The Future Nexus of the Brahmaputra River Basin: Climate, Water, Energy and Food trajectories
Y. C. Ethan Yang1*, Sungwook Wi1, Patrick A. Ray1, Casey M. Brown1 and Abedalrazq F. Khalil2
1Department of Civil and Environmental Engineering, University of Massachusetts-Amherst, Amherst, MA, USA
2The World Bank, Washington DC, USA
*Corresponding author, +1-413-577-3232, yceyang@umass.edu

Acknowledgements
The work has been supported financially by the World Bank project: Hydro-economic modeling of the Brahmaputra and Kabul River. Authors want to thank three anonymous reviewers for their constructive comments on the earlier version of the manuscript. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the World Bank. All input data used for both hydrologic model (precipitation, temperature and glacier coverage, etc.) and system model (water use, crop production and hydropower, etc.) are explicitly cited in the reference list.
The Future Nexus of the Brahmaputra River Basin: Climate, Water, Energy and Food trajectories

Highlights

• This paper applied ex post scenario analysis under the “nexus thinking” concept to identify where development paths are in conflict in the Brahmaputra River
• Results of the hydro-economic water system model quantify precipitation change is the dominant single driver that affect water-energy-food nexus in the basin
• The combination of “temperature change and precipitation change” and “precipitation change and Chinese diversion” are two dominant drivers that affect water-energy-food nexus in the basin
• Interactive parallel coordinate plots have been developed and made available as web-based decision support tools (e.g., http://people.umass.edu/yceyang/ChinaWEF.html)
The Future Nexus of the Brahmaputra River Basin: Climate, Water, Energy and Food trajectories

Abstract
Advance knowledge of conflicting trajectories of water-energy-food (WEF) nexus is highly relevant for water policy and planning, especially for basins that cross national boundaries. The Brahmaputra River Basin in South Asia, home for 130 million people, is such a basin. Development of new hydropower projects, upstream water diversions and possible climate changes introduce concerns among riparian countries about future water supply for energy and food production in the basin. This study presents a new hydro-economic water system model of the basin coupled with ex post scenario analysis under the “nexus thinking” concept to identify and illustrate where development paths are in conflict. Results indicate that the ability of future development to remain free of conflict hinges mostly on the amount of precipitation falling in the basin in the future. Uncertain future precipitation along with uncertain future temperature and the unknown amount of upstream water diversion combine to strongly influence future water, energy and food production in the basin. Specifically, decreases in precipitation coupled with large upstream diversions (e.g., diversion in the territory of China) would leave one or more riparian countries unable to secure enough water to produce their desired energy and food. Future climate projected by General Circulation Models suggest a warmer and wetter climate condition in the region, which is associated with an increase in streamflow and easing of conflicts at the WEF nexus in the basin. The methodology presented here is expected to be generally useful for diagnosing the conditions that may cause water resources development goals to not be achieved due to either changes in climate or water use among competing users.

Keywords: The Yarlung Tsangpo River, The Jamuna River, water resources systems analysis, transboundary water management, ex post scenario analysis
1. Introduction

Advance knowledge of conflicting trajectories of transboundary water resources development at a basin scale is highly relevant for national and international policy making. While military conflict may or may not arise as a result of conflicting water resources development plans (Gleick, 2011; Wolf, 2007), without coordination it is unsurprising that such plans may exceed the available water resources of a basin and not achieve desired objectives of riparian countries. In particular, concerns that the multiple uses of water (e.g., for energy and food production) may overlap and lead to unanticipated consequences for one sector or another, popularly referred to as a “nexus,” may be especially vexing in rapidly developing transboundary basins.

The Brahmaputra River Basin (BRB) in South Asia is such a basin, with development of new hydropower/water diversion projects and possible climate changes introducing concerns among riparian countries about future water supply for energy and food production (Ray et al., 2015). The Brahmaputra (also called the Yarlung Tsangpo in China and the Jamuna in Bangladesh) has a total drainage area of about 570,000 km$^2$. Its main stem and tributaries flow through four countries: China, India, Bhutan and Bangladesh (Figure 1). It is the foundation of water, energy and food for an estimated 130 million people living within the basin, and since the river flows through some of the most highly disputed areas in South Asia, the potential for riparian conflicts of interest over water resources development is significant. For the Brahmaputra River’s water resources that have been largely undeveloped, conflicts of interest have so far taken the form of downstream states’ objections to the proposed water-related plans of upstream states. Now that upstream states are enacting water development plans, these plans have a potential for increasing conflict between states. For example, ten dams comprising six gigawatts (GW) of hydropower generating capacity are currently under construction in the basin (Rahaman, 2012). Both China and India are evaluating the potential effects of transboundary water diversions made for use both inside and outside of the BRB. Bhutan is rapidly developing its hydropower resources, in partnership with India. Bangladesh is eager to gain greater protection from monsoon floods, and secure water resources for the agricultural irrigation.

To better understand the interconnection of water, energy and food security and reduce the conflicts of interest among riparian countries, “nexus thinking” has been suggested by several previous studies (Biggs et al., 2015; Rasul, 2014; Rasul and Sharma, 2015; Scott et al., 2015). First conceived by the World Economic Forum (WEF, 2011), nexus thinking is advocated as an advance on current and often sector-focused governance of natural resource use. It aims to link water, energy and food together systematically and provide tools to increase resource use efficiency. It ensures policy coherence and coordination across sectors and stakeholders to build synergies and generate co-benefits (Rasul and Sharma, 2015). In South Asia, Rasul (2014) pointed out the limited efforts to understanding the spatial and regional dimensions of the water-energy-food (WEF) nexus in the Himalayan region, and argued that proactive decision-making supported by water resources system models is needed for the development of the region’s water resources. Rasul and Sharma (2015) suggested switching from sectoral-focused policy approaches to a nexus approach focusing on policy coherence among sectors.

As summarized by Scott et al. (2015) there are three aspects of institutional performance to be examined when pivoting from a sectoral approach to policy-making toward a nexus approach: 1) institutional levels (or spatial scales), from household to multinational; 2) institutional functions, which foster social consensus, enabling increased economic production and administrating laws and regulations justly; and 3) considering higher human needs of esteem
and self-actualization. International water treaties are good entry points to examine the institutional dimensions of the WEF nexus. These treaties usually address the questions of institutional levels and functions. Although transboundary waters in the South Asian river basins have led to international water treaties, such as the 1996 Ganges Water treaty between Bangladesh and India, the 1996 Mahakali treaty between India and Nepal, and the 1960 Indus Water Treaty between India and Pakistan, no multilateral or basin-wide international treaty has yet been established on the use of BRB waters (Uprety and Salman, 2011). We argue that nexus thinking, which includes the international level of cooperative management actions and addresses the socioeconomic needs of different riparian countries would be the first step in the formation of an international water treaty on BRB waters.

When developing an institutional framework for WEF nexus-based policy making, the impacts of change generally, and climate change in particular, must be explicitly addressed. Responses to climate change in the BRB can be distinguished according to the different hydrologic regimes within the basin: snow/glacier melt-dominated in the upper part (mostly the mountainous areas of China, India and Bhutan), and monsoon rainfall in the lower part (mostly the floodplains of India and Bangladesh). While there are numerous studies of the region’s historical and future climate, a great deal of uncertainty remains (Annamalai et al., 2007; Yang et al., 2008; NRC, 2012; Pithan, 2013). There is general agreement between observed and projected increases in temperature (Song et al., 2011; Gao et al., 2008; Xu et al., 2009). And the retreat of glaciers in the region has been attributed to the increasing temperature (Yao, 2008; Eriksson et al, 2009; Bajracharya and Shrestha, 2011). However, while projections of future climate have tilted towards increasing precipitation (Li et al., 2010; Turner and Annamalai, 2012; Menon et al., 2013), analysis of observed precipitation indicates decreasing trends (Jain and Kumar, 2012; Deka et al., 2013). Given that the physical processes that drive the South Asian Monsoon are not completely understood (Beniston et al., 1997; Annamalai et al., 2007; Yang et al., 2008) and not fully represented in global/regional climate models, interpretation of climate projections as deterministic limits on the range of future climate change is not warranted (Stainforth et al., 2007; Brown and Wilby, 2012).

Assessing the joint impacts of development and climate change on the WEF nexus in the BRB requires careful consideration and simulation of both physical processes and institutional decision-making. This study presents a modeling framework combining physically-based hydrologic modeling, hydro-economic modeling, and ex post scenario analysis within a decision-scaling framework (Brown, 2010) to elicit the conditions under which development trajectories conflict and where they align. Trajectories represent the transient nature of both climate change and development and highlight the delayed nature of conflicts that is invoked by decisions made in the present. Policy-relevant, ex post scenario analysis (Groves and Lempert, 2007) allows problematic scenarios to emerge from the analysis and is used in response to the degree of uncertainty associated with future climate and changes in other factors. This proposed modeling framework quantifies the WEF nexus under these uncertainties and addresses the institutional dimension by targeting the concern of increasing economic production and fostering social consensus at international level.

2. Methodology

The effects of climate change and development choices on the use of water resources in the BRB are explored with a coupled modeling framework using ex post scenario analysis. The first modeling part is based on a physically-based hydrologic model applied to the spatially
distributed basin system, in which the hydrological water cycles are simulated at a daily temporal scale. The modeled streamflow is used as an input to drive the second model, a water resources system model, which takes into account the human water use activities in the basin to estimate the economic value of water in different uses. The effect of climate change and development choices are evaluated using the ex post scenario analysis, which identifies bounds of natural and social drivers to inform WEF nexus decision making.

2.1 Ex post scenario analysis

Plans on basin-wide water use typically rely on optimization models with objective functions that are often related to maximizing discounted net economic benefits (Harou et al., 2009). However, a well-known limitation of this approach is that it struggles to incorporate difficult-to-quantify political or social objectives (Harou et al., 2009) that may be important factors in basin development decisions. As a result, the so-called “non-inferior solution set” may in fact be inferior to other solutions from a perspective of decision makers. In addition, the majority of approaches to river basin planning are often limited in their way of dealing with uncertainty, due mainly to the computational intensity required for the uncertainty analysis.

This study proposes an alternative approach based on explicit recognition of the limited ability of models to quantify the objectives of real decision making processes. We capitalize on the recent climate change risk assessment framework in which the focus is on seeking strategies that perform well over a wide range of future uncertainties rather than attempting to identify optimal strategies (e.g. Robust Decision Making, Lempert and Collins, 2007; Decision scaling, Brown, 2010 and Dynamic Adaptive Policy Pathways, Haasnoot et al., 2013). The framework inverts the typical scenario analysis approach used in traditional river basin management studies with a “policy-relevant scenario identification process” (Groves and Lempert, 2007) to better inform policy making and we adopt the term “ex post scenario analysis.” Rather than primarily exploring the impacts of different drivers and in some cases seeking optimal adaptation to their consequences, this study defines the future system performance that is sought, and in inverse fashion diagnoses the conditions under which that future system outputs are “acceptable” or “unacceptable.” This is similar to the concept of “running the analysis backward” in Robust Decision Making (Lempert et al, 2006). These outputs then provide a clear threshold for decision making. In addition, the approach avoids ex ante assignment of probabilities to the values of different drivers, such as climate change, because such assignments are difficult to justify, and when used the study becomes dependent on the quality of them (Brown et al., 2012).

2.2 Coupled Modeling Framework - Hydrologic model

In this study the hydrologic model HYMOD_DS (Wi et al., 2015) was developed to simulate the BRB system. The model is spatially distributed, meaning the entire BRB area is disaggregated to match the gridded spacing of climate inputs. Within each grid cell, the soil moisture accounting, evapotranspiration, snow/glacier processes and flow routing are modeled at a daily time step. Gridded daily temperature and precipitation products with a spatial resolution of 0.5° from the Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE) dataset (Yatagai et al., 2012) were used as climate input data. To account for a downward bias in the APHRODITE precipitation data reported by Palazzi et al. (2013), the APHRODITE precipitation data were bias-corrected using the precipitation data from the Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2014).

HYMOD_DS was developed specifically for modeling mountainous regions of South Asia and includes a glacier modeling component that requires prior information on the glacier
volume in the basin. The glacier coverage in the BRB was obtained from the Randolph Glacier Inventory version 3.2 (RGI 3.2, Pfeffer et al., 2014) and glacier volume was estimated using the multivariate glacier area-volume scaling relationships proposed by Grinsted (2013). Monthly streamflow observations were used to calibrate and assess the HYMOD_DS performance and were obtained from: the Global Runoff Data Centre (GRDC, 2015), the Bangladesh Water Development Board (BWDB), feasibility studies of proposed dams (CISMHE, 2009, 2011; NPC, 2010), and published literature (Gao et al., 2008). The detailed description on the model structure parameters are provided in Wi et al. (2015).

2.3 Coupled Modeling Framework - Water resources system model

Water resources systems models and/or hydro-economic models are commonly used to illustrate the effects on the water system of changing natural divers (e.g. climate change) and social drivers (e.g. development choices like water diversions or new dams), and to evaluate different basin development plans (Brown et al., 2015). In South Asia, water resources system models have been used for many locations, notably the Ganges (World Bank, 2012) and the Indus Basins (Duloy and O’Mara, 1984; Ahmad et al., 1990; Yu et al., 2013). However, no such modeling effort has been initiated for the BRB. Previous modeling studies of this basin have tended to focus on agricultural production (Hassan et al., 2014; Ruane et al., 2013; Yu et al., 2010), and streamflow/flood simulation in the downstream states (Artan et al., 2008; Gain et al., 2011; Pervez and Henebry, 2014; Yang et al., 2015).

The BRAhmaputra HydroEconomic MOdel (BRAHEMO) was developed to address this gap. It utilizes an optimization framework that searches for optimal decision plans for water allocation between energy production and agriculture. In this study, decisions on the spatial and temporal allocation of water for agriculture, hydropower production and streamflow are optimized in order to maximize an objective function that is the sum of the basin-wide net economic benefits. The use of an objective function that maximizes net economic benefits results in decisions leading to economically efficient plans achievable from the best water allocation.

Decisions related to the number, location and size of new dams are not part of the optimization. As a result, monthly water allocation for irrigation is the most influential decision variable within the model. Water allocations for domestic water supply and hydropower generation are other decision variables in the model; however, their influences to objective function are lower. This is because domestic water supply is given the highest priority and is satisfied first in the model. Most of the current and under-construction dams in the BRB have only small storage; therefore, the water uses for hydropower generation are controlled by streamflow only. More details are given in the following section.

The BRAHEMO was created in the environment provided by the General Algebraic Modeling System (GAMS). BRAHEMO includes a number of constraints on the decision variables, such as: 1) mass balance on water, 2) hydropower generation capacity, 3) available crop land, 4) crop water requirement, and 5) groundwater pumping limits. Five kinds of data are needed for BRAHEMO: agricultural data, hydropower data, domestic water use data, groundwater pumping data, and streamflow data at inflow points. In this application the streamflow is estimated using the HYMOD_DS model. The schematic of the BRAHEMO showing all agricultural demand sites and existing/planned dams is given in Figure 2. A detailed description of the BRAHEMO is given in the Appendix.
3. Uncertainty Framework

Scenario-led analyses make prejudgments regarding possible future scenarios that are overconfident and thus prejudice the study results (Brown, 2010). To address a highly uncertain future with potential planning conflicts that cannot be entirely anticipated, this study explores a wide ranging ensemble of future conditions related to climate change and development. In this way, all problematic scenarios can be uncovered using ex post scenario analysis. The problematic scenarios can later be deemed unlikely or even implausible in some cases. However, it is submitted that it is beneficial to know of problematic scenarios, even if they are unlikely, because history has shown that our ability to reliably estimate what is likely or not is not strong (Brown et al., 2012; Ray and Brown, 2015). The basin’s historical conditions form a baseline scenario. Performance of the coupled model (HYMOD_DS and BRAHEMO) is first evaluated in terms of its ability to reproduce the historical conditions. When run through BRAHEMO, projected future scenarios provide insight into the combined effects of climate change, water diversions and dam developments. Multiple aspects of the response of the basin system to a variety of future scenarios are evaluated, including crop production, hydropower generation, and flood affected area (FAA, in Bangladesh only).

3.1 Baseline scenario setup

As described in the Model Evaluation section below, the ability of the coupled modeling system to reproduce four key outcomes over the course of the validation period (1977-2006) was examined. Once the modeling system had been validated, a baseline scenario was developed to represent a plausible future in which all historical conditions are unchanged. In the baseline scenario climate forcing data is bootstrapped from the 1977-2006 historic record (0°C change in average annual temperature and 0% change in average annual precipitation) to generate a synthetic climate time series that is a continuation of the historic. Long-term average crop area is used to cap the physical availability of land. The model determines dam activation according to the respective year of commissioning, so the result of hydropower generation can fit the increasing trend due to historical water infrastructure development. In the baseline scenario, only hydropower dams currently operational are included. As no significant water diversions have yet been established, none are included in the baseline scenario.

3.2 Natural driver - climatic uncertainty

This study identifies and analyzes ex post scenarios that illustrate the range of future climate conditions over which a certain level of system performance is achievable. To evaluate a range of potential climate change effects, the daily historical precipitation (P) and temperature (T) are resampled and perturbed to construct 30-year daily time series of P and T representing plausible climate changes. Specifically, temperature increases ranging from 0 °C to 10.5 °C with an interval of 1.5 °C are added into the 30-year resampled temperature daily data, and precipitation changes ranging from -40% to +40% with a 10% interval are also use as a multiplier for the precipitation daily data. These changes in P and T, yielding 9 precipitation conditions and 8 temperature conditions respectively, lead to 72 representations of (step changes) climate changes. The 72 representations are used as inputs to the HYMOD_DS, which translates the climate traces into 72 streamflow traces that be used to drive the BRAHEMO. We repeat the procedure of resampling the historic record 30 times (with each of the 30 referred to as a single “trial”) to sample the internal climate variability, in addition to changes in (perturbations of) mean climate conditions. Each trial represents one plausible climate condition for the past 30 years. The 72 climate change representations along with each trial of the resampled 30-year
climate bring the total number of simulations involved in this study to 2160 (30×72). The
likeness of each of the climate perturbations is not knowable, and not immediately relevant.
The likelihood of the ex post climate scenarios, however, is of relevance to policy-making, and is
informed by a range of climate data, including historical trends and climate change projections
from the latest Intergovernmental Panel on Climate Change (IPCC) ensemble of GCMs, the Fifth
Phase of the Coupled Model Intercomparison Project (CMIP 5, Taylor et al., 2012). The method
by which trends and CMIP5 projections are used to quantify the likelihood of the climate
changes represented in particular ex post scenarios is presented in the Discussion section.

3.3 Social driver - human development

3.3.1 Hydropower dam development scenarios

Bhutan, China, and India are all interested in developing the untapped hydropower in the
BRB (both on the main stem and the tributaries) so construction of hydropower dams (as
summarized in Table S1) is a focus. We classify dams as under construction and under planning
or consideration based on published literature (Rahaman and Varis, 2009; ADB, 2010; Rahaman,
2012). In China two dams at Pangduo and Zangmu are classified as “under construction” with
expected project completion years of 2018 and 2015, respectively. Bhutan has four “under
construction” dams at Dagachhu, Mangdechhu, Punatsangchhu-I and Punatsangchhu-II, all with
expected completion dates in 2017. India has four “under construction” dams, all of which are
expected to be completed around 2015: Subansiri Lower, Lower Tista III, Lower Tista IV and
Tista Barrage.

Many of the future dams under construction are characterized as run-of-the-river
hydropower plants where little or no water storage is provided for hydroelectricity generation.
For example, all of the future dams in Bhutan feature run-of-the-river power generation. Dams
on the Tista River in India are also characterized as run-of-the-river power plants due to the
small storage. The Subansiri Lower hydropower dam in India is described as run-of-the-river
type by NHPC Limited (http:// http://www.nhpcindia.com/). The Zangmu hydropower dam in
China is also a run-of-the-river facility. On the other hand, the Pangduo hydropower project in
China includes reservoir storage, and the head-volume relationship is developed based on web
data (http://baike.baidu.com/view/4743896.htm). Characteristics of most of the dams in the
BRAHEMO are collected from the Global Energy Observatory: http://globalenergyobservatory.org/.

In this paper there are two hydropower dam development scenarios represented by
“Current” and “Future.” “Current” is the water infrastructure in the baseline scenario. In the
“Future” scenario all dams that are currently under construction are added to the model. The
basin-wide effects of dams currently “under planning or consideration” are not evaluated in this
paper due to insufficient data.

3.3.2 Water diversion scenarios

China and India are both considering transboundary water diversions to transfer water
from the BRB to water-scarce regions elsewhere within their borders. According to the “Greater
Western Route Water Diversion Project” (Zuo et al., 2008), proposed water diversion routes
include: 1) starting from Shuo-Ma-Tan (on the main stem of the Brahmaputra), water will be
diverted through dams and tunnels to the Niyang River; 2) more dams and tunnels built on the
Niyang River help divert water to the Yigon Tsangpo River; and 3) from Yigon Tsangpo, water
is sent further north to the Yangtze and Yellow Rivers. Water transfer in India has been proposed
by “National River Linking Project,” to divert water from the Brahmaputra River to the Ganges River through linked canals (Rahaman and Varis, 2009). The “Manas-Sankosh-Tista-Ganga” link is the primary route. Two dams have been proposed on the Manas River and the Sankosh River, with lengths of link canals in excess of 250 km. To evaluate a wider range of potential water diversions effect we explore the effect of each diversion on the basin by incrementally increasing the diversions from zero to reasonable maxima as described in the available literature (Zuo et al., 2008; NIH 2015): modeled Chinese diversions vary from 0 to 60 BCM per year, and modeled Indian diversions vary from 0 to 30 BCM per year, in increments of 10 BCM. This results in 10 water diversion scenarios: 1 baseline, 6 Chinese diversions, and 3 Indian diversions. Combinations of Indian and Chinese diversions are not explored; Chinese diversions are considered only while holding Indian diversions unchanged from historic, and vice versa for Indian diversions.

In total, in addition to the baseline scenario, the BRAHEMO was run 43,200 times (30 trails of resampled 30-year climate each perturbed with 72 combinations of temperature and precipitation changes, 10 water diversion scenarios, and two hydropower dam development scenarios = 30x72x10x2 = 43,200).

4. Results

4.1 Model Evaluation

We evaluate models (HYMOD_DS and BRAHEMO) performances by fitting the outcomes to historical record. Example parameters that can be adjusted to fit the historical conditions are maximum soil moisture storage, channel routing and diffusivity and wave velocity, and temperature threshold for snow/glacier melting in HYMOD_DS and crop water productivity coefficient, irrigation efficiency, and hydropower generation efficiency in BRAHEMO.

The performance of the HYMOD_DS is evaluated based on the Nash-Sutcliffe Efficiency (NSE), ratio of the root mean square error to the standard deviation of measured data (RSR) and percent bias (PBIAS) (Nash and Sutcliffe, 1970; Muñoz-Carpena, 2013). The HYMOD_DS was applied to 9 subbasins of the BRB, and the available streamflow observations were used for both the model calibration and validation purposes (Figure 3). Overall, the performance of the HYMOD_DS for these sub-basins is satisfactory (model performance is deemed satisfactory when NSE ≥ 0.5, RSR ≤ 0.7 and PBIAS within ±25%, Moriasi et al., 2007) for both the calibration and validation periods. An exception was noted for the validation period at the Demwe subbasin (Lohit River), with a low NSE (0.33), possibly due to the high-elevation and glacierized nature of the basin and the limitations of the climate data used to force the HYMOD_DS (e.g., temperature, precipitation, and ice reserves in glaciers). The Lohit River makes up less than 6% of total runoff of the Brahmaputra River flow; therefore, basin-wide outputs are not greatly affected by the low performance of the HYMOD_DS at Demwe. The evaluation of the HYMOD_DS led to the conclusion that the hydrologic regime of the entire Brahmaputra River is reasonably represented by the glacio-hydrologic model and can be used to drive the BRAHEMO.

Because of the limited data availability (such as actual water withdrawal in each demand site and hydropower generation from each individual dam), not every output from the BRAHEMO could be fully diagnosed. For the purposes of this study, particular attention is given to these coupled model outputs: 1) streamflow at outlet of the basin; 2) national crop production in each country; 3) hydropower generation in Bhutan; and 4) FAA in Bangladesh. Figure 4a show the time series of both observed and modeled streamflow at the basin outlet: Bahadurabad.
The result indicates that the system model captures the general monthly pattern of streamflow but underestimates monsoon flow for several years and the low flow period toward the end of the simulation. The monsoon flow underestimation stems partially from the calibration settings of hydrologic model, and the low flow underestimation is possibly due to the uncertain year-to-year water use (in addition to hydrologic model calibration values). As more data relevant to monsoon season rainfall pattern and human water uses become available, these biases can be further evaluated and reduced.

Long-term average crop production values for selected crops in each country (excluding Bhutan) are compared to historical data (Figure 4b). Most of the crop productions match the long-term average while the vegetation in India shows a relatively high production. We lump potato, cabbage, tomato, onion, etc., as “vegetable” in the model. Since no detailed data are available for these vegetables, it is difficult to judge how much the model is overestimating. More detailed crop data would help to improve this part of the model.

Figure 4c shows the goodness of fit of a time series of hydropower generation in Bhutan between modeled and historical data. The model fit is excellent for all periods other than 1988-1998, during which time hydropower production in Bhutan was slowly rising in response to storage capacity ramp-up.

Figure 4d presents a comparison of the modeled 30-year FAA in Bangladesh to the historical data. An underestimation is noted for extreme floods due in part to the underestimation of the monsoon flow and the attenuation of peak floods attributable to the monthly time scale of the BRAHEMO. Apart from the underestimation of FAA during extreme floods, the current water system and its related crop and energy production are reflected well in the BRAHEMO.

4.2 Nexus perspective of modeled countries

This study assesses the interaction between water, energy and food in the BRB and demonstrates the alternative basin trajectories under different climate and social conditions. A “trajectory” is defined as a multi-faceted model outcome (streamflow, crop production, hydropower generation and/or FAA) under a specific future situation driven by temperature, precipitation, and infrastructure (dam and diversion) status. To better visualize nexus thinking, parallel coordinate plots are used to visualize the multiple dimensions of alternative basin trajectories under uncertainty (both climate and human development). Parallel coordinate plots illustrate the interrelationships between concerns of water, energy and/or food in each country. In each figure, the first four (or five, in the case of Figure 6) columns are drivers (e.g., changes in temperature, precipitation, water infrastructure, and upstream diversions). The remaining columns are model outputs regarded as major concerns (food production, hydropower generation, and/or flood affected area).

A common method in decision making under uncertainty approaches is the use of thresholds that mark the level of “acceptable” performance. The concept is based on a goal determining robust solutions by finding those that are able to provide acceptable performance over a wide range of uncertain factors, rather than seeking a single optimal and potentially brittle, solution. The approach is adopted here to highlight the conditions under which basin stakeholders are likely to be satisfied, and those conditions where one or more will be unsatisfied and thus defined as “unacceptable.” The combination of conditions for each of these cases make up ex post scenarios.

In this study, we used long-term (30-year) averages of modeling results as system performance thresholds to define “acceptable” (bold blue lines) and “unacceptable” (pink thin lines) trajectories for the basin. For China and India, “unacceptable” basin trajectories are
defined as any set of possible future conditions in which either in crop production drops below long-term historical average and/or hydropower production drops below expected future energy demand (defined as long-term average of modeling results under future development with no upstream diversion, temperature and precipitation change). For Bangladesh, “unacceptable” basin trajectories are defined as containing either crop production drops below long-term historical averages, and/or increases in FAA above long-term historical average. It should be noted that these thresholds are chosen for illustrative purposes only. Alternative thresholds could also be specified according to the preferences of a decision maker.

Figure 5 shows the effects of driver changes in China. In short, if China is determined to satisfy their food production and hydropower production, the only way that it can divert significant amounts of water (e.g., larger than 10 BCM) from the basin is under more precipitation and not substantially higher temperature condition. Viewed in detail, dam investments, large Chinese diversions, increasing temperature, and decreasing precipitation all have potential to drive China-specific trajectories into “unacceptable.” While Chinese diversions of water out of the basin may well result in net benefits to the Chinese nation, the net benefits within the bounds of the BRB would be negative under certain conditions. For example, any combination of the continuation of the current system, or a precipitation decrease of 10%, or Chinese diversions greater than 50 BCM per year would preclude the achievement of “acceptable” basin trajectories. With new dam investments, hydropower generation would be significantly increased, but no improvements to crop production in China would be achieved, as that is not the purpose of these dams. Enactment of the new system would not switch basin trajectories from “unacceptable” to “acceptable.”

Figure 6 shows the effects of changing drivers on India. Chinese diversions have the effect of reducing India’s rice production, especially when those diversions exceed 50 BCM. Chinese diversions have no effect, however, on India’s ability to generate hydropower, as most of the Indian hydropower potential is located on tributaries, and the influence of upstream Chinese diversions only extends to the mainstem. Indian water diversions would slightly improve crop production (in West Bengal) and would not affect hydropower generation. Finally, a continuation of the current system accompanied by decreasing precipitation would result in “unacceptable” trajectories, because the current system cannot satisfy future energy demand. Note that neither Figure 5 (China) nor Figure 6 (India) shows a gradient of trade-offs between crop production and hydropower generation (since blue lines are always associated with highest values of last two columns). This is because most dams are run-of-the-river type, meaning that setting the objective function to maximize total economic benefit has the same effect as maximizing crop production. A similar “lack of trade-offs” pattern between hydropower and irrigation has been observed in a study of the Ganges river basin (Wu et al., 2013).

Figure 7 shows the trade-offs relevant to Bangladesh: FAA and rice production. With “acceptable” trajectories defined by rice production above long-term average and FAA below long-term average, the ex post scenarios identify problematic levels of precipitation increase and Chinese water diversions. Precipitation increase more than 30% might benefit the rice production, but would also result in more FAA. Therefore, under nexus thinking, all trajectories with more than 30% precipitation are “unacceptable.” Similarly, 60 BCM of Chinese diversions are also “unacceptable,” even though such diversions might reduce the downstream FAA. Temperature change and Indian diversions would not seem to appreciably affect either rice production or FAA in Bangladesh. In general, Chinese diversions greater than 50 BCM per year result in all countries’ basin trajectories becoming “unacceptable.” Therefore, there is no winner inside the
basin when China diverts more than 50 BCM per year out of the BRB. (Note: the potential economic benefit gains in China outside of the basin are outside of the scope of this work.)

Results shown in parallel coordinate plots or tabular format are only snapshots of those that can be explored using these models. The results highlighted are those deemed most interesting and relevant by the authors. To better inform policy making, interactive versions of these parallel coordinate plots have been developed and made available as web-based decision support tools (e.g., http://people.umass.edu/yceyang/ChinaWEF.html). These tools provide a powerful vehicle for policy makers and their advisors to explore scenarios/trajectories (all drivers and all major concerns) of interest in order to understand their consequences on water, energy and food security.

4.3 Policy Implications of basin trajectories

The results of this study have relevance for the policy making of transboundary water resources management regarding water, energy and food security in the basin. In this section, we apply nexus thinking at international level (compare to national level in the previous section) and summarize the effect of different drivers on the basin-wide WEF nexus (Tables 1-3). We use these results to examine the institutional functions of this nexus approach for fostering social consensus (Scott et al., 2015) and possibly the possible water treaty/regulation for the BRB.

These tables present the effects of drivers on basin trajectories first in terms of single drivers (e.g. temperature, Chinese diversions, expanded infrastructure systems), and then as combinations of drivers. The same thresholds are used to define “acceptable” and “unacceptable” trajectories. The tables quantify the level for each driver (or combination of drivers) that leads to “acceptable” results for at least 90% of basin trajectories. The value of 90% is arbitrary, and used to expand the negotiation space, as it would be difficult to achieve 100% acceptability. Together these results provide clear messages for concerns on water, energy and food. In these tables, “Any” indicates that changing this driver (or combination of drivers) does not result in trajectory change. Results show that precipitation change ($\Delta P$) is the dominant single driver and the combination of “temperature change and precipitation change” ($\Delta T + \Delta P$), and “precipitation change and Chinese diversion” ($\Delta P + ChDiv$) are the two dominant combinations affecting the WEF nexus in the basin.

Table 1 shows that China-India flow is invulnerable to changes in single drivers within the tested ranges but the $\Delta P + ChDiv$ combination is critical. For example, if China diverts no water, and precipitation increases by 20% or more, India does not need to worry about the incoming streamflow to their territory regardless of how other divers might change (i.e., even if temperature increase 10.5 $^\circ$C). The negative effects of Chinese diversions up to 20 BCM per year are offset by a precipitation change of +30%; and the negative effects of Chinese diversions up to 30 BCM per year are offset by a precipitation change of +40%.

Table 2 also shows that precipitation change, $\Delta T + \Delta P$ and $\Delta P + ChDiv$ combinations are dominant for flood affected area in Bangladesh. If precipitation remains the same or becomes less, Bangladesh does not need to worry about increasing flooded area. A 10% increase in precipitation, would be offset by the occurrence of either a temperature increase of at least 7.5$^\circ$C or Chinese diversions of at least 60 BCM per year. However, when precipitation increases more than 20%, Bangladesh will always face the threat of increasing FAA (regardless of the ability of other drivers to offset the negative effect).

Table 2 shows that precipitation increases always have positive effects on food production in each country. For example, if basin-wide precipitation increases by at least 20%,
food production in Bangladesh and India becomes invulnerable to changes in other drivers (i.e.,
even if temperature increases 10.5 °C and China diverts up to 60 BCM per year). Note that nexus
thinking should also consider that 20% increase of precipitation is the critical point identified in
Table 1 for Bangladesh’s increasing FAA concern. Chinese food production becomes
invulnerable to other drivers’ changes if basin-wide precipitation increases by 40%.

When temperature changes and water diversions are considered together with
precipitation, both strengthening and worsening effects are observed (Table 2). Warming offsets
the positive effect of precipitation increases, which means larger temperature increases will
result in the need for larger precipitation increases. For example, under temperature increases up
to 4.5 (7.5) °C condition, India (Bangladesh) does not need to worry about its rice production if
basin-wide precipitation increases more 10%.

The combinations of ∆P+ChDiv and ∆P+InDiv (precipitation increases and Indian
diversions) result in differing effects in each country. For example, Bangladesh needs to worry
its rice production mostly when upstream (both China and India) diversions are combined with
precipitation decreases (except for larger than 50 BCM Chinese diversion). Indian rice
production would be jeopardized by Chinese diversions but precipitation increases can
compensate this negative effect. For example, 40% precipitation increases can offset the effect of
60 BCM Chinese diversions on Indian rice production. Indian diversions can mitigate the
precipitation decreases effect on its rice production. For example, 30 BCM Indian diversions will
compensate 20% precipitation decreases. Chinese diversion between 30 and 40 BCM combined
with 20% to 30% precipitation increases will make its barley production invulnerable to other
driver changes.

Note that “Infrastructure System” change (i.e. existing dams to new dams) is not able to
affect management concerns on either the “Water” or the “Food” part of the WEF nexus (Tables
1 and 2) for any riparian countries. The “Energy” part is a different story (Table 3). No single
driver can guarantee the satisfactory hydropower generation for Bhutan, China or India. But the
combination of precipitation increases (30% in Bhutan and 10% in India) and infrastructure
system (∆P+InfrSys) will provide a chance to let Bhutan and India’s hydropower generation free
of concern. China, on the other hand, will not have this luxury even with their “Future”
hydropower projects are all in place.

Results of these tables which represent the summary concerns of the basin could also be
presented in parallel coordinate plots as shown in Figures S1 to S4. We summarize figures and
tables of ex post scenarios analysis in these two Result sections (4.2 and 4.3) in Table 4 to show
key conditions (drivers and their magnitude) that cause absolute “unacceptable” trajectories for
each individual concerns for policy implementation purpose. “Absolute” means that under these
conditions, changing other drivers will not be able to overcome the negative impacts. Overall,
decreasing precipitation and Chinese diversion are two key drivers.

5. Discussion

5.1 Likelihood of basin trajectories

In this section, we discuss the likelihood of changes. We have avoided discussion of
likelihood to this point, as it is not immediately relevant to the analysis of WEF nexus
vulnerabilities, and can prove a distraction from the establishment of performance thresholds.
However, if risks are understood to be a function of impact and probability (Dessai and Hulme
2004), then risks of water, energy and food security cannot be communicated without at least a
general sense for the likelihood of problematic future conditions. We sketch out approximate
domains of likelihood (and unlikelihood) here.

The likelihood of natural drivers (temperature and precipitation change) can be informed
by the latest future climate projections from IPCC (the CMIP 5 ensemble). Although results from
GCMs might introduce another layer of uncertainty but it is still useful to quantify the likelihood
of future climate. We process all 37 GCMs from four RCP scenarios and results suggest a
warmer (temperature increases between 0.5 to 5 °C) and possibly wetter (precipitation changes
between -10% and 40%) future for this basin to the year of 2050. This warmer and wetter future
climate projection is consistent with previous studies in this region (e.g. Kumar et al., 2013).
Chinese and Indian trajectories would likely benefit from this warmer and wetter climate (not
considering ancillary effects of warmer and wetter climates such as increased incidence crop-
damaging pests, fungus/mold and disease). Bangladesh’s rice production would also likely
benefit, but the risks of increased fluvially-flooded area become a major concern.

The likelihoods of social drivers are even more difficult to estimate than natural drivers.
Current model structure models the existing and under construction dams but it does not mean
that the likelihood of “Future” system is 100%. Several modeled dams (e.g. Subansiri and Teesta
V) are under debated for the issues of ecological conservation, water sharing and sediment
regulation. If these dams do not commission due to these debates, the “acceptable” trajectories
for hydropower generation will be affected. The likelihood that China and/or India will
implement their water diversion plans is a political issue rather than a scientific question, and
therefore difficult to estimate statistically. Even if it is established that the two countries are
likely to divert water, the amount of water diverted remains highly uncertain. Zuo et al. (2008)
summarized the proposed plans of Chinese diversion from local engineers: 20 BCM per year is
frequently mentioned. The Interlinking of Rivers (NIH, 2015) suggested that the 30 BCM per
year is the capacity of Indian diversion cannal.

Population growth is certain but not modeled in this paper since we do not directly
address the water demand side. More population means more food and energy demand and will
raise the threshold for “acceptable” trajectories. Land use/crop pattern change is likely and will
affect the monthly agricultural water use. This can be tested as an adaptation action to
environmental change in the future study. The temperature change effect on crop yield and
irrigation requirement is likely but also not modeled since an agronomic model (e.g. DSSAT) is
needed.

5.2 Limitations and potential future studies

This study uses a coupled modeling framework to establish the knowledge platform
(parallel coordinate plots and basin trajectories summary tables) to quantify the transboundary
WEF nexus in the BRB via ex post scenario analysis. The methodology is applicable worldwide
as long as appropriate data are available, with the aim of providing advance knowledge to inform
policy dimensions of natural and social driver changes impact on the WEF nexus. However, the
reality of the basin is far more complex than is captured by the current modeling structure (and it
is probably fair to say that the reality is more complex than any modeling structure can capture).
For example, we do not consider the capital and operational costs of water diversions, the loss of
other ecosystem services, the diurnal variations in streamflow cause by the run-of-the-river dam,
the salt-water intrusion and sea-level rising issue in Bangladesh, and the extreme complicated
political issues between China and India.

We summarize several limitations still exist from a policy making perspective in this
section. First, the threshold definition for “acceptable” and “unacceptable” trajectories can be
improved. With input from policy makers, one can define “fuzzier” thresholds instead of binary thresholds. From the policy making perspective, the fuzzy threshold setting provides the full spectrum of choices. Second, a quantification of the likelihood of social drivers using universal standards (as is done for the quantification of the likelihood of climate change using GCM information) can provide more informative basin trajectories. This will reduce the uncertainty that policy makers encounter when making decisions under international sovereignty concerns, competing demand and deeply-rooted mistrust.

The current modeling framework itself has limitations as well. First, the influence of uncertainty in glacier volume due to differences in calculation methods and data sources affects modeling results of water availability from the stream. Table S2 demonstrates the difference of glacier volume from different data sources. Second, the centralized optimization framework used in current study assumes complete information exchange: perfect economic efficiency and the existence of a top-down basin-wide “controller” in the basin. This, of course, is not a good reflection of reality. As more detailed (agronomic, economic and hydrologic) data become available, an agent-based water resources system model (see for example Yang et al., 2009; Yang et al., 2012) could be built to better represent the real-world decentralized water resources decision making process. Finally, future versions of the system model would be improved by the addition of capabilities for consideration of environmental factors like environmental health, delta issues, water quality and sediment balance.

6. Conclusion

Advance knowledge of policy/institutional dimensions of natural and social drivers’ impacts on transboundary WEF nexus are highly relevant for national and international policy making. We demonstrate how to apply a coupled modeling framework with an ex post scenario analysis to establish such a knowledge platform to examine institutional dimensions of the WEF nexus (institutional level and functions by Scott et al., 2015) and inform policy making using the Brahmaputra River Basin as an example.

A physically-based distributed hydrologic model was applied to simulate the inflow of major tributaries, and to drive a water resources system model, the BRAhmaputra HydroEconomic MOdel (BRAHEMO). This coupled modeling framework is used to evaluate: 1) baseline scenarios under current climate and water uses; 2) the potential impact of climate change and human development from the perspective of the WEF nexus at the national level and 3) policy implementation from the WEF nexus results.

Using the parallel coordinate plots and basin trajectories summary tables, results indicate that precipitation change ($\Delta P$) is the dominant single driver, and the combination of temperature/precipitation change ($\Delta T/\Delta P$) and precipitation change/Chinese diversion ($\Delta P/\text{ChDiv}$) are two dominant combinations affecting the WEF nexus in the basin. Decreasing precipitation alone (e.g., more 20% relative to the historical), increasing temperature with smaller precipitation increase (e.g., a 7.5°C temperature increase in combination with a precipitation increase less than 20%), and high levels of upstream water diversions with smaller precipitation increase (e.g., Chinese diversions in excess of 30 BCM per year and precipitation increases not greater than 20%) will most likely push future basin trajectories to evolve into “unacceptable” zones.

By introducing the likelihood concepts, modeling result can further inform policy making with uncertainty. For example, the latest GCM projections from the IPCC are good sources of likelihood for future climate. According to the IPCC, the most likely climate change impact will
not result in “unacceptable” basin trajectories, except for the FAA in Bangladesh. Likelihoods for social drivers are difficult to evaluate. New dams, even they are likely to be done, are not expected to have a significant influence on “Water” and “Food” in the basin and will make “Energy” more robust (as most of them are run-of-the-river type). Likelihoods of upstream diversions would require further studies in political science, sociology and economics.

Appendix - BRAhmaputra HydroEconomic MOdel

The objective function of the BRAhmaputra HydroEconomic MOdel (BRAHEMO) sums profits from agricultural production and hydropower generation, and post-calculate the flood affected area (FAA) in the downstream states:

\[
\text{Basin wide Profit} = \sum_{Z} \sum_{C} (\text{Crop Price}_{Z,C} \times \text{Crop Production}_{Z,C}) - \sum_{Z} \sum_{C} \text{Crop Cost}_{Z,C} + \sum_{N,M} (\text{Energy price} \times \text{Hydropower}_{N,M})
\]

(1)

where \( Z \) is the index for water demand sites, \( C \) is the index for crops, \( N \) is the index for dams and \( M \) is the index for month.

Five classes of data are needed for the BRAHEMO: agricultural data, hydropower data, domestic water use data, groundwater pumping data, and streamflow data from HYMOD_DS. Agricultural use is by far the largest demand of water in the Brahmaputra River. The primary sources for agricultural data (crop type, historical crop area, crop yield, crop price, etc.) in the basin are: the Indian Department of Statistics, the Tibet Statistical Yearbook, the Bangladesh Ministry of Agriculture, and the National Statistics Bureau of Bhutan. Seven major crops in the basin were modeled: barley, wheat, rapeseed, rice, tea, potato and vegetable. Two key equations related to agriculture part of the model are given below: crop production (Equation 2) and irrigated water calculation (Equation 3)

\[
\text{Crop Production}_{Z,C} = \text{Crop Yield}_{Z,C} \times \text{Crop Land}_{Z,C} = \text{Crop Water P}_{Z,C} \times (\text{IrrWater}_{Z,C} + \text{EffPrecip}_{Z,C})
\]

(2)

where \( \text{Crop Water P} \) is crop water productivity in the units of mass per water volume, \( \text{IrrWater} \) is the total irrigated water and \( \text{EffPrecip} \) is the effective rainfall.

\[
(\text{GWAG}_{Z,M} + \text{SWAG}_{Z,M}) \times \text{Efficiency}_Z = \sum_{j} (\text{IrrFract}_{Z,C,M} \times \text{IrrWater}_{Z,C})
\]

(3)

where decision variables: \( \text{GWAG} \) and \( \text{SWAG} \) are groundwater pumping and surface water diversion for irrigation purpose, respectively. \( \text{IrrFract} \) is crop irrigation requirement monthly time table. We relied on CropWat (FAO, 1993) to provide information on the monthly irrigation water requirement (including double cropping in India and Bangladesh), coefficient of crop water productivity and effective rainfall for each crop in each demand site.

Data related to the existing hydropower generation (dam storage, installed capacity, gross head and electricity price, etc.) were collected from previous literature (e.g., Rahaman and Varis, 2009; Rahaman, 2012; ADB, 2012). All existing dams in the basin function as run-of-the-river dams, and can be modeled by assuming a constant head when calculating the generated hydropower. Equation (4) describe the actual monthly hydropower generation for each reservoir in the BRAHEMO. Monthly hydropower generation is calculated by standard hydropower equation where dam release \( (\text{Dam release}_{N,M}) \) and head \( (\text{Head}_{N,M}) \) are both decision variables.
and also capped by installed capacity (Installed Cap\textsubscript{N}) of each dam. Power generation efficiency (\textit{eff}\textsubscript{N}) is one of the calibrated parameters.

\[ \text{Hydropower}_{N,M} = \text{Max}[\text{Installed Cap}_{N}, 0.002725 \times \text{Dam release}_{N,M} \times \text{Head}_{N,M} \times \text{eff}_{N}] \] (4)

Due to limited data availability on basin-wide aquifer dynamics, groundwater is conceptualized as a “local reservoir” for each demand site in BRAHEMO. The annual pumping cap for each demand site is based on related literature or government data (Zhang and Li, 2005; CGWB, 2102; Ahmad, 2014). Assam, India pumps approximately 5.3 billion cubic meters (BCM) of groundwater per year for agricultural irrigation, which is the largest use of groundwater currently in a single demand site in the model. Equation (5) and (6) describe the annual pumping for both domestic and irrigation purpose in each demand site \( (Z) \) in the BRAHEMO, where both groundwater pumping for irrigation purpose (\textit{GWAG}) and domestic water purpose (\textit{GWDO}) are decision variables in the model.

\[
\begin{align*}
\text{Groundwater pumping cap for irrigation}_{Z} &> \sum_{M=1}^{12} \text{GWAG}_{Z,M} \quad (5) \\
\text{Groundwater pumping cap for domestic}_{Z} &> \sum_{M=1}^{12} \text{GWDO}_{Z,M} \quad (6)
\end{align*}
\]

The domestic water demand for each demand site is established as a hard constraint in the BRAHEMO, meaning that domestic water demands are given the highest priority in the system. The domestic water demand in India and Bangladesh was estimated based on the population using the data from Indian Department of Statistics and Bangladesh Bureau of Statistics. Bhutan’s domestic water demand was estimated using data from the National Statistics Bureau and Gleick (2011). Data in China were gathered from the Chinese Statistical Yearbook on Environment published by National Bureau of Statistics. Equation (7) describe this monthly constraint for each demand site in BRAHEMO, where both groundwater pumping (\textit{GWDO}) and surface water diversion (\textit{SWDO}) for domestic water demand are decision variables in the model.

\[
\text{Domestic Water demand}_{Z,M} = \text{GWDO}_{Z,M} + \text{SWDO}_{Z,M} \quad (7)
\]

Flood affected area (FAA) in Bangladesh was calculated using an empirical regression function linking the maximal monthly water volume at the Bahadurabad gaging station with the maximal water level, and further linking with the FAA damage equation. Several FAA damage functions were tested in Yang et al. (2015) to identify the most appropriate format for this purpose. The FAA is calculated after the basin-wide water allocation; therefore, its results were not optimized in the BRAHEMO but explored as “post-processed” results only. Equation (8) is currently used in BRAHEMO for FAA calculation, detailed definition of each parameter are given in Yang et al. (2015).

\[
\text{Flood Affected Area} = \frac{\text{Max Flooded Area}}{(1+\text{MinFC}\times e^{-G(FC-CFC)})^{1/\epsilon}} \quad (8)
\]

where Max Flooded Area = 120,000 km\(^2\); MinFC = 17.82; G = -9.78; FC is maximal water level; CFC=20.40; \( \epsilon \)=5.241
Reference


GRDC. 2015. The Global Runoff Data Centre, 56068 Koblenz, Germany.


Figure 1. Map of the location of streamflow gages, current and planned dams, and glacier area in the Brahmaputra Basin.
Figure 2. Schematic of the BRAhmaputra HydroEconomic MOdel (BRAHEMO)
Figure 3. HYMOD_DS modeling performance for each subbasins evaluated with 3 metrics
Figure 4. Comparison of model (BRAHEMO) results to historical data: (a) streamflow at Bahadurabad; (b) national annual crop production; (c) hydropower generation in Bhutan; (d) flood affected area in Bangladesh
Figure 5. Hydropower generation and barley production in China under the impacts of climate change and upstream diversions. Blue lines represent scenarios above thresholds and pink lines represent scenarios below thresholds. Results show that all drivers are critical for Chinese food and energy supply in the basin. Large Chinese diversion and decreasing precipitation result in all trajectories to become “unacceptable.”
Figure 6. Hydropower generation and rice production in India under the impacts of climate change and upstream diversions. Blue lines represent scenarios above thresholds and pink lines represent scenarios below thresholds. Results show that all drivers are critical for Indian food and energy supply in the basin. Among them, decreasing precipitation is the most dominant driver that results in all trajectories to become “unacceptable.”
Figure 7. Flood affected area and rice production in Bangladesh under the impacts of climate change and upstream diversions. Blue lines represent scenarios within thresholds and pink lines represent scenarios outside of thresholds. Precipitation change and Chinese diversion cause tradeoff between FAA and rice production in Bangladesh while positive precipitation change benefit rice production it results in more FAA.
Table 1. Summary table of required conditions for a 90% probability of achieving “acceptable” basin trajectories for Water

<table>
<thead>
<tr>
<th>Conditions for Acceptable Trajectories: Water</th>
<th>China-India flow</th>
<th>Bangladesh Flooded area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivers or combinations of drivers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Any</td>
<td>$\leq 0%$</td>
</tr>
<tr>
<td>ChDiv</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>InDiv</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>InfrSys</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta T + \Delta P$</td>
<td>Any</td>
<td>$\Delta T \geq +7.5 \degree C; \Delta P \leq +10%$</td>
</tr>
<tr>
<td>$\Delta T + ChDiv$</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta T + InDiv$</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta T + InfrSys$</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta P + ChDiv$</td>
<td>ChDiv=0 bcm; $\Delta P \geq +20%$ ChDiv$\leq 20$ bcm; $\Delta P \geq +30%$ ChDiv$\leq 30$ bcm; $\Delta P \geq +40%$</td>
<td>ChDiv$\geq 60$ bcm; $\Delta P \leq +10%$</td>
</tr>
<tr>
<td>$\Delta P + InDiv$</td>
<td>Any</td>
<td>InDiv = “Any”; $\Delta P \leq 0%$</td>
</tr>
<tr>
<td>$\Delta P + InfrSys$</td>
<td>Any</td>
<td>InfrSys = “Any”; $\Delta P \leq 0%$</td>
</tr>
<tr>
<td>InfrSys + ChDiv</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>InfrSys + InDiv</td>
<td>Any</td>
<td>Any</td>
</tr>
</tbody>
</table>

$\Delta T$ = temperature change; $\Delta P$ = precipitation change; ChDiv = Chinese diversion; InDiv = Indian diversion; InfrSys = infrastructure system
Table 2. Summary table of required conditions for a 90% probability of achieving “acceptable” basin trajectories for Food

<table>
<thead>
<tr>
<th>Drivers or combinations of drivers</th>
<th>Bangladeshi rice</th>
<th>Chinese barley</th>
<th>Indian rice</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>$\geq+20%$</td>
<td>$\geq+40%$</td>
<td>$\geq+20%$</td>
</tr>
<tr>
<td>ChDiv</td>
<td>$\leq30bcm$</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>InDiv</td>
<td>$\leq20bcm$</td>
<td>Any</td>
<td>$\leq20bcm$</td>
</tr>
<tr>
<td>InfrSys</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta T + \Delta P$</td>
<td>$\Delta T \leq+7.5^\circ C; \Delta P \geq+10%$</td>
<td>$\Delta T \leq+6^\circ C; \Delta P \geq+30%$</td>
<td>$\Delta T \leq+4.5^\circ C; \Delta P \geq+10%$</td>
</tr>
<tr>
<td>$\Delta T + ChDiv$</td>
<td>$\Delta T = \text{&quot;Any&quot;;}$; ChDiv$\leq30bcm$</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta T + InDiv$</td>
<td>$\Delta T = \text{&quot;Any&quot;;}$; InDiv$\leq20bcm$</td>
<td>Any</td>
<td>$\Delta T = \text{&quot;Any&quot;;}$; InDiv$\leq20bcm$</td>
</tr>
<tr>
<td>$\Delta T + InfrSys$</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>$\Delta P + ChDiv$</td>
<td>ChDiv$\leq20bcm$; $\Delta P \geq-40%$; ChDiv$\leq30bcm$; $\Delta P \geq-30%$; ChDiv$\leq40bcm$; $\Delta P \geq-10%$; ChDiv$\leq50bcm$; $\Delta P \geq0%$; ChDiv$\leq60bcm$; $\Delta P \geq30%$</td>
<td>ChDiv$\leq30bcm$; $\Delta P \geq20%$; ChDiv$\leq40bcm$; $\Delta P \geq30%$</td>
<td>ChDiv$\leq40bcm$; $\Delta P \geq10%$; ChDiv$\leq50bcm$; $\Delta P \geq20%$; ChDiv$\leq60bcm$; $\Delta P \geq40%$</td>
</tr>
<tr>
<td>$\Delta P + InfrSys$</td>
<td>InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq20%$; InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq30%$; InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq10%$; InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq20%$</td>
<td>InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq40%$; InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq30%$; InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq20%$</td>
<td>InfrSys$= \text{&quot;Any&quot;;}$; $\Delta P \geq20%$</td>
</tr>
<tr>
<td>InfrSys $+ ChDiv$</td>
<td>InfrSys$= \text{&quot;Any&quot;;}$; ChDiv$\leq30bcm$</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>InfrSys $+ InfrSys$</td>
<td>InfrSys$= \text{&quot;Any&quot;;}$; InDiv$\leq20bcm$</td>
<td>Any</td>
<td>InfrSys$= \text{&quot;Any&quot;;}$; InDiv$\leq20bcm$</td>
</tr>
</tbody>
</table>

$\Delta T =$ temperature change; $\Delta P =$ precipitation change; ChDiv = Chinese diversion; InDiv = Indian diversion; InfrSys = infrastructure system
Table 3. Summary table of required conditions for a 90% probability of achieving “acceptable” basin trajectories for Energy

<table>
<thead>
<tr>
<th>Drivers or combinations of drivers</th>
<th>Bhutan</th>
<th>China</th>
<th>India</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta T)</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta P)</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>ChDiv</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>InDiv</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>InfrSys</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta T + \Delta P)</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta T + \text{ChDiv})</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta T + \text{InDiv})</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta T + \text{InfrSys})</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta P + \text{ChDiv})</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta P + \text{InDiv})</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\Delta P + \text{InfrSys})</td>
<td>(\text{InfrSys = “Future”;} \ P \geq 30%)</td>
<td>Any</td>
<td>(\text{InfrSys = “Future”;} \ P \geq 10%)</td>
</tr>
<tr>
<td>(\text{InfrSys + ChDiv})</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>(\text{InfrSys + InDiv})</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
</tbody>
</table>

\(\Delta T = \) temperature change; \(\Delta P = \) precipitation change; ChDiv = Chinese diversion; InDiv = Indian diversion; InfrSys = infrastructure system
Table 4. Summary table of key conditions causing “unacceptable” basin trajectories

<table>
<thead>
<tr>
<th>Concerns</th>
<th>Key conditions causing unsustainable basin trajectories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow from China to India</td>
<td>precipitation decrease more than 10%; Chinese diversion more than 60 BCM</td>
</tr>
<tr>
<td>Flood affected area in Bangladesh</td>
<td>precipitation increase more than 20%</td>
</tr>
<tr>
<td>Barley production in China</td>
<td>precipitation decrease more than 20%; Chinese diversion more than 60 BCM</td>
</tr>
<tr>
<td>Rice production in India</td>
<td>precipitation decrease more than 40%</td>
</tr>
<tr>
<td>Rice production in Bangladesh</td>
<td>none</td>
</tr>
<tr>
<td>Hydropower generation in China</td>
<td>current system; precipitation decrease more than 10%; Chinese diversion more than 50 BCM</td>
</tr>
<tr>
<td>Hydropower generation in India</td>
<td>current system; precipitation decrease more than 10%</td>
</tr>
<tr>
<td>Hydropower generation in Bhutan</td>
<td>current system; precipitation decrease more than 10%</td>
</tr>
</tbody>
</table>