



# Valuation of the Teesta River water by Hydro Economic Model

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## Abstract

Hydro-Economic Models (HEMs) are powerful tools to analyse water scarcity and water management problems. The Teesta River which flows from India to Bangladesh has long been a source of dispute between India and Bangladesh. A win–win solution for the problem is important for the 1.2 billion people of the two neighboring countries. A Hydro-Economic Model (HEM) on the Teesta may provide sufficient information for the solution of the dispute. Most HEMs that treat transboundary water issues consider a narrow scope of water values including agriculture, hydropower, municipal, and tourism. However, water has many additional values. This study adds to the HEM literature by considering the values of fisheries, navigation, environment or sediment transport. A Teesta Hydro-Economic Model (THEM) was developed to represent a large range of economic values of water use during the dry season. Results show that the total water use value for a dry season is USD 41.5 million for India and USD 77 million for Bangladesh. The study shows that the benefit per unit volume of water for hydropower is the lowest among all types of water use. After performing an economic analysis, this study found a potential for trade-off between hydropower use in India and environmental use in Bangladesh. This study gives an idea about how to maximise the benefits from the river and how to mitigate the water sharing dispute.

**Keywords** Hydro-Economic Models (HEMs) · Teesta · Water use benefits · Trade-off · Hydropower use · Environment use

## Introduction

Hydro-Economic Models (HEMs) are powerful tools to analyse water scarcity and drought, and can also be used to resolve water management problems [1, 2]. The Teesta River which flows from India to Bangladesh has been a source of dispute between India and Bangladesh for a long time [3]. Resolving the dispute can improve friendship, ease tension, and improve the integrated development of the Ganges–Brahmaputra–Meghna (GBM) basin. The possibility of a win–win solution for the problems can be an example which is important for the 1.2 billion people of the

two neighboring countries [4–6]. A Hydro-Economic Model (HEM) on the Teesta may provide sufficient information for the solution of the dispute.

Different types of HEMs have been developed in different river basins including Nile Economic Optimization Model (NEOM) for the Nile Basin, Ganges Economic Optimization Model (GEOM) for the Ganges Basin, and Water-AIM model for the Colorado River [7–10]. Most HEMs that treat transboundary water issues consider a narrow scope of water values including agriculture, hydropower, municipal, and tourism. However, water has many additional values. This study adds to the HEM literature by considering the values of fisheries, navigation, and environmental or sediment transport in addition to agriculture, hydropower, municipal, and tourism benefit.

A Teesta Hydro-Economic Model (THEM) was developed to represent a large range of economic values of the current (baseline) scenario, in which India releases about 30% of Teesta water from the Gajaldoba barrage for Bangladesh during the dry season. As the water sharing dispute is only in the dry season due to scarcity of water, the model operates for the dry season, November to April (six months) of a year. It operates on 10 days time step, as river inflow/

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diversion data is available on a 10-day basis. The model was coded in GAMS and solved using the CONOPT 3 solver which is a non-linear, optimization model.

## The Teesta River Basin Baseline Study

This section describes the Teesta basin, basin baseline hydrology, baseline water use and the sources of data used to model them (Scenario Modelled) and Teesta River Basin Schematic. More detailed information and data documentation is provided in appendices.

### The Teesta basin

The Teesta River originates from a glacial lake in Sikkim, India, at an elevation of 5,280 m [11]. As it flows towards the plains, the Teesta meets a number of tributaries. The Teesta basin covers nearly 95 percent of the mountainous state of Sikkim (The Asia Foundation 2013). In West Bengal, the Teesta covers 3, 225 square kilometers across the districts of Darjeeling and Jalpaiguri, before entering Bangladesh in Dimla upazila of Nilphamari District. The Teesta River and its basin area are shown in Fig. 1.

The Teesta River is fed mainly by rainwater, though snow-melt water is the major component for a few lean months. The average flow in August is about fifteen times larger than in February which means there is a great variation of flow across the year (Rudra 2009). The basin hydrology includes both surface and subsurface flow. The groundwater pool of the Teesta basin is unconfined and flows southward to the Bay of Bengal. No comprehensive study to estimate the groundwater resource in the Teesta basin has been done so far.

The length of the river within Sikkim is about 151 km. Further south it flows for 123 km in the Jalpaiguri and Koch Bihar districts of West Bengal, 121 km in Bangladesh, and finally meets the Jamuna/Brahmaputra at Sundarganj/

Chilmari. The total catchment area is 16,760 km<sup>2</sup> and 57.86% of this area falls in Bangladesh. The catchment area of Teesta River covers five northern districts of Bangladesh: Lalmonirhat, Rangpur, Kurigram, Nilphamari, Gaibandha comprising 9667 km<sup>2</sup>, with an estimated population of 9.15 million (The Asia Foundation 2013).

### Basin hydrology

The flow available at Dalia is the outflow from the Gajaldoba barrage plus the groundwater flow regenerated between Gajaldoba to Dalia. There is a little contribution (less than 5%) by the tributary Dharala. Bangladesh also diverts maximum water from the Dalia barrage keeping very little for river flow (Haque, ME 2017). The flow available at Kaunia is the outflow from Dalia barrage and regenerated groundwater inflow or baseflow from Dalia to Kaunia. There is no diversion at Kaunia, water flows freely to the Brahmaputra. Thus, all water from this point is available for the environment or fisheries, or navigation. The inflow and release data for all the locations were available only for 2005–2010. The inflow and release at Gajaldoba (data is confidential) for different periods and different years are shown in Fig. 2.

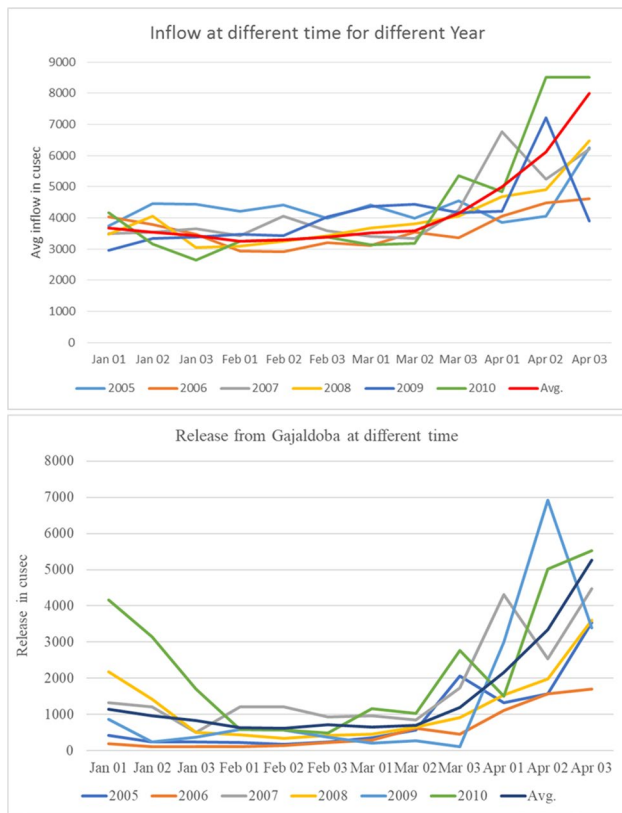
### Basin water uses

The Teesta River water that is diverted is mostly used for crop production, hydropower production, and domestic water supply while instream flows support fisheries, navigation, and other ecosystem services.. There is very little use of the river for religious purposes [12].

**Hydropower:** The upper Teesta basin (upstream of the Gajaldoba barrage) is a major source of hydropower for India. India has planned to construct a total of 38 hydel power projects with a planned capacity of more than 5000 MW of electricity and small storage facilities in the upper Teesta basin [11],The Asia Foundation 2013). Seven projects have been completed, and many more are ongoing

Fig. 1 Teesta Basin





**Fig. 2** Inflow and Release at Gajaldoba

[13]. However, the hydropower upstream of Gajaldoba is not within our study area, rather our study area is from Gajaldoba to downstream. Our concern is three hydel power plants in the Mahananda main canal situated at chainage 5.503 km, 21.275 km and 31.241 km with a total capacity of 67.5 Mega Watt ( $3 \times 22.5$  MW). The Mahananda main canal withdraws water from the right bank of the Mahananda River at Fullbari through the Mahananda barrage. The Teesta Canal transfers water from the Gajaldoba barrage to the Mahananda Canal (inter-basin transfer) via Teesta Mahananda Link Canal (TMLC). The Mahananda nearly dries up during the lean season, and power generation depends only on the Teesta water. Each of the hydel power plants has three turbines, each turbine has the capacity of generating 7.5 MW of electricity. To run even one of the three turbines at full capacity, about  $60 \text{ m}^3/\text{s}$  flow is required at the site. Running of hydel power plants through inter-basin transfer of water is against international water law and facing criticism from both local and international civil society (Haque, ME 2017; [14]).

**Agriculture:** There are two barrages and two irrigation projects on the Teesta River; one is at Gajaldoba in India, and the other is at Dalia, Bangladesh. The Indian irrigation project is known as Teesta Barrage Project (TBP) and the Bangladeshi one is known as Teesta Barrage Irrigation

Project (TBIP). Detailed descriptions of the TBP and the TBIP are provided in Appendix A and Appendix B.

**Domestic water use:** Shiliguri, the largest city in North Bengal is supplied domestic water from the Teesta. The Municipality received about 69 Million litre per day or 0.70 cumec from the TBP during 2009. Allocation of one cumec of water would be required in the future [14]. According to National Water Policy, domestic supply is the highest priority [15].

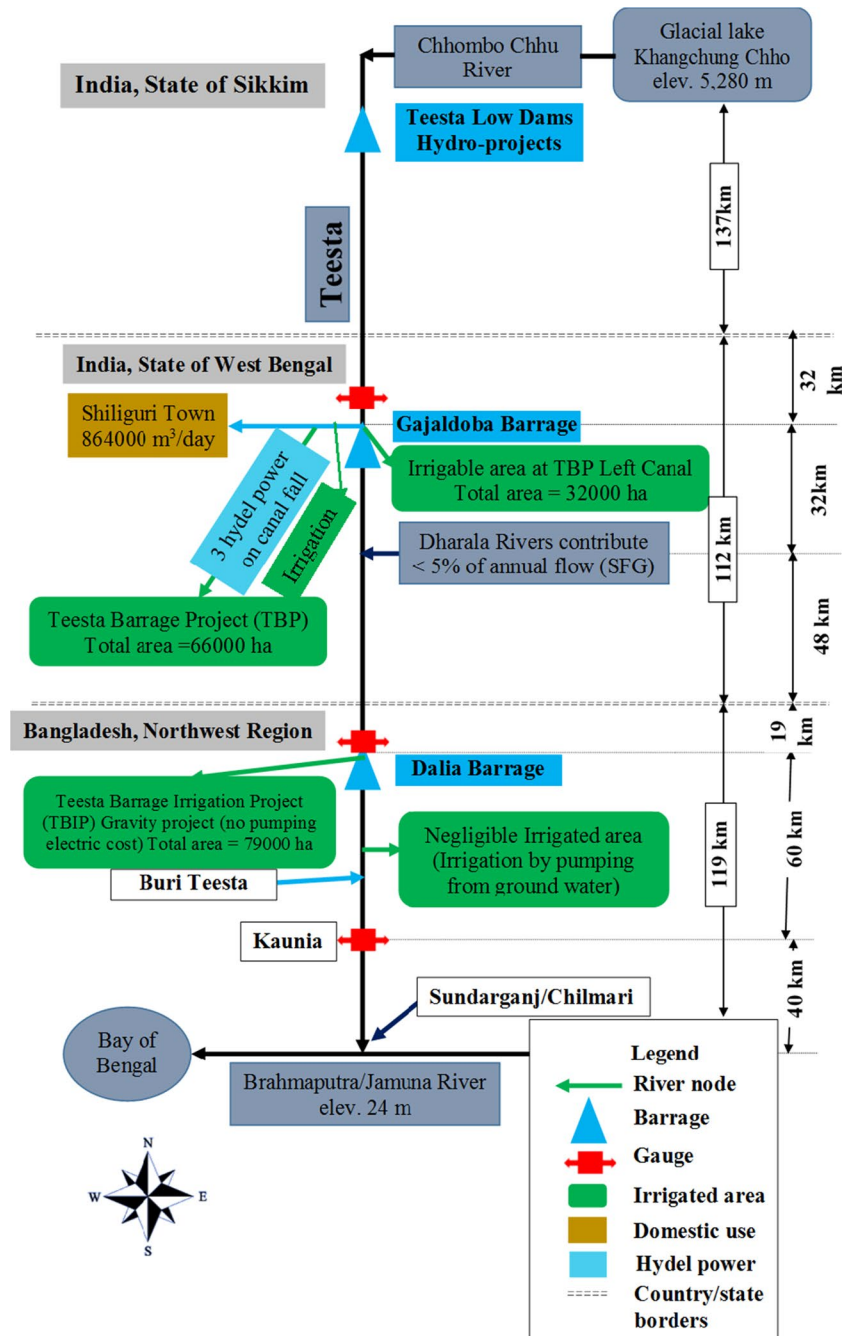
### Scenario modelled

For this study, only the current/baseline scenario was considered. Data from 2008–09 was used to represent basin baseline/current conditions because the average flow (4074 cusec) for that year is close to the average flow (4143 cusec) of the years 2005–2010 for which records exist. Moreover, the amount of water released from the Gajaldoba barrage in that year (1410 cusec) is also similar to the average for all years (1559 cusec). This choice of baseline year is also consistent with the use of flow benefit with equations for fisheries and navigation benefits based on a primary survey carried out in the basin in 2009 (Mullick, Md Reaz Akter 2011b). Moreover, all the key economic parameters required for the study were only available for 2009. India has diverted water from immediate upstream of the Gajaldoba barrage since 2000 which reduces to 30% of pre-diversion levels. Therefore, the model limits the maximum diversion of water for hydropower at Gajaldoba to 70% of the total flow at Gajaldoba.

### Teesta River basin schematic (TRBS)

Only part of the Teesta is included in this model. Our study area starts from Gajaldoba barrage and ends in Sundarganj/Chilmari, the outfall of the river at Brahmaputra, about 200 km further downstream. The Teesta River system is represented in the Teesta River Basin Schematic (TRBS) as a network of nodes and links where nodes mean the junction of river reaches and links represent the linkage between these objects [10, 16]. There are three basic types of nodes: reservoirs, irrigation withdrawals, and inflows from tributaries [17]. The basic schematic of the model used for analyzing water allocation in the TRBM considers inflows from the main river, three groundwater inflows, water diversions from two river nodes to two big irrigation projects, one municipal diversion from the first node, and one hydropower production station which is on the diversion canal (Fig. 3). From the first node, water can be diverted to both the right and left canals of the barrage. Water from the left diversion can only be used for irrigation while the right diversion can be used for irrigation, municipal water supply, hydropower, and then irrigation again.

**Fig. 3** Simplified Network of the Teesta River System



Although there are some smaller diversions between Dalia and Kaunia by low-lift pumps for irrigation or domestic use, they are negligible. The hydroelectric projects situated upstream of the river are shown as a single point as Teesta low dams hydro-projects. There are many tributaries upstream of the Gajaldoba barrage which are not included as our focus is from Gajaldoba to Sundarganj/Chillmari. In our study area, only two tributaries are included—the Dharala which meets Teesta at Domohoni, 32 km downstream of Gajaldoba barrage, and the Buri Teesta which falls in Teesta, 15 km downstream of Dalia barrage.

### Model description

The model objective, Sets, Parameters, Variables, and Equations for the GAMS model have been described in the next sections. These are similar to many other Hydro-economic models described in many other studies (Bhaduri & Bekchanov 2017; [1, 17]).

## Model objective

The model is both optimisation and simulation. The objective is to optimise total economic benefits from agriculture, hydropower, and municipal use of the whole river basin (Eq. 4.1). The other benefits including fisheries, navigation, environment, and sediment transport are benefits of instream flow. They were not included in the objective function rather, the model assessed how the levels of these benefits change when more water is released for Bangladesh from India.

$$\text{Max}Z = \sum_{i,j,t} \text{BEN\_Ag}_{i,j,t} + \sum_t \text{BEN\_Hydro}_{t,l} + \sum_{i,t} \text{BEN\_M}_{t,l} \quad (2.1)$$

where,

$\text{BEN\_Ag}_{i,j,t}$  is the agricultural benefits at country  $i$ , crop  $j$  and time  $t$ ;

$\text{BEN\_Hydro}_{t,l}$  is the hydropower benefits at time  $t$  and location  $l$ ;

$\text{BEN\_M}_{t,l}$  is the municipal benefits for the same subscript.

Many constraints were included in the model. For example, the model can divert a maximum of 70% of the water from the Gajaldoba barrage and municipal diversion is the priority. There is a provision to use groundwater for irrigation if the river water is scarce – the model used groundwater when the total water demand for irrigation was less than the water available in the irrigation canal. First, the model chose river water, next it selected groundwater if river water was not available. The other constraints were maximum cultivable land, land use pattern (crop mix), and minimum flow required for fisheries, navigation, and hydropower benefits which are described in the relevant sections.

## Set

Sets are the dimensions over which the storage scaling model is defined. They are the basic building blocks of a GAMS model, corresponding exactly to the indices in the algebraic representations of models [18]. The following sets and set elements have been used in this model:

$i$  Flows /inflow, divert, municipal use, groundwater flow, release/

$t$  Time /2007Nov01–2010Apr03/

$j$  Crop /Boro, Wheat, Potato, Tobacco, Winter Vegetables/

$l$  Flow location /Gajaldoba, Dalia, Kaunia/

The inflow at Gajaldoba was available for 10 days, whether inflow at Dalia and Kaunia was available for daily basis. So daily data were converted to 10 days by making their average. Starting with year and month, the time for the first 10 days was denoted by 01, the second 10 days by 02, and the third 10 days were indicated by 03. For example, 2008Jan02 means the second 10 days of January 2008.

Accordingly, every month there are 3 time periods, and every year, there is a total of 18 time periods. The third 10 days of a month is sometimes 11, 9 or 8 days, thus mean was calculated accordingly.

## Parameter

Parameters are known data (known values) input to the model. The description and units of Parameters for this model are described in Appendix C and the Data section described how the values were collected. The value and source of the parameters are described later on. All flow data were in  $\text{m}^3/\text{second}$  (cusec) which were converted to volume by multiplying with time.

## Variables

Variables are unknown whose values are determined by the model. There are choice variables between different uses. First, there are options for water to be used between two irrigation projects—one is TBP, and another is TBIP. Then there are options to choose the most beneficial crops among many crops. Moreover, there are options to choose between different uses. A GAMS variable, like all other indenters, must be declared before it is referred to. The list of variables used in this model is attached in Appendix D.

## Water balance equations

**Inflows:** The groundwater flow at Gajaldoba is assumed zero as it is included with inflow. During the dry season, the Dharala has a 5% contribution (around 10 cumeec), whereas the Buri Teesta contributes nothing (Haque, ME 2017). Moreover, the Dharala inflows have been included with groundwater as there is no correct data from the Dharala inflows. The equation for inflows at any node/location can be written as follows

$$\text{Inflow}_{t,l} = [\text{OUTflow}_{t,(l-1)} + \text{GWflow}_{t,l}] \quad (4.2)$$

where,

$\text{Inflow}_{t,l}$  – Inflow from upstream of any node in  $\text{m}^3/\text{sec}$  in time  $t$  and location  $l$ ,

$\text{OUTflow}_{t,(l-1)}$  – Outflow from a previous node or barrage in  $\text{m}^3/\text{sec}$ ,

$\text{GWflow}_{t,l}$  – Total groundwater flow to the reach (measured at the end node) in  $\text{m}^3/\text{sec}$ ,

**Outflow:** Water diverted from the Dalia barrage is used for irrigation to TBIP hydropower and domestic use in Shiliguri town. Agricultural demand was available monthly, so it has been divided into 10 days. The water conveyance loss factor which includes evaporation, seepage, and other losses has been assumed 2.5 for both projects (Mullick, Md

Reaz A et al. 2010; [14]). Therefore, actual water withdrawal requirements were measured by multiplying water demand with the conveyance loss factor. The equation for outflows at any node has been written as

$$\text{OUTflow}_{t,l} = [\text{Inflow}_{t,l} - \text{TDivert}_{t,l}] \tag{4.3}$$

Total water diversion at any location has been written as

$$\text{TDivert}_{t,l} = \frac{\sum_j \text{TWD\_Cr}_{i,j,t}}{\text{ConversionFactor}} + \text{Hydro\_divert}_{t,l} + \text{WDem\_m}_{t,l} \tag{4.4}$$

where,

- OUTflow<sub>t,l</sub>* – Outflow from a node or barrage in m<sup>3</sup>/sec,
- TDivert<sub>t,l</sub>* – Total water diverted from a node in m<sup>3</sup>/sec.
- $\sum_j \text{TWD\_Cr}_{i,j,t}$  – Sum of Total water divert for all Crops. It has been divided by Conversion Factor, time (10daysx24hoursX3600seconds) to convert to cumec.
- Hydro\_divert<sub>t,l</sub>* – Diversion for hydropower.
- WDem\_m<sub>t,l</sub>* – Total Demand for Municipal use (For this model Shiliguri town).

The total water demand for a crop depends on field water requirements for that crop and the quantity of land cultivated for that crop. The total water demand for a crop was calculated as

$$\text{TWDC}_{i,j,t} = \text{WDem}_{cri,j} * \text{Convey\_loss\_f}_j * \text{HECTRES\_V}_{i,j,t} \tag{4.5}$$

where,

- WDem<sub>cri,j,t</sub>* – Crop water requirements for 10 days in m.<sup>3</sup>
- Convey\_loss\_f<sub>j</sub>* – Conveyancelossfactor, 2.5forthismodel,
- HECTRES\_V<sub>i,j,t</sub>* – Land cultivated for crop j, country i, and time t,

**Data**

Hydrological data were collected from the Bangladesh Water Development Board (BWDB), Water Resource Planning Organization (WARPO), Joint River Commission (JRC), and Bangladesh Meteorological Department (BBOM). Some data were in cubic feet/sec (cusec) and some were cubic metre/sec (cumec). All data were converted to cumec. For consistency, all other benefit economic values were quantified in the same year (2009). All values were in Bangladeshi Taka or Indian Rupees and thus were converted to USD.

The retail price of electricity in West Bengal on 01.04.2010 was 5.70 (domestic) and 6.66 (industry) rupees/KWh, we used the average of the two 6.16 rupees/KWh (2019b). The wholesale price of electricity has been assumed 35% of retail price (*Bulk Energy* 2019). Therefore,

the wholesale price assumed was 2.156 rupees/KWh which is equivalent to USD37.52/MW. The population of Shiliguri town in 2009 was 513,264 (GoI 2019c). Assuming 135 L/day/person consumption, the total water required for 10 days is 692,906.4 m<sup>3</sup>. The installation cost of water supply infrastructure was not included as it is sunk cost [10, 19]. The data, value, and source are mentioned in Appendix D.

**Benefits assessment**

The river flows and diversions provide many services including a) natural functions like habitat for aquatic animals, water purification service, water regulation service, and drainage service, b) economic services like water for agriculture and forests (including orchards), navigation, fishing activities (Haque, AE et al. 2014).

In the context of available data, this study quantified the value of seven water diversion and flow-related services: irrigated agriculture, domestic use, hydropower, fisheries, navigation sediment transport, and instream flow environmental usage value.

**Irrigation benefits**

To represent irrigation returns the production economics of the five main crops that are irrigated in the dry season was modeled. Crop information used in the modeling including field water requirement (excluding rainfall), yield, production cost (including water price), and crop prices in India and Bangladesh are summarized in Appendix E. Some data for Indian crops, such as winter vegetables were not available. Therefore, the same data for Bangladeshi crops were used.

Based on the water demand, yield, production cost, and crop price, the optimisation model chooses to cultivate the most profitable crop in all areas available to irrigate within water constraints. Specifically, the model chooses Potatoes for both countries to be the most profitable crop. Therefore, constraints requiring the cropping pattern to represent the baseline crop mix were introduced for all the scenarios. The ratio of different crops used in this set of constraints is shown in Table 1.

For these constraints we used the parameter *AlfaC* (crop mix ratio), the total land cultivated (*HECTRES\_V<sub>i,j,t</sub>*) for different crops is then calculated by the following formula

**Table 1 Crop Mix Ratio of different crops cultivated**

Country	Boro	Wheat	Potato	Winter Veg	Tobacco
India	35%	25%	20%	20%	
Bangladesh	55%	15%	15%	10%	5%

$$\text{HECTRES\_V}_{i,j,t} = \text{AlfaC}_j * \text{Cultivable\_land}_i \tag{4.6}$$

where

$\text{Cultivable\_land}_i$  – is the total cultivable land for that project

The sum of irrigated land at a diversion point for different crops in a year/season must not exceed the total irrigable land and this is expressed by the following formula [20]

$$\sum_j \text{HECTRES\_V}_{i,j,t} \leq \text{Cultivable\_land}_i \tag{4.7}$$

Net revenue is the per hectre profit which is calculated by the Residual Imputation Method. The Residual Imputation Method involves calculating net revenue ( $\text{Net\_rev\_cr}_{i,j}$ ) by deducting crop production costs other than water from revenue expressed as yield times price. In short, it can be written as follows

$$\text{Net\_rev\_cr}_{i,j} = \text{Price\_cr}_j * \text{Yield\_cr}_{i,j} - \text{Cost\_cr}_{i,j} \tag{4.8}$$

Revenue ( $\text{REV\_ag}_{i,j,t}$ ) from each crop for 10 days is the net revenue from that crop multiplied by the land cultivated ( $\text{HECTRES\_V}_{i,j,t}$ ) minus groundwater cost. Usually, farmers pay the price of groundwater together for the whole six months. It was divided by 18 to calculate 10 days cost. It can be written as follows

$$\text{REV\_Ag}_{i,j,t} = (\text{Net\_rev\_cr}_{i,j} * \text{HECTRES}_{V_{i,j,t}} - \text{Price}_{\text{gwi}} * \text{GWP}_{\text{Cr}_{i,j,t}}) / 18 \tag{4.9}$$

Agricultural benefits ( $\text{BEN\_Ag}_{i,t}$ ) for the dry season for a project is the sum of revenue of all crops

$$\text{BEN\_Ag}_{i,t} = \sum_j \text{REV\_Ag}_{i,j,t} \tag{4.10}$$

Total agricultural benefits ( $\text{T\_BEN\_Ag}_i$ ) for each country for the whole dry season is the sum of times

$$\text{T\_BEN\_Ag}_i = \sum_t \text{BEN\_Ag}_{i,t} \tag{4.11}$$

Grand total agricultural benefits ( $\text{G\_T\_BEN\_Ag}_i$ ) is the total of all projects

$$\text{G\_T\_BEN\_Ag}_i = \sum_i \text{T\_BEN\_Ag}_{i,t} \tag{4.12}$$

### Hydropower benefits

There are three hydro-power units fed by Teesta Diversion in India. The way that hydropower production depends on

the amount of water diverted is represented by the variable hydropower production ( $\text{PRO\_Hydro}_{(t,i)}$ ) in MW which was estimated by the following formula

$$\text{PRO\_Hydro}_{t,i} = \min[22.5, (7.5 * \text{Trunc}(\text{Hydro\_divert}_{t,i}/60))] \tag{4.13}$$

where

$\text{Hydro\_divert}_{t,i}$  – Flow in the diversion canal in cumec

$\text{Trunc}$  – GAMS term that converts the decimal value to a lower integer.

Hydropower revenue was calculated by multiplying the production with the wholesale price of electricity [17]. The hydropower installation cost that has already been invested – known as a sunk cost, was not included [10]. It was assumed that overhead cost is 10% of total revenue and net revenue ( $\text{Net\_rev\_hydro}_{(t)}$ ) and this was calculated accordingly. Operation and maintenance (O & M) cost of hydropower stations ranges from 1 to 4%. The International renewable energy agency (IRENA) assumes 2.2% for large hydropower and 2.2% to 3% for smaller projects, with a global average of around 2.5% [21]. A recent study indicates that the average O&M cost is USD 45/kW/year for large-scale hydropower projects and around USD 52/kW/year for small-scale hydropower plants [22]. Therefore, for each MW production, O & M cost for 10 days is USD 52\*1000/36 which was called Conversion Factor (CF). Thus, the hydro-power benefits

( $\text{Ben\_Hydro}_{t,i}$ ) for 10 days is

$$\text{BEN\_Hydro}_{t,i} = \text{Net\_rev\_hydro}_t * \text{Pro}_{\text{Hydro}_{t,i}} - \text{CF} * \text{Pro}_{\text{Hydro}_{t,i}} \tag{4.14}$$

Total Hydropower benefits ( $\text{T\_BEN\_Hydro}$ ) for six months (November to April) were calculated by summing all the 10 days benefits which can be written as

$$\text{T\_BEN\_Hydro} = \sum_t \text{BEN\_Hydro}_{t,i} \tag{4.15}$$

### Domestic benefits

Like other South Asian cities, the water tariffs currently in use in Siliguri town is subsidized and not generating sufficient revenues to ensure that utilities can recover their financial costs [9]. The domestic benefits have been calculated considering the demand, price of water, and estimated price elasticity of demand ( $\text{Price\_elasticity}_i$ ) with the standard consumer surplus model of urban water value [23]. The price elasticity of demand for developing countries ranges from -0.3 to -0.6 [24]. We assumed a median value of -0.45

which means water is price inelastic as water has few and poor alternatives and is a necessary good. Then the slope of elasticity ( $SLOPE\_Elasticity_{i,t}$ ) was derived from following formula

$$SLOPE\_Elasticity_{i,t} = Price\_elasticity_i * MW\_price_{i,t} / WDem_{i,t} \tag{4.16}$$

Then the intercept, which is a price when quantity demanded is zero was calculated by the following formula

$$INTERCEPT_{i,t} = MW\_Price_{i,t} + SLOPE\_Elasticity_{i,t} * WDem_{i,t} / MW\_Price_{i,t} \tag{4.17}$$

Then the municipal benefits were calculated considering Consumer Surplus, which is defined as the difference between the total amount that consumers are willing to pay for a good or service and the total amount that they actually do pay (i.e. the market price). In our model, we used the following formula to calculate the municipal benefits ( $BEN\_M_{i,t}$ )

$$BEN\_M_{i,t} = 0.5 * (INTERCEPT_{i,t} - MW\_price_{i,t}) * WDem_{i,t} \tag{4.18}$$

where.

$WDem_{i,t}$ —Municipal water demand.

$MW\_price_{i,t}$  – Municipal water price

**Fisheries and Navigation benefits**

The fisheries and navigation benefits of the Teesta River in 2009 were quantified by Mullick, Md Reaz A et al. (2010). He carried out a primary survey on a 60 km reach of Teesta, Dalia to Kaunia on 91 fishermen and 21 boatmen out of 920 fishermen and 52 boatmen in the catchment area. He collected the variations of income of individual fishermen and boatmen with changes in the river flow within a year and applied the data to a regression that related flow change to economic return change for the two water flow benefits. The fisheries’ benefits for this model is the total change in income for all fishermen for a change in flow predicted with Mullick’s regression equation. Similarly, the navigation benefits are calculated as the change in total income that boatmen earn by carrying goods or passengers predicted for a change in flow with Mullick, Md Reaz A et al. (2010) regression. He did not consider any initial cost or operating cost as the marginal cost is only the price of the boat or net, whereas the operating cost includes labor, time, and boating (which is run manually). This is justified because the total cost of fishing and boating is nearly insignificant. The alternative job for the boatman and fisherman is only agriculture and agriculture cannot employ many laborers. Moreover, the demand for agriculture labor is very low during the late

wet season what is the best time for fishing and boating. According to his study, per cumec aggregated marginal revenue is TK 72616, 57,436, 42,256, 27,076 for the flow of 50, 100, 150, and 200 cumec consecutively. At first, he developed one total benefits function (quadratic equation) for individual fishermen and the flow (Mullick, Md. Reaz Akter et al. 2014). Then they developed an aggregated total benefits function by multiplying the individual benefits with the total number of fishermen. The first derivative of the TB

function is the marginal benefits function (linear equation). The total benefits function is nearly linear up to 300 cumec flow. He also discovered one constraint. The fisheries benefit is zero when the flow is less than 50 cumec and navigation benefits become zero when the flow is less than 24 cumec. As dry season flow in the Teesta is below 300cumec, based on his equation, the following linear equation was developed for fisheries benefits ( $BEN\_F_{(t,l)}$ ) in this model

$$BEN\_F_{t,l} = \max(0, Rev_{f(t,l)} * (OUTflow_{(t,l)} - 50)) \tag{4.19}$$

Total Fisheries benefits ( $T\_BEN\_F_i$ ) for total time

$$T\_BEN\_F_i = \sum_t BEN\_F_{t,l} \tag{4.20}$$

Grand Total Fisheries benefits (Total benefits for the three locations,  $G\_T\_BEN\_F$ )

$$G\_T\_BEN\_F = \sum_l T\_BEN\_F_l \tag{4.21}$$

Mullick et al. [25] also developed similar equations for navigation benefits and quantified the marginal navigation revenue ( $Rev_{n_{t,l}}$ ) for the same reach which is TK 7150 per month per cumec flow or \$ 34.56 per 10 days. Thus, navigation benefits ( $Ben\_N_{t,l}$ ) in this model was calculated by the following equations

$$BEN\_N_{t,l} = \max(0, Rev_{n_{t,l}} * (OUTflow_{t,l} - 24)) \tag{4.22}$$

Total navigation benefits ( $T\_BEN\_N_i$ ) for total time

$$T\_BEN\_N_i = \sum_t BEN\_N_{t,l} \tag{4.23}$$

Grand total navigation benefits (Total benefits for the three locations,  $G\_T\_BEN\_N$ )

$$G\_T\_BEN\_N = \sum_l T\_BEN\_N_l \tag{4.24}$$

In this study, the model computed the fisheries and navigation benefits from Gajaldoba to Dalia, Dalia to Kaunia, and Kaunia to Sundarganj based on the outflow from these three



locations, Gajaldoba, Dalia, and Kaunia. The benefit, that model showed is for 60 km length, it was modified according to the length of each reach. In our case, Gajaldoba to Dalia is 100 km, Dalia to Kaunia is 60 km and Kaunia to Sundarganj is 40 km. We weigh per kilometer benefit for the three stretches by river stretch length to calculate the total benefit.

**Environmental benefits**

As mentioned previously, the Teesta River flows into to the Brahmaputra River which in turn is a tributary to the Padma River which meets the Meghna and the combined course flows to the Bay of Bengal. Therefore, if water is released from Gajaldoba barrage, it not only benefits the Teesta basin area but also augments the flow in the Brahmaputra, the Padma, and the Meghna Rivers. The benefits due to the augmentation of flow downstream beyond the study boundary were not assessed directly, rather a benefits transfer method using values from a Ganges River study was used. According to a study by Wu et al. [9], the value of low flows to Bangladesh at the Ganges above the Farakka ranges from 0.00 USD/m<sup>3</sup> to 0.10 USD/m<sup>3</sup>, and the value of water in irrigation ranges from 0.01 USD/m<sup>3</sup> to 0.1 USD/m<sup>3</sup>. The length of the Ganges from Farakka to the Bay of Bengal is around 200 km and the length of Brahmaputra to its outfall at the Bay of Bengal is also 200 km. As the length covered by both rivers before falling to the sea is equal, the ecosystem benefits produced by the rivers can be assumed to be similar. As a conservative assessment, the value for low flow augmentation has been assumed to be 0.01 USD/m<sup>3</sup> in this study. This value includes all ecosystem services including fisheries, navigation, salinity prevention, and so on. As a whole, the benefits have been addressed as environmental benefits (*BEN\_ENV\_Bd<sub>t,l</sub>*) and calculated by multiplying the value with the flow released from Kaunia and time.

$$BEN\_ENV\_Bd_{t,l} = Ben\_env_{t,l} * Time * OUTflow_{t,l} \quad (4.25)$$

where,

*Ben\_env<sub>t,l</sub>* – EnvironmentBenefits, forthisstudy0.01USD/m<sup>3</sup>

*OUTflow<sub>t,l</sub>* – FlowthatleavestheTeestabasinthroughtheBrahmaputraincumec

Time –Days \* Hour \* Minute \* Seconds

Total environmental benefits (*T\_BEN\_ENV\_Bd*) for six months (November to April) were calculated by summing all the 10 days benefits which can be written as

$$T\_BEN\_ENV\_Bd = \sum_t BEN\_ENV\_Bd_{t,l} \quad (4.26)$$

**Dredging/Sediment transport benefits**

The downstream of the Gajaldoba barrage has been silted up due to low flow during the dry season. The river needs to be dredged not only for navigation but also to carry water during the high flood. A study named “Feasibility of Capital Dredging and Sustainable River Management of Bangladesh” has been carried out in Bangladesh for the proposed dredging [26], which suggested a 15-year dredging plan. It is anticipated that if there is normal (pre-barrage condition) dry season flow in the river, it would reduce dredging costs due to self-dredging (auto-dredging) by the flow. A conservative estimate of the benefits of self-dredging is that the normal flow will reduce 10% of the annual dredging cost. According to BWDB [26], the 15-year dredging cost for the Teesta would be Tk 999,735 (lakh taka) which means the yearly dredging cost is USD 8,331,1250. Therefore, the cost saved for sediment transport by normal dry season flow (pre-barrage condition) is USD 462,840 for 10 days. This is the dredging benefit (*Ben\_Dredge<sub>t,l</sub>*), which is cost saved by pre-barrage condition flow. The inflow at Gajaldoba was assumed as pre-barrage condition flow. The benefits in Bangladesh (*BEN\_Dredge\_Bd<sub>t,l</sub>*) were quantified by multiplying dredging benefits with the ratio of the outflow at Gajaldoba to the inflow at any time like the following equation.

$$BEN\_Dredge\_Bd_{t,l} = Ben\_Dredge_{t,l} * \frac{OUTflow_{t,l}}{Inflow_{t,l}} \quad (4.27)$$

The total benefits for the whole year were calculated by summing all the values. The length of Teesta in India after Gajaldoba is 80 km, whereas the length of Teesta in Bangladesh is 120 km. Therefore, dredging benefits in India would be two-thirds of dredging benefits in Bangladesh.

**Calibration and validation**

**Hydrologic** The model was calibrated by trial and error to fit model predictions suitably close to observed values.

The model was calibrated to check the output values with observed/historical values of outflow, crop production, hydropower production, and the ratio of groundwater and river water used by the model in each basin country in the baseline scenario. As the flow of 2008–09 is average flow thus was used as a baseline scenario and was used for calibration. At first, the model was prepared for the baseline scenario for the year 2008–09. The amount of water released was compared to the inflow. The model shows that the average amount of water released from Gajaldoba barrage is

26.95% of water inflow at Gajaldoba which is 30.03% for observed outflow. Therefore, it may be said that the model outflow is close to the observed outflow. Then the model outflow was compared with the observed outflow at three locations. The result is shown in Fig. 4.

**Economic** In the baseline scenario, agriculture benefits for the year 2008–09 was \$274/ha for Bangladesh and \$256/ha for India. There is no data/study for the actual agricultural benefits/profit in Bangladesh and India. The per hectre agricultural profit/benefits for Vietnam is \$257.78/ha [16], which is close to that of India and Bangladesh. As Vietnam, India, and Bangladesh are all developing countries, the model result seems to be realistic. The contribution to the Gross Domestic Product (GDP) of Bangladesh by crops in 2009–10 was 7,53,391 million taka which is equivalent to USD 10,762 million and the cultivated area was 76,17,563 ha [27]. The cultivated area in TBIP in Bangladesh is 79,000 ha which is 1.03% of the total cultivable area of Bangladesh. Therefore, the GDP contribution from the Teesta barrage project can be assumed to be 1.03% which is USD107.62 million. While calculating GDP, the cost is not considered, GDP is the revenue from agriculture. On the other hand, the

benefit calculated in this model is the net benefit which mean revenue minus cost. The model shows that agricultural benefits for the year 2008–09 (USD21.67 million) is 20.14% of the revenue (USD107.62 million). It can be concluded that the model result is consistent with the developing country context.

The benefits of FNDE (fisheries, navigation, dredging, and environment) in Bangladesh are USD 27.0/ML and in India is USD 4.5.0/ML (2019 value). There is no study on the environmental benefits of South Asian Rivers. On the other hand, the environmental benefits (including fisheries, navigation, and recreation) from inflows from the Amu Daria River to the Aral Sea were USD 4/ML in 2006 [28, 29]. However, environmental values depend on the length of the river-the more distance the flow travels the more benefits it produces. It can be said that the result of this model is similar to other developing countries.



Fig. 4 Model outflow vs Observed outflow for 2008–09, 2007–08 and 2009–10

## Results

The model aimed to assess the economic value of Teesta water for various uses including agriculture, hydropower, domestic, fisheries, navigation, dredging, and environment considering national impacts for Bangladesh and India. The result of 2008–09 which is the focus of this study is presented in this section. The results presented in Table 2 describe the economic value of river water for various use in both India and Bangladesh. More detailed descriptions of each sectoral use are described below.

**Agriculture benefits** The agricultural benefits for 2008–09 (November to April) in Bangladesh are USD 42.241 million in the baseline scenario. The agricultural benefits for 2008–09 in India are USD 32.555 million in the baseline scenario.

**Hydropower benefits** There is no hydropower production in Bangladesh and therefore the benefits are zero. The hydro-power benefits for 2008–09 (November to April) in India is USD 5.817 million which can be assumed as average benefits for the dry season.

**Domestic benefits** There is no significant domestic use in Bangladesh and therefore the benefits are zero. The domestic benefits in India for the municipal use at Shiliguri town are USD 688 thousand at present. However, water use may

increase in the future as the population of Shiliguri town is increasing.

**Fisheries, Navigation, Dredging, and Environment (FNDE) benefits** All these benefits are produced from instream use and thereby grouped. The fisheries benefits in Bangladesh for the year 2008–09 (November to April) are USD 1.630 million for baseline. Besides, the navigation benefits for Bangladesh are USD 194 thousand. On the other hand, the fisheries benefits for India for the same period are USD 97 thousand. The navigation benefits for the same year for India are USD 29 thousand. The navigation benefits are the income that boatman earn by carrying goods or passengers. The fisheries and navigation benefits in this study are the total revenue/income of fishermen and boatmen. We do not have the actual cost of them. The dredging benefits in Bangladesh for the same period are USD 2.970 million. The dredging benefits in India are estimated to be around USD 2.385 million. The environmental benefits in Bangladesh which is downstream of the Teesta are estimated to be around USD 29.968 million.

**Total benefits** The total benefits for the year 2008–09 for the dry season (November to April) are USD 41.571 million for India and USD 77.003 million for Bangladesh. Therefore, the total benefits in Bangladesh are higher than that of India.

**Benefits per unit volume of water use** This section describes the benefits per unit volume of water used for the base case. The benefits and volumes of water used for different sectors are presented in Table 3 and each sectoral water use is described below:

**Table 2** Benefits of water use from different sectors under the current/base scenario

	Values are in 2019 thousand USD	
	India	Bangladesh
Agriculture	32,555	42,241
Hydropower	5,817	-
Domestic	688	-
Fisheries	97	1,630
Navigation	29	194
Environment	-	29,968
Dredging	2,385	2,970
Total	41,571	77,003

**Agricultural use** The agricultural water uses for 2008–09 (November to April) in Bangladesh are 700,369 mega litres and benefits are USD 42.241 million in the baseline scenario. The per unit benefit for agricultural use is USD 60.31/ML. On the other hand, the water used in agriculture for the same time in India is 653,818 mega litres and the benefits are USD 32.555 million. The per unit benefit for agricultural use is USD 49.79/ML. The per unit benefit for agricultural use in Bangladesh is higher than that of India.

**Table 3** Benefits and volumes of water used for 2008–09

Sector	Benefit (USD)		Water Used (ML)		Unit Benefit (USD/ML)	
	India	BD	India	BD	India	BD
Agriculture	32,554,879	42,240,624	653,818	700,369	49.79	60.31
Hydropower	5,817,068	-	1,036,800	-	5.61	0.00
Domestic	687,680	-	12,472	-	55.14	0.00
FNDE	2,511,557	34,762,630	560,583	1,288,937	4.48	26.97

**Hydropower and Domestic use** There are no hydropower and domestic use in Bangladesh and therefore the benefits are zero. The water use for hydropower production and domestic purpose in India is shown in Table 5–2. It is seen that the water use for India’s hydropower in 2008–09 is 1,036,800 mega litres and the total benefits are USD 5,817,068. It is seen that the water used for domestic purpose for India for 2008–09 is 12,472 mega litres and total benefits are USD 687,680. The per unit benefits for hydropower and domestic use are USD 5.61 and USD 55.14 per mega litre respectively.

**Fisheries, Navigation, Dredging, and Environment (FNDE) use** The total water used for FNDE in India is 560,583 mega litres and in Bangladesh is 1,288,937 mega litres. The per unit benefit for FNDE use is USD 4.48/ML for India and USD 26.97/ML for Bangladesh.

## Discussion

**Agricultural benefits are higher than any other benefits** The benefits at different sectors in both countries for 2008–09 are shown in Fig. 5. The benefits from agricultural use are higher than any other uses in the Teesta River like many other studies [30, 31]. The importance of this sector is very high as agriculture dominates the economy of both India and Bangladesh. In the Teesta basin, 70 percent of the population are directly involved in farming and heavily rely on agricultural products as their income-generating activities [5]. This sector provides not only employment but also ensures food security.

**Hydropower benefits in India are not as significant as agriculture** Hydropower benefits in India are not as large as agriculture benefits in India (Fig. 5). This result is different from other studies where hydropower benefit is close to

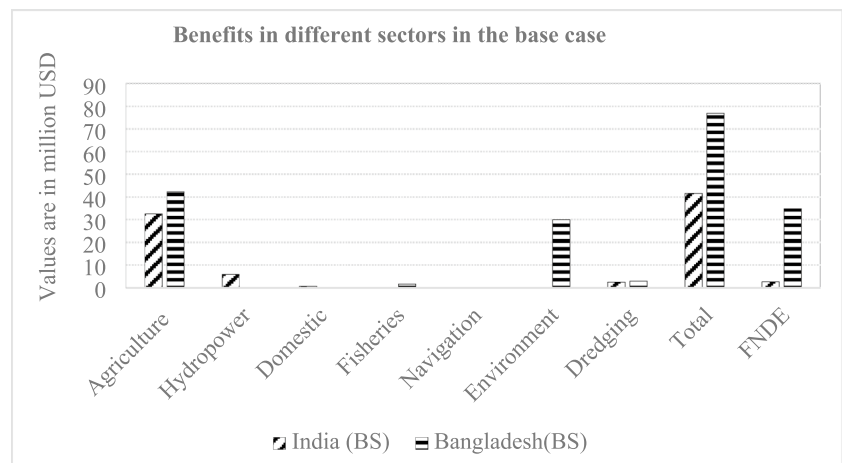
agricultural benefit [32, 33]. Because the hydropower plant is located not in the Teesta main river, but rather on the diversion canal where water is diverted from the river. The water is diverted to the Dauk River after producing hydropower. This diversion to another river basin causes huge water loss without any significant benefits. Though hydropower use does not consume water, the water at Teesta Canal has no use after the production of hydropower.

**Environmental benefits in Bangladesh are significant** The environmental benefits in Bangladesh are very significant and higher than all other benefits except agriculture (Fig. 5). It suggests that if the water flows through the river, its value is also very high. The other studies that assessed the benefits of environmental flow also found that environmental benefits are very significant [2], Kirby, J et al. 2014a; [34].

**The sum of all instream benefits (FNDE) is significant** The volume of water that flows through the river, not only produces environmental benefits downstream of the Teesta but also increases dredging, fisheries, and navigation benefits in the Teesta river both in India (80 km) and Bangladesh (120 km). Therefore, the same quantity of water that produces all four instream benefits (fisheries, navigation, dredging, and environment) in Bangladesh has been named together as FNDE. Individually, the dredging and fisheries benefits are not as big as agriculture or the environment. In contrast, the benefits from all the instream uses (FNDE) are significant (Fig. 5). This result is consistent with other similar studies [2], Kirby, JM et al. 2014b).

**The value of domestic and navigation benefits are small, but their contribution is vital** It is seen from (Fig. 5) that, the total domestic and navigation benefits are very small compared to agriculture and environmental benefits. However, the opportunity cost of domestic water and navigation water is very high. Water from the Teesta canal is the only source

**Fig. 5** The benefits at different sectors in both countries for 2008–09



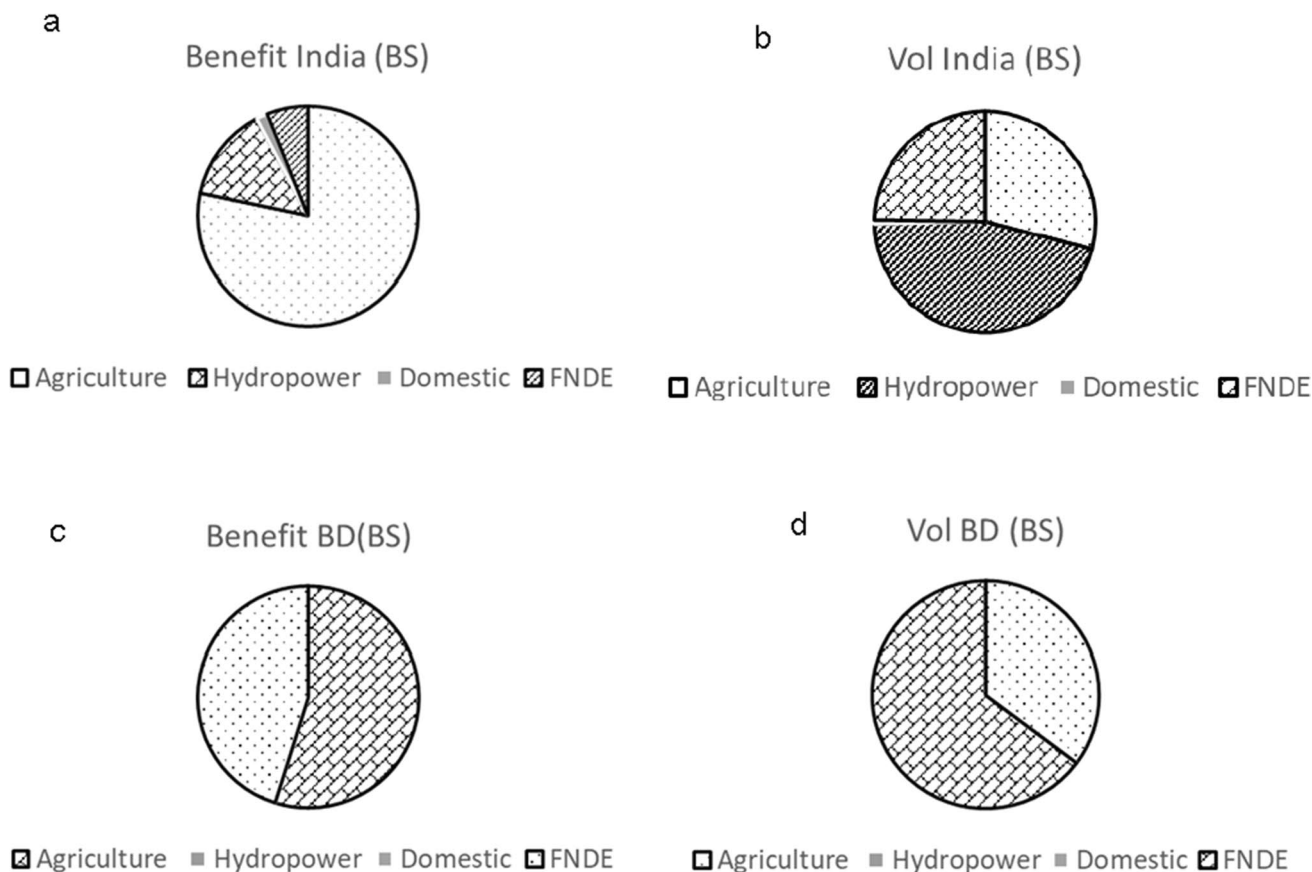
of water for Shiliguri town, especially in the dry season. Because the Mahananda River, which passes through Shiliguri town, dries up during the dry season. The domestic water fee (USD 0.125/m<sup>3</sup>) that the city dwellers pay is very small compared to the other cities in developing countries. In the same way, the charge that people pay to the boatman for carrying goods through the river by boat is much less than the carrying cost by road or rail. The alternative cost of carrying goods by road or rail is much higher. Hence the contribution of domestic and navigation use is very important though its monetary value is small.

**Hydropower uses the highest volume of water but does not produce the highest benefits** It is seen from Fig. 5 that the highest water use is attributed to hydropower but the benefits for hydropower are not the highest rather benefits for agriculture are the highest. On the other hand, the volume of water used for agriculture is much smaller than that of hydropower. Usually, the water use value for hydropower varies significantly across the river as hydropower production depends mostly on the height of the dam not the quantity of flow

[10]. The hydropower produced in the Teesta Canal fall is not significant as the terrain is flat.

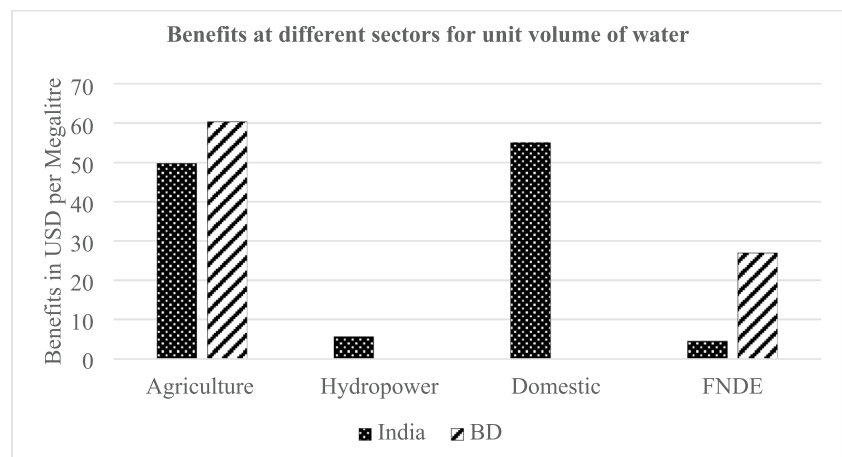
**The volume of instream water use is higher than the volume of off-stream water use in Bangladesh** The volume of water used for fisheries, navigation, dredging, and environment (FNDE) in Bangladesh is bigger than that of agriculture. On the other hand, the volume of instream water use is lower than the volume of off-stream water use in India ( Fig. 6).

**Benefits per unit volume of water for hydropower is lowest** The next graph (Fig. 7) shows that per unit benefits from hydropower (USD 5.7/ML) is the lowest among all types of water use where agriculture and domestic use produce the highest benefits. Though water is not consumed in hydropower, water is not used for irrigation or any other purpose after producing hydropower from the Teesta canal fall hydel power station. Benefits from agricultural use is USD 60.9/ML in Bangladesh and USD 50.8/ML in India (2010 value). The highest irrigation benefits from the Ganges is USD 100/ML [9] and from the Nile is USD 80/Megaliter [10]. The



**Fig. 6** Ratio for (a) Benefits from water use, India; (b) Volume of water use, India; (c) Benefits from water use, Bangladesh; (d) Volume of water use, Bangladesh

**Fig. 7** Unit benefits in different sectors for 2008–09



benefit of water used for the environment is USD 19.7/ML in Bangladesh.

**Benefit per unit volume of water for the environment is much higher than hydropower** The benefits of FNDE (fisheries, navigation, dredging, and environment) in Bangladesh are USD 27.0/ML and India are USD 4.5.0/ML. It is to be noted that the same amount of water that produce FNDE benefits in India, also produces FNDE benefits in Bangladesh. Therefore, the total benefits of FNDE per unit ML of water would be the sum of FNDE benefits in India and FNDE benefits in Bangladesh which is USD 31.5/ML. Therefore, the benefits per unit volume of water for the environment are much higher than that of hydropower. Moreover, the installation cost of hydropower was not included which would further decrease the benefits per unit volume of water for the hydropower.

### Potential for Inter-sectoral trade-off

The previous section's results suggest that there is potential for a trade-off between hydropower benefits in India, and other water use benefits both in India and Bangladesh including agriculture, domestic, environment, fisheries, navigation, and dredging. The conclusions about trade-offs differ from those drawn in some similar studies where hydropower water use was estimated to be comparatively more beneficial than any other uses [10]. The reason for this dissimilarity is that hydropower is produced instream in those rivers whereas hydropower is produced off-stream in the Teesta.

As there are no big cities on the river, there is no scope to extend domestic use both in India and Bangladesh. On the other hand, agricultural water has an alternative source in the Teesta basin which is groundwater whereas the environmental use including fisheries, navigation, and dredging benefit have no alternative. The Teesta basin is flooded every year.

Therefore ground water is recharged every year. A study by [35] shows that GW level in the Teesta basin is stable over the last few decades though GW is being extracted during dry season. Quantifying the trade-off between reduced hydropower production in India, and improved in stream flow supported benefits to fisheries, navigation and dredging benefits in both countries, is an important first step towards a mutually beneficial benefit sharing arrangement. The probability of a net benefit gain arise primarily because of high potential instream use values other than hydropower including fisheries, navigation, dredging and environment downstream of the study area boundary. Moreover, more instream flow is likely to provide additional benefits which are not quantified in this study such as tourism, amenities and micro-climate related benefits which are not included in this study. On the whole, the likelihood is that less benefit is created from off-stream hydropower diversions from the Teesta than would be generated if the water were left in the Teesta where they would generate benefits for both India and Bangladesh.

It is to be mentioned that the hydropower projects on the canal can be operated in full swing during the rest of the year (May–October) when there is plenty of flow in the river. The periodic maintenance of hydropower plants and canal maintenance can be done during this time. It is also mentioned that there are many hydropower projects with small storage facilities in the upper Teesta, upstream of Gajaldoba barrage [11], (The Asia Foundation 2013). Though these projects may interrupt the natural flow in the downstream, they do not divert water from the river. Therefore, these hydropower projects are not that harmful for the environment of the Teesta thus can be exempted from trade-off.

## Conclusion

This study discovers the economic value of the Teesta River water for various use. The value does not seem very significant compared to other river basins because it was only for six months. The model was not run for longer time due to lack of long-time data. If the value is estimated for 20/30 years (like other HEMs), it would look significant. The study shows that the benefit per unit volume of water for hydropower are the lowest among all types of water use and the benefits per unit volume of water for the environment is much higher than that of hydropower. The conclusions differ from those drawn in some similar studies where hydropower water use was estimated to be comparatively more beneficial than any other uses [10]. The reason for this dissimilarity is that hydropower is produced instream in those rivers whereas hydropower is produced off-stream in the Teesta. It gives a clear indication of trade-off between off-stream hydropower versus instream flow. This study gives an idea about how to maximise the benefits from the river and how to mitigate the water sharing dispute.

Like many other studies, this study did not account for the construction and operating cost of infrastructures which was assumed as a sunk cost. If construction and operating costs are considered, the benefits per unit volume of water for agriculture and hydropower may decrease. However, the benefits per unit volume of water for agriculture can be increased by increasing water efficiency. The water efficiency at both TBP and TBIP is only 40%, which is less than many other countries [36]. The seepage loss of both projects is very high as the canals are earthen. This loss can be minimized easily by converting the earthen canals to concrete. This may include some costs but will reduce maintenance costs. Further study could evaluate how much investment can improve efficiency by how much and the costs and benefits that this would involve.

One limitation of this research, arising from data and research effort constraints, is the limited scope of flow-related benefits considered. While we model a broader scope than is considered in many HEM studies, we recognise the potential for additional flow-related benefits. An important recommendation for future research is continued effort to expand the scope of flow-related water benefits included in evaluations of water sharing opportunities. There is a clear opportunity to expand the consideration of benefits in diverse categories such as tourism, amenity, micro-climate, soil fertility, groundwater recharge, water quality, thermal power cooling, and water-dependent ecosystem benefits, to name a few. Another direction for future research, to better support the realisation of improved transboundary outcomes, is the evaluation of more and less cooperative strategies with methods.

## Appendix A

Teesta Barrage Project (TBP), India.

The Teesta Barrage Project (TBP) is the largest multi-purpose water resources project in the state of West Bengal, India (Fig. 8).

The Project has three different phases which envisages utilization of potential of the Teesta River in the field of irrigation, hydropower generation, navigation and flood moderation. It was planned to irrigate 922 thousand hectre of land under the 1st phase, generation of 650 MW electricity in the 2nd phase and it schemed navigational plan by link between Ganga and Brahmaputra under the 3rd phase. The 1st phase was again divided into three stages which aimed to irrigate 546 thousand hectre of land under the 1st stage, 223 thousand hectre under the 2nd stage and 153 thousand hectre under the 3rd stage.

In addition to the ambitious TBP, NHPC Limited (formerly the National Hydroelectric Power Corporation) is in the process of developing two “low dams” in Darjeeling District of West Bengal — Teesta Low Dam III (132 megawatts) and Teesta Low Dam IV (160 megawatts).

The 1st phase of the project was started in the year 1976 and is still under progress (Until March/2016 Rs. 1465.76 Cr out of Rs. 2988.61 Cr has been spent). The 1st sub stage includes the following works (*Irrigation and Waterways Department, Government of India*):

- A) Construction of a barrage across river Teesta at Gajaldoba in the Jalpaiguri district (Fig. 9).
- B) Construction of distributaries, minors, sub-minors and water courses covering a length of 2450.00 km.
- C) Construction of 27 nos. Regulator and fall structures, including 3 nos. of Power Falls.
- D) Construction of 166 nos of bridges on main canals including crossings of Railway and Highway.
- E) Construction of residential and non-residential buildings and other infrastructures.
- F) Construction of Inspection paths, approach roads and other allied works.
- G) Two pick-up barrages, one across the Mahananda River and other across river Dauk at.
- H) Construction of five main canals namely:
  - i. Teesta- Mahananda Link Canal (TMLC) for the length of 25.75 km.
  - ii. Mahananda Main Canal for the length of 32.33 km.
  - iii. Dauk Nagar Main Canal for the length of 80.20 km.
  - iv. Nagar Tangon Main Canal for the length of 42.20 km.
  - v. Teesta- Jaldhaka Main Canal for the length of 30.31 km.

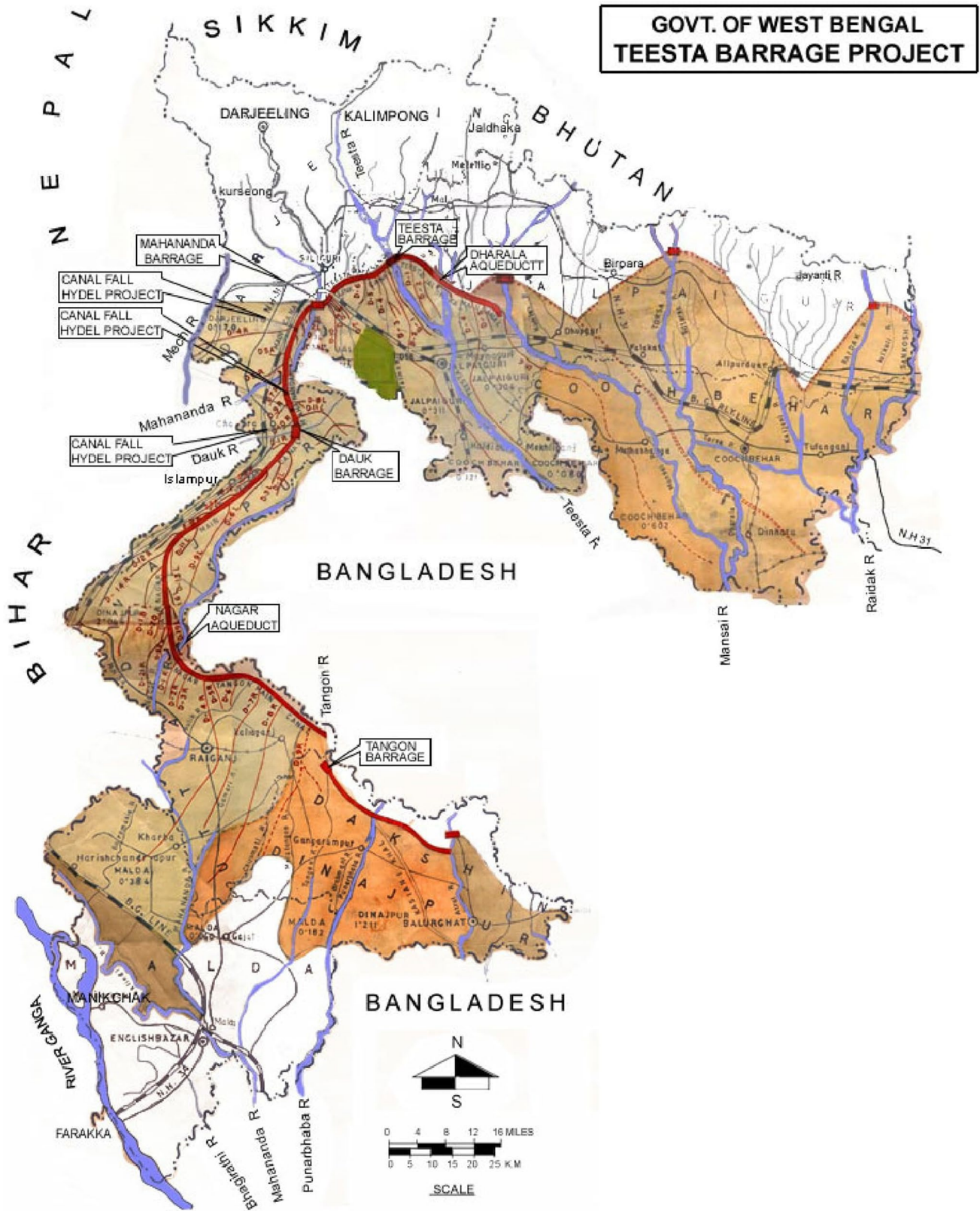


Fig. 8 Teesta Barrage Project, Gajaldoba, India



**Fig. 9** Teesta Barrage Gajaldoba



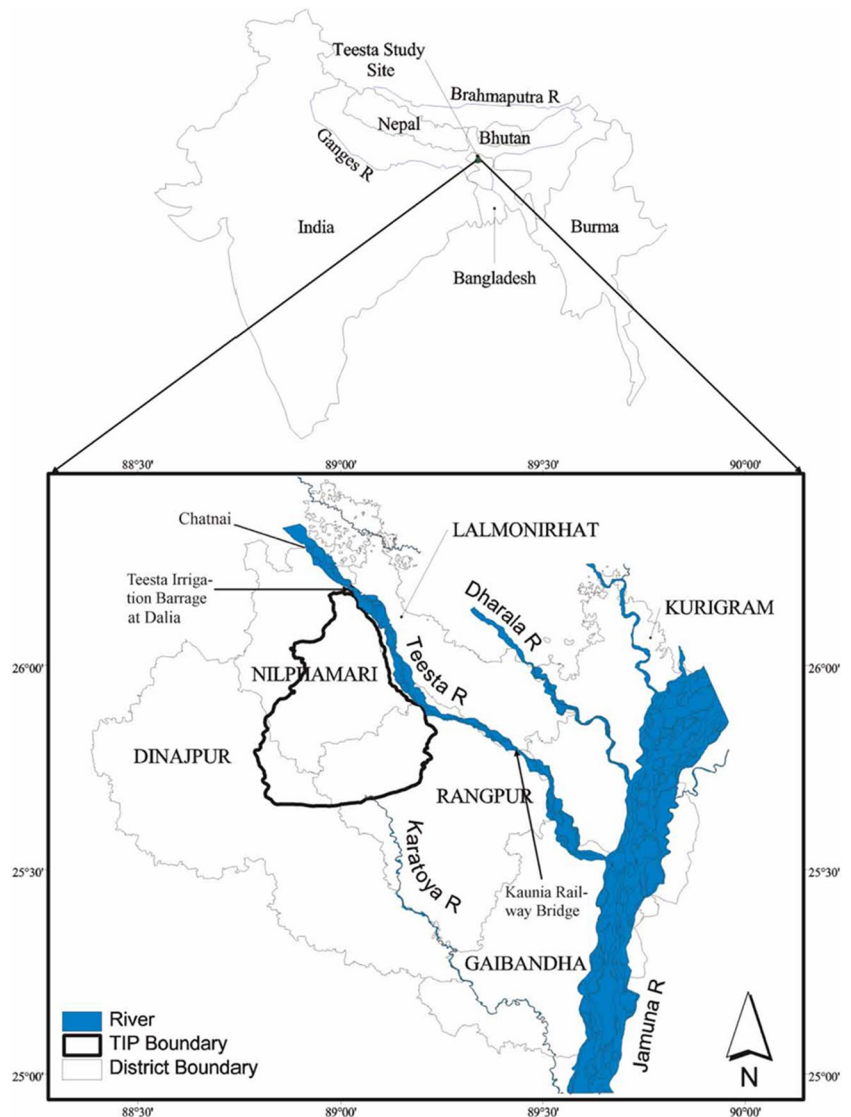
Until 2016, 78% of main canal, approximately 51% of the distribution system has been completed. Three hydro-power projects for generation of 67.5 MW ( $3 \times 22.5$  MW) at Lichipukhri, Haptiagach & Bholagach at 5.503 km, 21.275 km & 31.241 km respectively on canal falls of Mahananda main canal, have already been commissioned by State Power Department.

### Appendix B

Teesta Barrage Irrigation Project (TBIP), Bangladesh.

Bangladesh started Teesta Barrage Irrigation Project (TBIP) on the Teesta in Dalia in 1979 with an aim to irrigate 750,000 ha of land (Fig. 10). After completing 1st

**Fig. 10** Teesta Barrage Irrigation Project (TBIP) in Bangladesh



Phase in 1990 covering 154,000 ha irrigation, 2nd Phase is not started yet due to scarcity of water.

Salient features of the Teesta Barrage Irrigation Project (TBIP) are described in Table 4. The Photo of Gigantic barrage is shown in Fig. 11.

(Source: Teesta Barrage project, BWDB 1993).

### Appendix C

Table 5.

### Appendix D

List of variables used in the model.

- Z Total benefits.
- OUTflow<sub>t,l</sub> Outflow from the node at location l, time t.
- GWP\_Cr<sub>i,j,t</sub> Groundwater pumped in m<sup>3</sup> for crop j, country i, and time t.
- RWD\_Cr<sub>i,j,t</sub> River water diverted in m<sup>3</sup> for crop j, country i, and time t.
- TWD\_Cr<sub>i,j,t</sub> Total Water Demand in m<sup>3</sup> for crop j, country i, and time t.

- HECTRES\_V<sub>i,j,t</sub> Land cultivated for crop j, country i, and time t.
- REV\_Ag<sub>i,j,t</sub> Revenue from crop j, country i, and time t.
- BEN\_Ag<sub>i,t</sub> Agricultural benefits at time t for each country for 10 days.
- T\_BEN\_Ag<sub>i</sub> Total agricultural benefits for each country.
- G\_T\_BEN\_Ag Grand Total agricultural benefits for total time.
- PRO\_Hydro<sub>t</sub> Hydropower production from Teesta-Mahananda canal.
- BEN\_Hydro<sub>t</sub> Hydropower benefits for 10 days by time t.
- T\_Ben\_Hydro Total hydropower benefits.
- BEN\_M<sub>i,t</sub> Municipal benefits for 10 days for each country.
- T\_BEN\_M<sub>i</sub> Total municipal benefits.
- BEN\_F<sub>t,l</sub> Fisheries benefits for 10 days for each reach or location.
- T\_BEN\_F<sub>l</sub> Total fisheries benefits for each reach or location.
- BEN\_N<sub>t,l</sub> Navigation benefits for 10 days for each reach or location.
- T\_BEN\_N<sub>l</sub> Total navigation benefits for each reach or location.
- BEN\_ENV\_Bd<sub>t,l</sub> Environmental benefits in Bangladesh.
- T\_BEN\_ENV\_B<sub>l</sub> Total environmental benefits in Bangladesh.

**Table 4** Components of TBIP

Items whole project	1st phase	Items whole project	1st phase
1. Benefitted area: 750,000 Ha	182,000 Ha	9. Main canal: 34 km	34 km
2. Irrigable area: 540,000 Ha	132,000 Ha	10. Branch canal: 275 km	120 km
3. Barrage (515 M) 1	1	11. Secondary canal: 450 km	360 km
4. Canal head regulator (110 M) 1	1	12. Tertiary canal: 2720 km	590 km
5. Closure dam (2470 m) 1	1	13. Drainage canal: 50,000 km	960 km
6. Flood by-pass (610 m) 1	1	14. Irrigation structure: 1512	391
7. Silt trap: 1	1	15. Drainage structure 2320	
8. Flood embankment: 80 km	80 km	16. Turn out: 15,000	5000

**Fig. 11** Teesta Barrage, Dalia



**Table 5** Parameter

Category	Name	Description	Unit
Water balance	Inflow <sub>t,l</sub>	Flow of the river by time and location	m <sup>3</sup>
	GWflow <sub>t,l</sub>	Groundwater flow to the river by time and location	m <sup>3</sup>
	Eflow <sub>t,l</sub>	Environmental flow by time and location	m <sup>3</sup>
Agri benefits	WDem <sub>cr<sub>i,j,t</sub></sub>	Crop water demand at country i, crop j, time t	m <sup>3</sup> /ha
	Yield <sub>cr<sub>i,j</sub></sub>	Yield for crop j and at country i	ton/ha
	Cost <sub>cr<sub>i,j</sub></sub>	Production costs of crop j and country i	USD/ha
	Price <sub>cr<sub>j</sub></sub>	Price of crop j	USD/ton
	Price <sub>gw<sub>i</sub></sub>	Price of groundwater at country i	USD/m <sup>3</sup>
	Alfa <sub>cr<sub>j</sub></sub>	Percentage of area for crop j	%
	Cultivable <sub>land<sub>i</sub></sub>	Total cultivable land at country i	ha
	Convey <sub>loss<sub>f<sub>j</sub></sub></sub>	Ratio between water withdrawal requirement vs field water requirement	number
Hydro benefits	Hydro <sub>divert<sub>t,l</sub></sub>	Diversion for hydropower by time and location	m <sup>3</sup> /s
	Hydro <sub>price<sub>t</sub></sub>	Price of hydropower by time	USD/MWh
	Net <sub>rev<sub>hydro<sub>t</sub></sub></sub>	Revenue after deducting operation and maintenance cost	USD/MWh
Domestic use	MW <sub>price<sub>i</sub></sub>	Municipal water price at country i	USD/m <sup>3</sup>
	WDem <sub>m<sub>i</sub></sub>	Municipal water demand at country i	m <sup>3</sup>
	Price <sub>elasticity<sub>i</sub></sub>	Price elasticity of demand at country i	number
Other benefits	Rev <sub>f<sub>t,l</sub></sub>	Fisheries revenue by time and location	USD/cumec
	Rev <sub>n<sub>t,l</sub></sub>	Navigation revenue by time and location	USD/cumec
	Ben <sub>env<sub>i</sub></sub>	Environmental benefits by location	USD/m <sup>3</sup>
	Ben <sub>Dredge<sub>t,l</sub></sub>	Benefits by self-dredging	USD /ha

BEN\_ENV\_In<sub>t,l</sub> Environmental benefits in India.

T\_BEN\_ENV\_In<sub>i</sub> Total environmental benefits in India.

BEN\_DREDG\_Bd<sub>t,l</sub> Benefits of auto dredging by river flow at Bangladesh.

T\_BEN\_DREDG\_Bd<sub>i</sub> Total benefits of auto dredging by river flow at Bangladesh.

T\_BEN\_DREDG\_In<sub>i</sub> Total benefits of auto dredging by river flow at India.

## Appendix E

Table 6.

**Table 6** Crop information (Among all values, the value in the yellow box was used)

Country	Parameter	Boro Paddy	Wheat	Potato	Winter Veg	Tobacco	Reference
India	Water requirement (m <sup>3</sup> /ha)	1400–16000	4000–4500	4000–4500	3450		(Rudra 2009)
	Yield (ton/ha)	3.33	2.22	26.09			(Rudra 2009)
		2.55 (rice, not paddy)	2.68	2.4	8		(GoI 2019a)
		2.12 (rice, not paddy)	2.83	20			(GoI 2019a)
	Production cost (USD/ha)	575.12 (WB)	546.97 (India avg)				[37]
Minimum Crop Price (USD/ton)	165.91	191.43				[38]	
BD	Water requirement (m <sup>3</sup> /ha)	10,190	2750	3240	3450	2880	(Mullick, Md. Reaz Akter 2011a)
	Yield (ton/ha)	4.5	2.5	15	8	1.25	(Mullick, Md. Reaz Akter 2011a)
		6.8	3.73	20.79			[39]
		3.83591 (rice, not paddy)	2.41072	18.23	8.35354	1.418	[40]
	Production cost (USD/ha)	675.15	396.03	927.64	610.35	754.57	(Mullick, Md Reaz Akter et al. 2011)
		1590.37	879.2	1861			[39]
	Crop Price (USD/ton) for 2009–2010	194.96	319.03	72.5	116.01	870.07	(Mullick, Md Reaz Akter 2011b)
237.5		237.5	187.5			[39]	
	189.16	252.1	143.76			[40](P327)	

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**Data Availability** N.B water requirements is excluding rainfall.

## Declarations

**Competing interests** The authors declare no competing interests.

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