regret characteristics. Effectiveness of prioritized options is compared using the Water Evaluation And Planning (WEAP) model forced by four high resolution (~25 km) RCM simulations and their Multi-Model Ensemble (MME) under SRES A1B emission forcing for the period 2021–2050. Suitability of options for local adaptation requirements and implications for regional and national adaptation policy is then discussed.

2 Data and methods

2.1 The study area—Kangsabati reservoir catchment

In the upper reaches of the Kangsabati River, the last tributary of the Ganges in India, lies the Kangsabati reservoir catchment (3,494 km²); our study area (Fig. 1). This drought prone basin is characterized by heavy monsoon (JJAS) rainfall and dry summer months (MAM) with intermittent floods and droughts. The average annual rainfall is 1,400 mm and annual mean temperature is 25.9 °C. It is characterized by highly gullied lands and eroded residual hills due to high monsoon runoff. In absence of large scale irrigation facilities, farmers primarily practice rain-fed agriculture. Projected climatic changes and hydrological impacts indicate

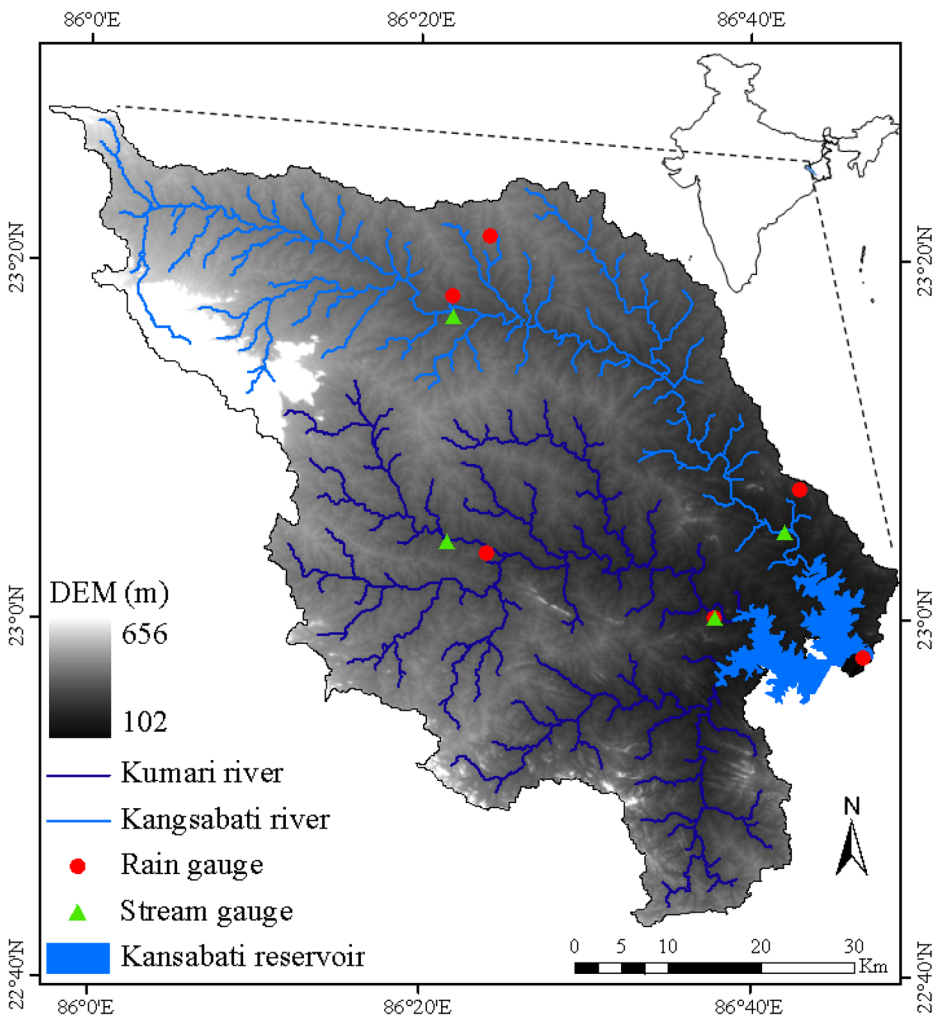


Fig. 1 Map of Kangsabati reservoir catchment

increasing temperature and precipitation extremes in this region (Mittal et al. 2013). For this study, the catchment is divided into two major sub-basins; Kangsabati and Kumari. Both sub-basins are further hydrologically divided into sub-catchments; Hatwara, Simulia and Tusuma in Kangsabati, and Rangagora, Kharidwar and Kangsabati dam in Kumari. Two discharge stations, Simulia and Tusuma, are located on the main river Kangsabati while, stations Rangagora and Kharidwar are located on the river Kumari (Fig. 1). Inflow to the Kangsabati reservoir comprises of the combined streamflow of Kangsabati and Kumari sub-basins.

2.2 Prioritization of adaptation options

Multi-level stakeholder consultations at state, district and community levels were held as a part of the project HighNoon (Figure S.1 in Online Resource). In the first phase, identification of adaptation options was carried out for upstream, midstream and downstream sections of the Kangsabati River basin through a series of workshops. Stakeholders with educational or experiential background in water resources and allied sectors, including policy makers, bankers, water managers, district level scientists of the Indian Council of Agricultural Research (ICAR), farmer organizations and individual farmers, took part in the consultations. A brainstorming tool based on vulnerability assessment and adaptation theory; the problem web-solution web, is used to first map problems (characteristics which make them vulnerable) and their interrelationships. After the creation of a common understanding through knowledge sharing amongst stakeholders, they suggest solutions (adaptation strategies) for specific target problems, based on their knowledge or experience (for details refer Bhave et al. 2013). In the second phase, identified adaptation options are prioritized using two methods; pair-wise comparison and scenario analysis (Figure S.1 in online resource). For this study seven options identified in the catchment (upstream) section are used for prioritization. These included, increasing forest cover, village pond, orchard development, check dams, decentralization of water management, river lift irrigation and agricultural education.

Increasing forest cover is a frequently used soil and water conservation measure, especially in upland areas, but faces challenges regarding land availability, while orchard development is useful for reducing soil erosion. Non-masonry dug ponds (village ponds—locally known as *happa*), with a natural drainage, are useful for fish cultivation, growing vegetables on its periphery and sometimes for local irrigation. Check dams are in-stream masonry structures located on 1st or 2nd order streams which serve as soil and water conservation measures, inducing groundwater recharge and potentially local irrigation in regions with high runoff. On the other hand, river lift irrigation makes irrigation possible at higher levels with low water losses and less acquisition problems, but it is energy and capital intensive and needs larger perennial streams. The options, decentralization of water management and agricultural education, require policy changes and a larger coordinated effort for its effects of better agricultural water management to become visible.

Pair-wise comparison, a matrix-based multi-criteria analysis tool which has often been used for comparing and prioritizing water resources management options (Hajkowicz and Collins 2007) is followed in this study. The criteria for comparing adaptation options are provided by the stakeholders specifying desirable characteristics of suitable adaptation options. The criteria determined through this process include, increase local water availability, runoff reduction, increase awareness regarding water usage, proximity to agricultural land, increasing soil moisture, cost and profit. These seven criteria are again compared pair-wise to determine the most important criteria. In this study, scenario analysis, which involves description of plausible future conditions due to uncertain factors (Coreau et al. 2009) is used to determine no-regret options, which are defined as ones suitable under all future scenarios. We have defined a

scenario space consisting of four possible future conditions (Figure S.1 in online resource) by having socio-economic development (low to high) on the vertical axis and climate change impacts (low to high) on the horizontal axis. Stakeholders assigned each adaptation option to a future scenario, for which it is considered suitable irrespective of the level of climate change impact and socio-economic development.

The analyses resulted in three prioritized options. First prioritized option is decentralization of water management which is a common management practice. Second and third options are water conservation practices; check dams and increasing forest cover (here after referred to as IFC). The water conservation practices are related to the stakeholder prioritized criterion of runoff reduction. Evaluation of options, check dam and IFC considered to be suitable under future climate conditions, requires the application of a water resources system modelling like WEAP, which may be used to compare the effect of these options on the prioritized criterion, runoff reduction. However, prior to the hydrological analysis of the options, an assessment of the suitable number and location of check dams as well as locally relevant increase in forest cover is necessary.

2.3 Identification of suitable check dam locations

Rainfall and resultant runoff are the defining hydrological components for identifying potential check dam locations. Runoff related information may be acquired based on physically derived basin characteristics in regions where rainfall is the major factor influencing it. For initial analysis, 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 slopes < 15 % indicate the amount of runoff which is considered appropriate for identifying check dam locations (Ramakrishnan et al. 2009). Locations so determined are prioritized in a Geographical Information Systems (GIS) environment using key morphometric characteristics such as drainage network, basin geometry, drainage texture and relief; and land use characteristics (Fig. 2). Such physical characteristics are useful criteria for prioritizing basin specific check dam locations (Ramakrishnan et al. 2009). Although first order streams are considered appropriate for siting 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. Additionally, due to land availability concerns, 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, are identified and used for hydrological analysis. Check dams located on the prioritized locations, are characterized by a constant storage capacity of $0.05 \times 10^3 \text{ m}^3$, no buffer storage and uncontrolled spillage. Other than evaporation losses from the check dam, runoff intercepted by check dams contributes to groundwater recharge. Analysis of check dams did not consider irrigation potential of these dams as they can only provide supplemental irrigation.

2.4 Historical and future land use change

Changing land use patterns significantly affect water resources availability by changing runoff characteristics (Stonestrom et al. 2009). Historical land use change studies are often carried out to understand the spatial dynamics in a river basin using satellite imagery. In order to quantify land use changes in the catchment, we used LandSat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM) and ETM + based images for years 1972, 1991, 2001 and 2011.

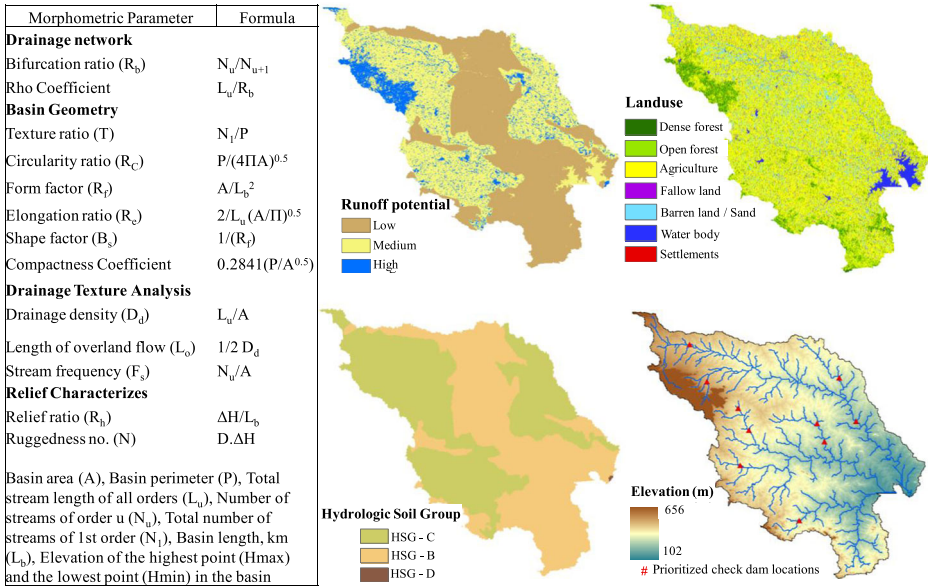


Fig. 2 Morphometric, hydrologic soil group, land use and slope criteria used for prioritizing check dam locations. Overlaying these layers in a Geographical Information System (GIS) environment resulted in prioritized locations for check dams

Unsupervised classification of these 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 (Fig. 3). The major changes observed over the time period indicate reduction in dense forest cover (defined as canopy cover >40 %), increasing area under agriculture and increased degradation of land. 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.

2.5 Regional climate models

For obtaining future climate conditions, four RCM simulations developed through the HighNoon project are used for the period 2021–2050. RCMs, REMO and HadRM3 (horizontal resolution ~25 km), forced with two CMIP3 GCMs; ECHAM5 and HadCM3, based on the SRES A1B scenario, result in four RCM simulations, REMO-ECHAM5, HadRM3-ECHAM5, HadRM3-HadCM3 and REMO-HadCM3. These four RCM simulations are the most comprehensive high resolution future climate projections available for this region and are therefore much useful for hydrological assessment (Mathison et al. 2012). Moreover, ensemble projections of future climate and subsequent hydrological analysis for the entire range of scenarios are a valuable source of information for adaptation planning (Refsgaard et al. 2013). Therefore, for the present study individual RCM projections along with their MME have been used, resulting in a total of five future climate simulations.

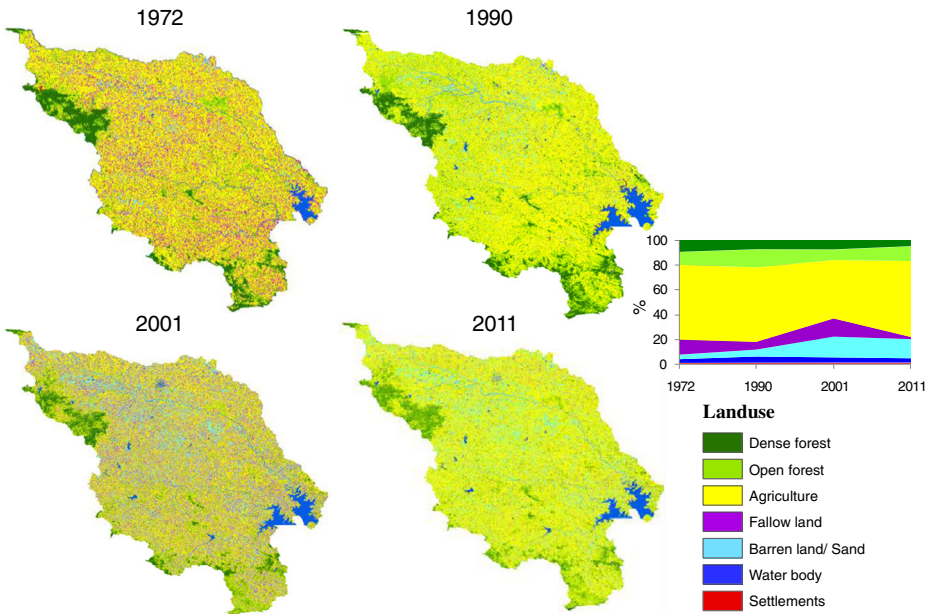


Fig. 3 Historical spatial changes in land use characteristics in the Kangsabati reservoir catchment

2.6 WEAP model and analytical approach

WEAP is a climate driven integrated water resources management model which includes a dynamically integrated rainfall-runoff hydrology module described in detail by Yates et al. (2005a, b). The WEAP modelling framework provides an advantage in analyzing climate change scenarios as it can incorporate expected changes in evapotranspiration associated with changing wind, humidity and temperature patterns. Therefore, this model provides a platform to analyse varying scenarios of a basin's climate, hydrological characteristics, water demand and land use (Mehta et al. 2013). Consequently, in this study, WEAP has been used to analyse climate change impacts and assess stakeholder prioritized adaptation strategies using five future climatic projections for the mid-21st century (Figure S.2 in Online Resource). 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. A monthly time step is used for calibration, validation and future scenario analyses so as to cover the residence time of the study area, during which all flows are assumed to occur (Purkey et al. 2008). The Food and Agriculture Organization (FAO) rainfall runoff method available in the WEAP hydrology module is used to simulate the hydrological processes including evapotranspiration, runoff and infiltration.

Historical observed climate and river gauge data are obtained for a network of stations operated by various authorities; India Meteorological Department (IMD), Central Water Commission (CWC) and the Irrigation and Waterways Department, Govt. of West Bengal (Table 1). Groundwater information is obtained from the Govt. of West Bengal (2003) and the web portal of the Central Ground Water Board (CGWB) which provides data on ground water

monitoring stations. LandSat image based land use classification for the years 1991, 2001 and 2011 is used as input for WEAP. For analyzing future streamflow, three WEAP scenarios are obtained for each of the five climatic projections derived from four RCMs and their ensemble. These three WEAP scenarios include a base scenario without adaptation, a scenario with check dams and another with IFC. A mid-21st century time-frame (2021–2050) is chosen for analyzing 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).

The WEAP model is calibrated and validated at the four streamflow gauging stations located in the catchment (Fig. 1, Table 1) which represent the natural streamflow of the region due to minimal anthropogenic interference. Observed climatic and discharge parameters for a 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, defined as “the percentage of rainfall available for evapotranspiration, while the remainder is available for runoff”, is 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.

3 Results

3.1 Calibration and validation

Results (Fig. 4 and Table 2), indicate reasonable ability of the model in simulating long term streamflow as well as monthly mean streamflow for the 20 year period (Fig. 4 inset diagram). 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). PBIAS statistics are better for the downstream river gauges of Kharidwar (–6.7 %) and Tusuma (–4.5)

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

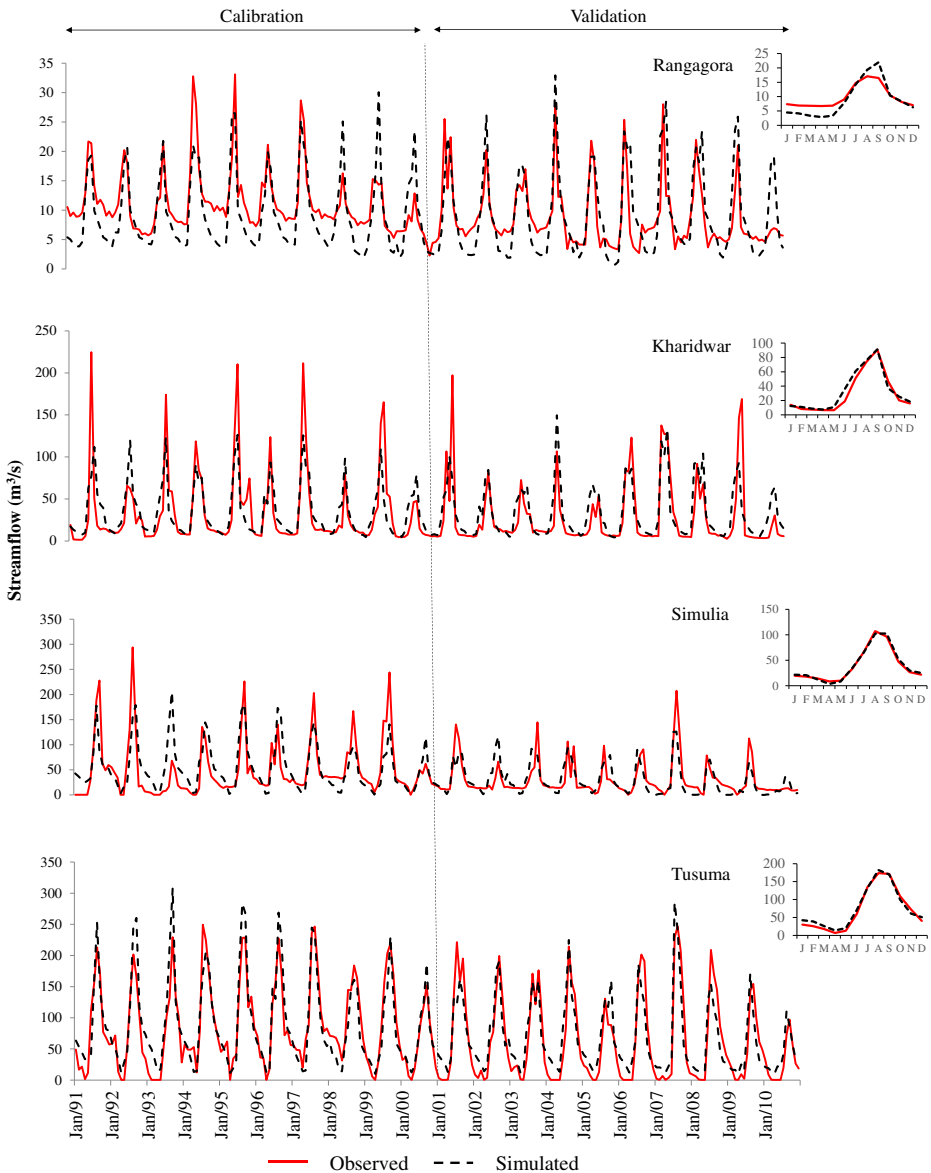


Fig. 4 Observed (*line*) and WEAP-simulated (*dotted*) monthly streamflow time series for the calibration and validation period at four ststations in the Kangsabati reservoir catchment. Inset diagram represents average monthly flows over the 20 year period (1991–2010)

compared to upstream gauges Rangagora (8.5 %) and Simulia (−6.4 %). Despite the simplified representation of groundwater contribution and the challenges of simulating streamflow characteristics of heavy precipitation months (JJAS), the model demonstrates good results for PBIAS (Moriassi et al. 2007). Overall, we find the validated model adequately reproduces the monthly streamflow and may be useful in exploring potential changes in streamflow due to climate change and to evaluate the effect of adaptation strategies.

Table 2 Statistical results of model calibration and validation period for four streamflow gauging stations in the Kangsabati reservoir catchment

Station	Calibration (1991–2000)			Validation (2001–2010)		
	NSE	PBIAS	R ²	NSE	PBIAS	R ²
Rangagora	0.9	8.5	0.8	0.9	12.5	0.8
Kharidwar	0.8	−6.7	0.8	0.8	−10.5	0.8
Simulia	0.8	−6.4	0.7	0.6	5.5	0.8
Tusuma	0.8	−4.5	0.9	0.8	−6.7	0.9

3.2 Projected hydrological changes resulting from future climate change simulations

The performance validation of the RCMs, REMO and HadRM3 driven by lateral boundary forcings from ERAInterim reanalysis data for 20 year period (1989–2008) in simulating temperature and precipitation patterns for this region provides confidence in the ability of these 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 compared to average of the observed period (Fig. 5). This increase may have significant impact on evapotranspiration, affecting the surface hydrological budget (Im et al. 2010). Due to greater conformity between models, a more coherent trend is observed for future temperature projections. Although a slight decrease in annual precipitation (−6.6 %) is demonstrated by the ensemble mean, there is lesser conformity between models regarding future precipitation changes. While REMO-HadCM3 (−5.1 %) and HadRM3-HadCM3 (3.3 %) project an increase, REMO-ECHAM5 (−12.9 %) and HadRM3-ECHAM5 (−2.5 %) project a decrease in precipitation. Forced by these five climatic model projections WEAP predicted monthly streamflows show a wide range of potential streamflow for the future. WEAP simulations of reservoir inflows demonstrate a decreasing trend where annual inflows for the MME indicate a reduction of about 23 %, from 1991 to 2050, which amounts to about $0.45 \times 10^3 \text{ m}^3$ (Fig. 5).

3.3 Simulated hydrological effect of adaptation strategies

Changes in future flow regimes will significantly impact water availability. The level of suitability of adaptation strategies will depend on ability to usefully influence the flow regime simulated for the scenario without adaptation. Integration of nine check dams in WEAP modelling generates a reduction in projected streamflow compared to the scenario without adaptation (Fig. 6). In the absence of irrigation from check dams, this streamflow reduction adds to the groundwater component in WEAP. Greater streamflow reduction is predicted in Kumari sub-basin (six check dams) compared to the Kangsabati sub-basin (three check dams). It follows that more check dams result in a greater cumulative effect on streamflow. However, magnitude of this cumulative effect decreases by up to 40 % by 2050 as indicated by the linear trend for the MME based projection. This reduction in cumulative effect is despite the modelling assumption of constant check dam storage capacity over the 30 year period. A reason for this may be the projected decrease in future streamflow, which also has an effect on reservoir inflow as shown in Fig. 5. Despite the wide range of projected monthly mean streamflow, a pattern of streamflow reduction is observed, with greater reduction during MAM compared to JJAS.

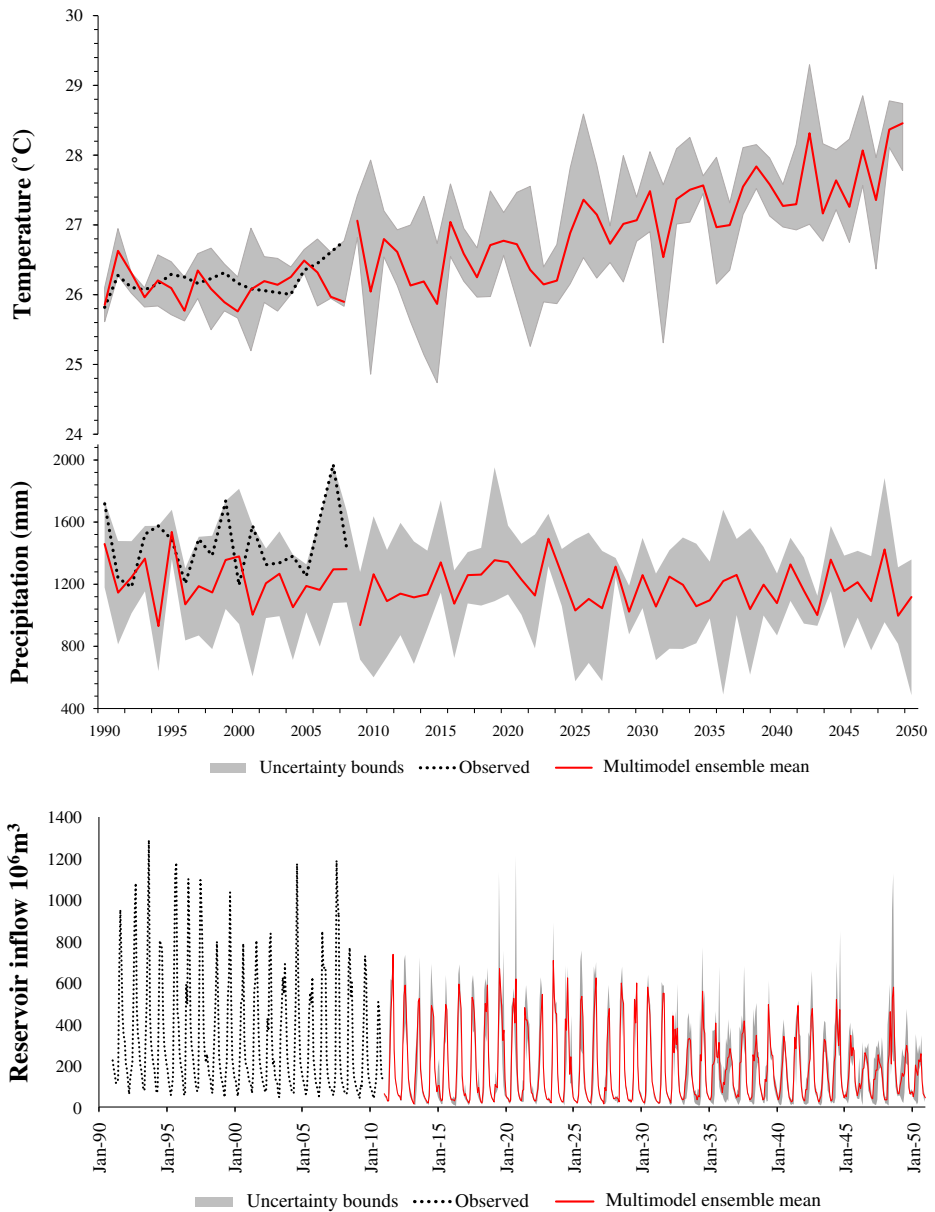


Fig. 5 Long term changes in observed (*dotted*) and projected (*line*) annual temperature, precipitation based on four RCMs under the A1B scenario and their ensemble for the study period is shown along with the corresponding reservoir inflow. The *shaded area* shows the model spread indicating the level of uncertainty in model prediction

The reduction in streamflow due to increasing forest cover (Fig. 7), compared to a scenario without adaptation, occurs primarily during JJAS monsoon months for both sub-basins. This reduced runoff contributes to groundwater recharge in the water balance accounting of WEAP. Change of land use affects runoff by altering effective precipitation. Monthly mean projections

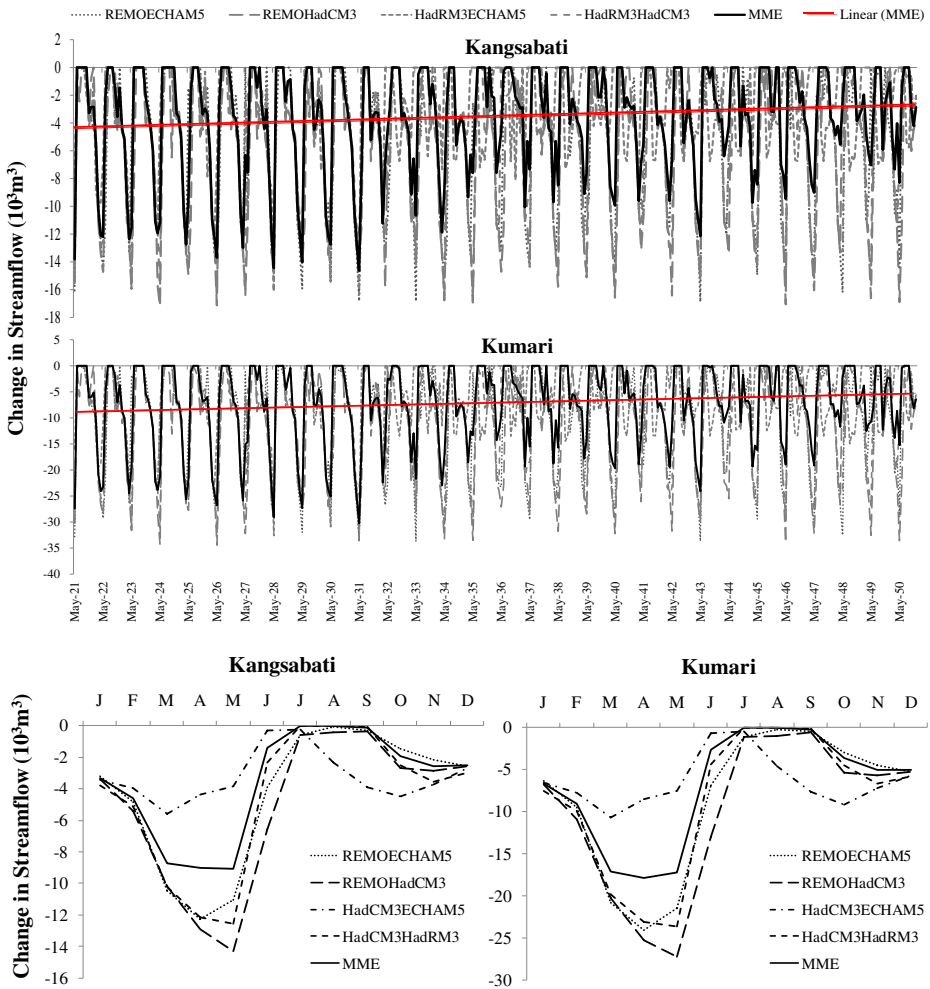


Fig. 6 Effect of check dams on runoff: Inter-annual and monthly variability in projected changes in streamflow at outlets of Kangsabati and Kumari sub-basins due to check dams. *Solid line* represents streamflow generated by ensemble climate projections, while *red line* is a linear trend line

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. We find that the overall effect of the changed land use increases by up to 47 % over the study period. Moreover, a difference of an order of magnitude is observed between the effect produced by IFC and check dams.

4 Discussion and conclusion

Increasing evapotranspiration caused by increasing temperature, coupled with decreasing trend of precipitation, will affect water availability in the Kangsabati reservoir catchment.

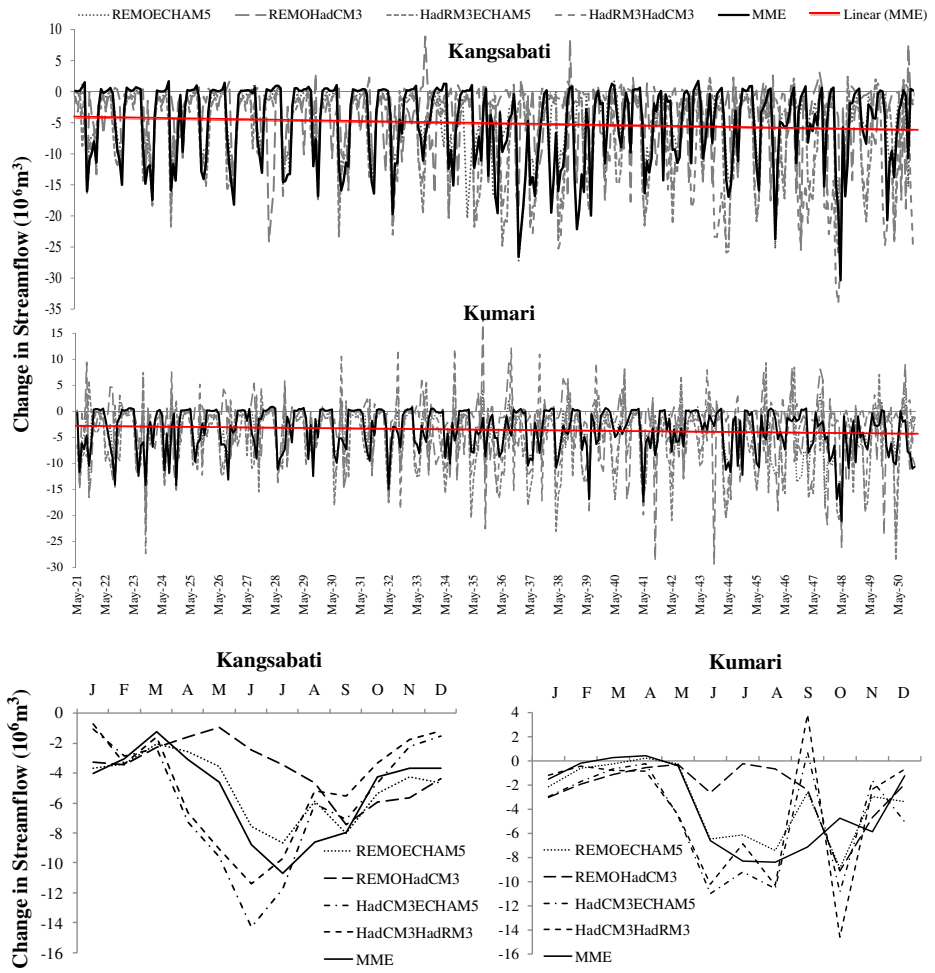


Fig. 7 Effect of increasing forest cover on runoff: Inter-annual and monthly variability in projected changes in streamflow at outlets of Kangsabati and Kumari sub-basins due to increase of dense forest cover and conversion of barren land into open forest. *Solid line* represents streamflow generated by ensemble climate projections while *red line* is a linear trend line

Although the effect of increased CO₂ levels is not accounted for in the estimation of evapotranspiration, uncertainty associated with this and other factors does not affect the inference that adaptation is essential. Moreover, historical trends of forest cover reduction, increasing population and water demand, if continued, will increase anthropogenic pressure on natural systems. Therefore, locally suitable adaptation options, which address biophysical and socio-economic aspects, are crucial in this region, making a combined assessment using biophysical modelling and participatory approaches appropriate (Arnell 2010). Climate change impact on runoff of the two sub-basins is different due to spatial and temporal variation in hydroclimatological response within the catchment. Results indicate that check dams and increasing forest cover as adaptation strategies have a similar type of impact; reducing streamflow. However, the timing and magnitude of

change differs considerably. Given the expected increase in high precipitation events, consecutive days without precipitation and increasing summer temperature (Mittal et al. 2013), a strategy which reduces peak monsoon streamflow and increases streamflow during dry season would be more beneficial. Such characteristics, demonstrated by option IFC, will also prove beneficial in providing consistent inflow to the Kangsabati reservoir and consequently greater reliability of irrigation water availability in the downstream areas.

Although pair-wise comparison was found to be satisfactory for prioritizing options when working with multiple stakeholders, a detailed MCA may enhance the value of the findings. We find that scenario analysis is useful in determining no-regret adaptation options and such an approach may be vital from a developing country perspective due to limited financial, technological and human resources available. Altering land use patterns is arguably the best way for adapting to climatic changes whilst keeping ecosystem services intact (Verburg et al. 2012). Also, future land use evolution will be a key factor influencing extent of climate change impacts on water resources. In such circumstances, cross-sectoral policy integration may assist in increasing robustness of adaptation (Huntjens et al. 2012). Such integration is illustrated by the ‘Green India Mission’, which adds the mandate of increasing forest cover from an adaptation perspective to existing mechanisms of the Ministry of Environment and Forests. However, since our results indicate that land use change is an important factor affecting local water resources availability, policy integration should also include water resources management.

Climate change adaptation policy making will also need to take into account the type, timing and magnitude of climate change impacts, stakeholder preferences and uncertainties associated with natural and anthropogenic systems (Refsgaard et al. 2013). Uncertainties associated with climatic projections, participatory approaches, WEAP model representation, influence reliability in determining suitable adaptation options. Indeed, with the new CMIP5 model outputs, regional climatic projections and consequent future hydrological impacts in this region may be altered. Determining the level of uncertainty is a complex issue, especially in a study where combined modelling and participatory approaches are used to analyse future hydroclimatological conditions. No-regret options which support robust adaptation planning will be therefore crucial. Moreover, amongst such options, if the difference between desired effect of adaptation strategies across multiple climatic projections and future scenarios is found to be in orders of magnitude, the effect may be valuable despite the level of uncertainty involved.

A common thread running through this study is the comparative assessment of ability of stakeholder identified no-regret adaptation options to produce a desired effect in order to mitigate the impacts of climate change. We find that a combined approach using multiple RCM projections, stakeholder based prioritization and hydrological modelling approaches may provide locally relevant information regarding the suitability of adaptation options for decision-making. We infer that despite the cascading uncertainties, often enough knowledge, especially with stakeholders, is available to justify action in the crucial water resources sector. Future work may involve comparing options which influence water demand characteristics whilst including more realistic projections of population increase, domestic water demand and land use change. Assessing the uncertainty range of future climatic and hydrological projections using scenario analysis tool may also increase confidence in decision-making.

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References

- Adger WN, Arnell NW, Tompkins EL (2005) Successful adaptation to climate change across scales. *Glob Environ Chang* 15(2):77–86
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements—FAO Irrigation and drainage paper 56, FAO, Rome
- Arnell N (2010) Adapting to climate change: an evolving research programme. *Clim Chang* 100:107–111
- Bandyopadhyay A, Bhadra A, Swarnakar RK, Raghuvanshi NS, Singh R (2012) Estimation of reference evapotranspiration using a user-friendly decision support system: DSS_ET. *Agric For Meteorol* 154:19–29
- Bhave AG, Mishra A, Groot A (2013) Sub-basin scale characterization of climate change vulnerability, impacts and adaptation in an Indian River basin. *Reg Environ Chang* 1–12. doi:10.1007/s10113-013-0416-8
- Central Ground Water Board. Water level information, Ground Water Information System. URL: <http://gis2.nic.in/cgwb/Gemsdata.aspx>
- Coreau A, Pinay G, Thompson JD, Cheptou PO, Mermet L (2009) The rise of research on futures in ecology: rebalancing scenarios and predictions. *Ecol Lett* 12(12):1277–1286
- de Bruin K, Dellink RB, Ruijs A, Bolwidt L, van Buuren A, Graveland J, de Groot RS, Kuikman PJ, Reinhard S, Roetter RP, Tassone VC, Verhagen A, van Ierland EC (2009) Adapting to climate change in the Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Clim Chang* 95:1–2
- De Winnaar G, Jewitt GPW, Horan M (2007) A GIS-based approach for identifying potential runoff harvesting sites in the Thukela River basin, South Africa. *Phys Chem Earth* 32(15):1058–1067
- Govt. of India (2008) National action plan on climate change. URL: http://pmindia.gov.in/climate_change_english.pdf
- Govt. of West Bengal (2003) Performance evaluation study and system analysis of Kangsabati reservoir project. Vol. I and II
- Hajkowicz S, Collins K (2007) A review of multiple criteria analysis for water resource planning and management. *Water Resour Manag* 21(9):1553–1566
- Huntjens P, Lebel L, Pahl-Wostl C, Camkin J, Schulze R, Kranz N (2012) Institutional design propositions for the governance of adaptation to climate change in the water sector. *Glob Environ Chang* 22(1):67–81
- Im ES, Jung IW, Chang H, Bae DH, Kwon WT (2010) Hydroclimatological response to dynamically downscaled climate change simulations for Korean basins. *Clim Chang* 100(3–4):485–508
- Immerzeel WW, Bierkens MFP (2012) Asia's water balance. *Nat Geosci* 5(12):841–842
- Mathison C, Wiltshire A, Dimri AP, Falloon P, Jacob D, Kumar P, Moors E, Ridley J, Siderius C, Stoffel M, Yasunari T (2012) Regional projections of North Indian climate for adaptation studies. *Sci Total Environ* 365. doi:10.1016/j.scitotenv.2012.04.066
- Mehta VK, Haden VR, Joyce BA, Purkey DR, Jackson LE (2013) Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. *Agric Water Manag* 117:70–82
- Mittal N, Mishra A, Singh R (2013) Combining climatological and participatory approaches for assessing changes in extreme climatic indices at regional scale. *Clim Chang*. doi:10.1007/s10584-013-0760-1
- Moors EJ, Groot A, Biemans H, Terwisscha van Scheltinga C, Siderius C, Stoffel M, Huggel C, Wiltshire A, Mathison C, Ridley J, Jacob D, Kumar P, Bhadwal S, Gosain A, Collins DN (2011) Adaptation to changing water resources in the Ganges basin, northern India. *Environ Sci Pol* 14(7):758–769
- Moriassi D, Arnold J, Van Liew M, Bingner R, Harmel R, Veith T (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans ASABE* 50:885–900
- Purkey DR, Joyce B, Vicuna S, Hanemann MW, Dale LL, Yates D, Dracup JA (2008) Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley. *Clim Chang* 87(1):109–122
- Ramakrishnan D, Bandyopadhyay A, Kusuma KN (2009) SCS-CN and GIS-based approach for identifying potential water harvesting sites in the Kali Watershed, Mahi River Basin, India. *J Earth Syst Sci* 118(4):355–368
- Refsgaard JC, Arbjerg-Nielsen K, Drews M, Halsnæs K, Jeppesen E, Madsen H, Markandya A, Olesen JE, Porter JR, Christensen JH (2013) The role of uncertainty in climate change adaptation strategies—a Danish water management example. *Mitig Adapt Strateg Glob* 18(3):337–359
- Stonstrom DA, Scanlon BR, Zhang L (2009) Introduction to special section on impacts of land use change on water resources. *Water Resour Res* 45(7)
- Verburg PH, Koomen E, Hilferink M, Pérez-Soba M, Lesschen JP (2012) An assessment of the impact of climate adaptation measures to reduce flood risk on ecosystem services. *Landsc Ecol* 27(4):473–486
- Yates D, Sieber J, Purkey D, Huber Lee A, Galbraith H (2005a) WEAP21: a demand, priority, and preference driven water planning model: part 2, aiding freshwater ecosystem service evaluation. *Water Int* 30(4):487–500
- Yates D, Sieber J, Purkey D, Huber Lee A (2005b) WEAP21: a demand, priority, and preference driven water planning model: part 1, model characteristics. *Water Int* 30(4):501–512