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Marginal benefit based optimal water allocation: case of Teesta River, Bangladesh

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Abstract

This article describes a hydrologic–economic optimization model for allocating available river flow between competing off- and in-stream demands, based on the marginal benefits (MBs) of sectoral water uses in a segment of the Teesta River in Bangladesh. Irrigation, capture fishery and navigation are the main direct water uses considered. The value of irrigation water was estimated using the residual imputation method. Losses in yield caused by lowered irrigation supply, resulting from reduced river flow, formed the basis for establishing the total and MB functions for off-stream river water use (irrigation). Total and MB functions for in-stream water use (capture fishery, navigation) were developed using field survey data of beneficiaries' income as a function of river flow. Analysis was enhanced by applying AQUARIUS, which allocates water between users to maximize consumer surplus based on MB functions. Model results show that in-stream uses could not compete with off-stream uses in the case of the Teesta, as substantial benefit was obtained from irrigation. Environmental flow to safeguard river health and in-stream use was considered to be a constraint in the optimization, which results in a sizeable reduction in irrigation benefit with a small increase in in-stream benefit. The necessary trade-offs between economic efficiency and environmental protection are depicted, providing insight into a justifiable water allocation strategy for the Teesta.

Keywords: Hydro-economic model; In-stream and off-stream uses; Optimal water allocation; Teesta River, Bangladesh; Total and marginal benefit function

Introduction

Satisfying freshwater demands for humans and nature at the same time is a global challenge for the 21st century that entails significant trade-offs while managing the resource, particularly in the context of increasing demands and limits to supply augmentation in a changing environment (Ward *et al.*, 2006).

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The natural environment, increasingly considered a discrete water-use sector, is thus sometimes perceived as being in competition with off-stream demands in many places in the world (Hollinshead & Lund, 2006). Poff *et al.* (2003) have noted contentious negotiations over water allocation between in-stream and ecosystem versus off-stream human demands in a number of river basins, such as the Klamath basin in Oregon and California; the Apalachicola–Chattahoochee–Flint basin in Georgia, Alabama and Florida; the Rangitata basin in New Zealand; and the Lower Balonne basin in Australia.

Reports depicting explicit off- and in-stream conflicts in the Ganges River basin have been rare. However, various water use activities represent conflicting interests between the water-use sectors in and across the political boundaries of nations sharing the basin. Smakhtin *et al.* (2004) reported that several major river basins in the world, including the Ganges, would move into a higher category of human water scarcity if environmental water requirements were also to be satisfied. In particular, the Farakka Barrage, commissioned in 1975 in the downstream part of the Ganges (in India) to divert 1,133 $m^3 s^{-1}$ of water from the Ganges to the Bhagirati–Hooghly River in order to restore the navigability of the latter, on whose banks the Kolkata port is situated, resulted in several conflicts between the off- and in-stream users and often resulted in problems such as lack of water for irrigation and for domestic and industrial supply, saline water intrusion, reduction in fisheries, impaired navigation, reduced forestry and increased sedimentation of the river downstream of the Farakka Barrage (Khan, 1996; Rahman, 2009).

Reallocation of water between sectors is therefore often claimed and commended, yet this action can be myopic unless the potential repercussions for societal gains and losses between the water-use sectors are well documented and addressed. Despite significant progress in the recognition and approbation of environmental water requirements, successful implementation of such plans has lagged behind. Recent research (e.g. Moore, 2004; Scatena, 2004) has argued that improved understanding of the socioeconomic benefits and costs of in-stream water allocation is necessary for the successful implementation of environmental flow. Adoption of an economic approach to water management that offers an appropriate balance between environmental needs and human consumption is becoming the standard for water professionals commissioned to chart efficient system operation (Molden, 2007). It is worth noting that water allocation based solely on water rights or the equity principle merely satisfies the efficiency criterion (Wang *et al*., 2008).

Because water is a scarce resource, its allocation needs to be efficient, maximizing the value it provides to society (Harou *et al*., 2009). Economics offers methods of appraising efficiency and equity in the allocation of water. Water managers at present are keen on applying economics in efficient water resource management rather than looking into the effects of water management on the entire economy. Although many existing models of optimal system operation have ignored the use of economics in water management, mathematical modeling studies linking relevant hydrology and economic ‘laws’ of supply and demand can offer valuable guidance in efficient water resources management. Integrated hydrologic and economic models, often called ‘hydro-economic models’ (HEMs), are well suited to support decision-making, benefit valuation, plan design, evaluation of alternatives and institutional design in tandem with policy issues (McKinney *et al*., 1999; Lund *et al*., 2006; Cai, 2008; Harou *et al*., 2009). By including an economic concept at the core of water resources management, HEMs can represent the hydrologic, economic, engineering and environmental aspects of a water resources system in a coherent framework (Harou *et al*., 2009).

Two approaches are common in designing HEMs: (1) compartmental models, in which prior estimated water-use benefit functions are included in the HEM as separate input; and (2) holistic models, in which estimation of benefit functions is endogenous to the model. HEMs commonly use the optimization technique and are, in general, deterministic in nature. Their spatial domains may range from a single farm to a sub-basin or an entire river basin and their temporal domains may range from a few days to even decades for planning purposes; however, a time horizon of 1 year is most often considered, which is then subdivided into monthly time steps (Harou *et al*., 2009).

In existing HEM studies (e.g. Rosegrant *et al*., 2000; Cai *et al*., 2003; Ringler & Cai, 2006), researchers have focused particularly on hydropower generation and lake and reservoir recreation as the two main in-stream uses of river waters. Thus far as mentioned by Harou *et al*. (2009) no application of an economic representation of in-stream flow has been described in the literature. Yet in many developing countries the allocation of in-stream flow, especially in its ramifications for the poor, can assume significant economic value and social importance.

The water allocation model described here was developed to analyze off- and in-stream water uses in terms of the marginal benefits (MBs) of sectoral water uses in the Teesta River, Bangladesh. The study establishes the MB functions for irrigation (off-stream use) and for capture fishery and small-scale navigation (in-stream uses), utilizes the benefit functions in allocating the available water (river flow) to these competing users and then describes the trade-offs between economic efficiency and the environmental protection criterion.

Various valuation methods are available to estimate economic benefit functions of off- and in-stream water uses (e.g. Young, 1996, 2005; Griffin, 2006). For off-stream water uses, valuation methods based on actual market behavior are preferred (Hussain *et al*., 2007), whereas a hypothetical market mechanism is widely adopted for in-stream water valuation. The majority of valuation studies to date have estimated the average aggregated value of the resource. To explore valuation results farther with an HEM requires defining a relationship between water-use and net economic benefit from each of the water-use sectors involved in each case. Different economic analysis approaches can be employed to estimate the total benefit (TB), depending on availability of data relating to the water use(s) concerned. Employing the concept of a production function, variations in benefit levels caused by changes in water availability and/or use can serve to develop a TB function. In the absence of irrigation market mechanisms and data constraints (as in some developing countries), the residual imputation method (RIM), which adopts the actual market prices of the various inputs and outputs of the crop production process, can suitably be applied to estimate the economic benefit of water used for irrigation.

For in-stream valuations, most studies to date have estimated mainly the value of recreational use of in-stream water, or ecosystem services rendered to society, rather than attempting a comprehensive value function. Establishing a certain figure for TB does not reflect the change in that benefit as a function of water use or availability. In the present study, primary survey data were used to estimate the benefit from in-stream water uses, where users' income and the variation in that income were treated as a function of river flow in developing an overall in-stream benefit function.

Study area

A segment of the Teesta River, the fourth largest river in Bangladesh in terms of discharge, was chosen for the study described here (Figure 1). The Teesta, originating in Sikkim, India, enters Bangladesh at Chatnai, Nilphamari District, and flows into the mighty Brahmaputra (known as the Jamuna in Bangladesh). Of a total length of 315 km, the Teesta in Bangladesh is about 113 km (Bari & Marchand,

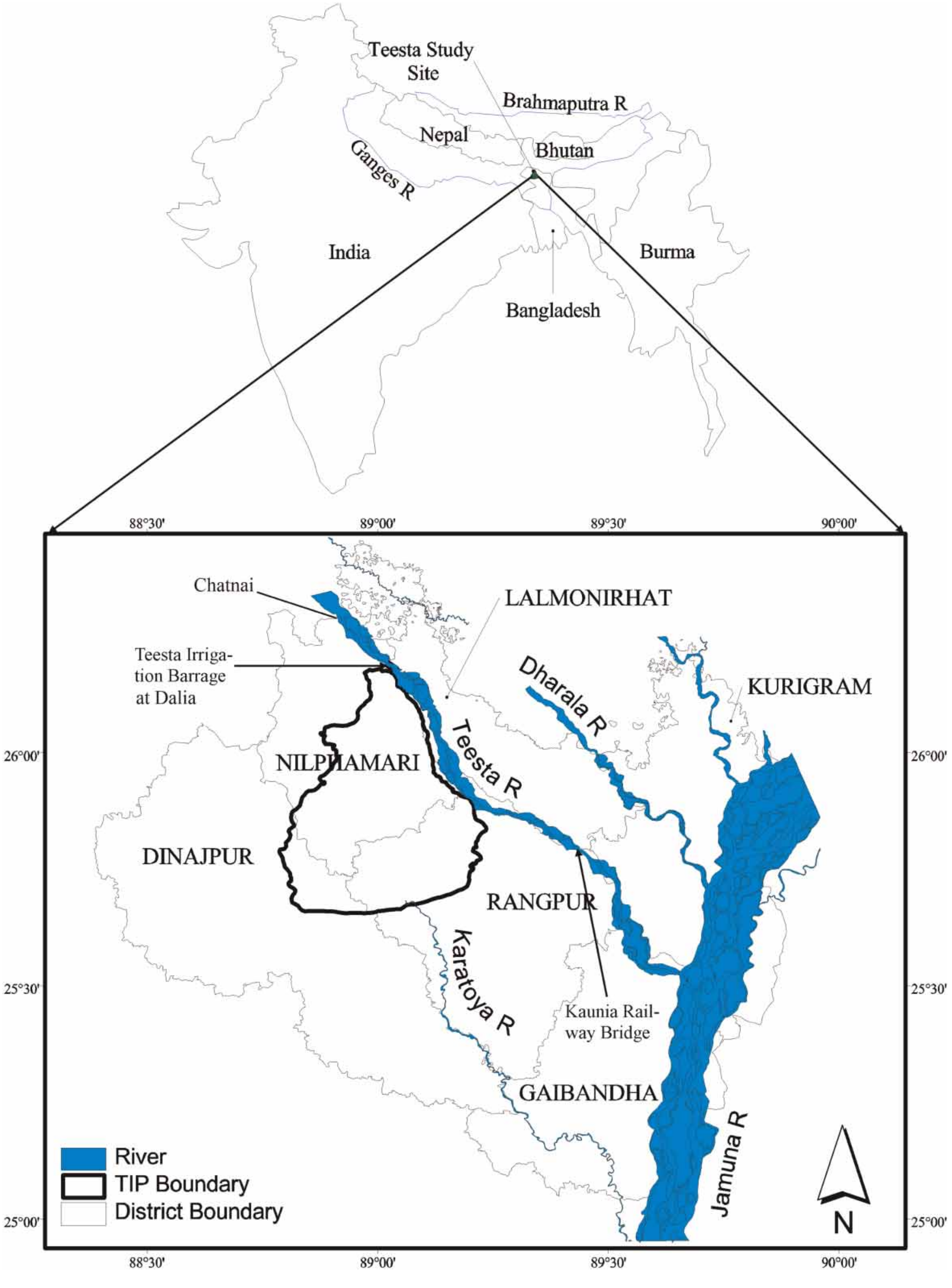

Fig. 1. Location map of the Teesta River and the Teesta Irrigation Project in Bangladesh.

2006). It is a sandy, braided river with a steep slope and exhibits high seasonal flow variability; it causes inundation of floodplains in the monsoon season but creates low-flow conditions in the dry season. The Teesta is the main source of water in the northwestern, drought-prone but agriculturally high-potential region of the country. Stream flow has been regulated since 1987, when India constructed an irrigation-purpose barrage at Gazaldoba in West Bengal. Another barrage for the same purpose was constructed at the Dalia point inside Bangladesh in 1990, to supply water to the Teesta Irrigation Project (TIP), which is the largest surface water irrigation project in Bangladesh operated by the Bangladesh Water Development Board (BWDB).

Despite these efforts at regulation, drastic flow reduction in the Teesta has been observed in recent years (mainly since 2000), signaling an alarming situation for agriculture as well as for other in-stream users downstream of the barrage in the Bangladeshi part of the river. This situation calls for effective management of the river's water. Table 1 presents the long-term flow characteristics of the Teesta at Kaunia (Kaunia railway bridge point), which is the only flow-measuring point downstream of the Teesta Barrage (at Dalia) and before the river's confluence with the Jamuna. Figure 2 depicts the dry season (December–March) mean monthly flows for the period 1967–2006. Considerable decrease in the dry season flow can be seen, especially for the months of January, February and March.

Along the river banks, there is no domestic or industrial abstraction of the river water. The only off-stream water use from the Teesta is irrigation. The TIP depends entirely upon the Teesta for its water supply. TIP has a design capacity to supply water to 540,486 ha of agricultural land covering seven administrative districts in the northwestern part of Bangladesh (BWDB, 2005). The project was planned to be implemented in two phases. However, only Phase I was implemented; it was completed in 1990. It covers a gross area of 154,250 ha and net irrigated area of 111,732 ha spreading over Rangpur, Nilphamari and Dinazpur districts (BWDB, 2005) (Figure 1). The entire TIP area is on the right side of the river and only one diversion canal takes water away from it. Data and information regarding the actual diversion of the flow from the Teesta to the irrigation project could not be obtained from the BWDB head office, but the BWDB TIP site office was able to provide an overview of the actual diversion. According to them,

Table 1. Long-term (1967–2006) seasonal flow characteristics of the Teesta: all flows are measured at Kaunia in $m^3 s^{-1}$.

Season (months)	Period	MMX	MMF	MMN
High-flow season (HFS) (June–September)	1967–76	3,813	1,947	948
	1977–86	3,263	1,884	1,030
	1987–96	3,867	2,116	1,207
	1997–2006	2,949	1,849	1,130
Intermediate-flow season (IFS) (April–May, October–November)	1967–76	1,223	520	321
	1977–86	1,013	507	299
	1987–96	1,106	516	297
	1997–2006	857	447	209
Low-flow season (LFS) (December–March)	1967–76	193	147	119
	1977–86	252	188	155
	1987–96	237	176	133
	1997–2006	137	95	52

MMX = mean monthly maximum flow; MMF = mean monthly flow; MMN = mean monthly minimum flow. *Source:* authors' calculations are based on the Teesta's flow data collected from the BWDB database.

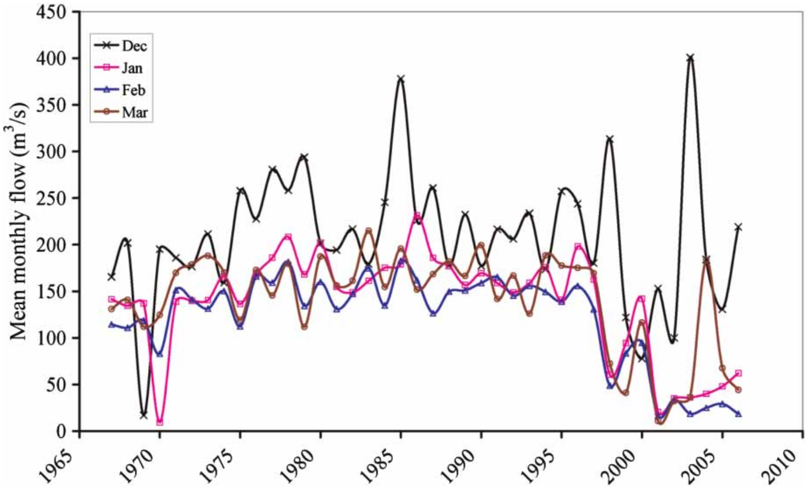

Fig. 2. Mean monthly flows for the dry season months at Kaunia, Teesta, for the period 1967–2006. *Source:* Authors' calculations based on Teesta flow data collected from the BWDB database.

in the dry season, when available flow does not meet the irrigation requirement, up to 90% of the flow is diverted to TIP. The TIP drainage system comprises a number of smaller rivers inside the project area that take away excess irrigation and rainwater, mainly to the Jamuna (BWDB, 2005). Thus excess diverted irrigation water is not available for other uses downstream of the barrage in the Teesta.

The average annual rainfall in the TIP region is about 2,400 mm yr^{-1}, of which more than 90% falls between May and October. Irrigation is mainly required from November to April. Even though the principal aim of TIP was to provide supplemental irrigation, particularly to the post-monsoon (November and December) rice fields, currently it supplies water for the entire dry season depending on the availability of water at the barrage (BWDB, 2008). Lowland rice, mainly of three varieties, is the main crop grown in the project area. Besides rice, other crops like wheat, vegetables, tobacco and potato also grow in the TIP area. Double- and triple-cropped areas are respectively 82 and 18% of the total, constituting a cropping intensity of 218%.

In addition to the proper functioning of the riverine ecosystem, the flow in the Teesta is important for direct in-stream uses such as capture fishery and small-scale navigation, as well as to maintain a certain channel depth. Furthermore, several informal in-stream uses such as subsistence irrigation and household consumption exist but are not well documented. Socioeconomic conditions in the study area are very poor and a river-flow-based livelihood is critically important to the more impoverished segments of the population. In-stream water requirements set forth in different management plans thus far have been based only on crude reckoning (Bari & Marchand, 2006). Thus an improved understanding of water allocation needs for off- and in-stream uses is a critically important issue for responsible water management authorities.

The riparian unions[1] along both banks of the Teesta are part of the study area for this research. The area contains 26 riparian unions. The total population of these 26 unions is about 555,300,

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[1] A union is the lowest administrative unit in Bangladesh, where the administrative hierarchy descends from division to district to sub-district to union.

with an average literacy rate of 34.4% (BBS, 2005). Of the total of 125,415 households in the 26 riparian unions at the time of the study, 53,655 (43%) were involved in the agriculture, forestry and livestock sectors, 40,817 (32.5%) lived by selling field labor, 920 (0.7%) households worked in the fishery sector and 2,028 (1.6%) were engaged in transport-related jobs (BBS, 2005). Only 14,803 households (11.8%) had access to sanitary latrines and 10,054 (8%) had electrical connections; these low percentages illustrate the very poor socioeconomic conditions in the study area.

Data and methods

Modeling approach

The integrated hydrologic–economic model (HEM) devised for this study is a compartmental type that includes hydrologic, economic and optimization components (Figure 3). The model is aggregated at regional-level water supply and demand along with economic benefit functions. The optimization module approaches the question of optimal water allocation subject to required hydrologic and environmental constraints.

The model can be schematized as a node-link network representing the spatial relation between off- and in-stream demands in the river basin, as shown in Figure 4. The nodes represent the demand sites and the links represent the linkages between river reaches. Flow balances are calculated for each node at each time period; flow transport is calculated in terms of the spatial linkages in the river basin network; water demands are assessed separately. The environmental flow requirement is estimated using an indicator of hydrologic alteration (IHA) software (Richter *et al.*, 1997) with a predefined range of variability approach (RVA) target. Water supply is determined through hydrologic simulation; water balance at each node of the river system is endogenous within the model. Water supply and demand are balanced based on the objective of maximizing economic benefit from water uses. Amalgamated consumer surplus from all water uses is maximized in the optimization section of the model, from the pre-established MB functions briefly described above.

The economic benefit functions, developed separately, feed the optimization model. Where multiple uses exist at a single node, the aggregated MB function is developed by adding the non-competitive

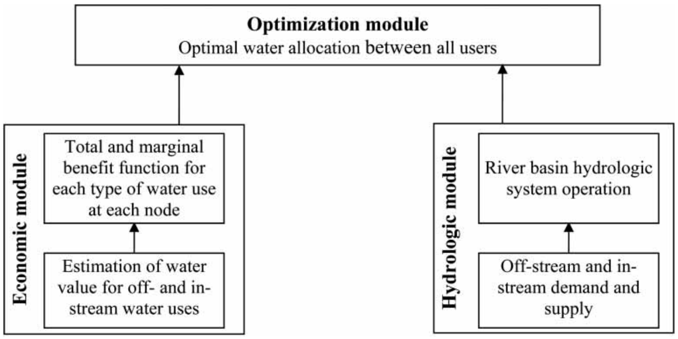

Fig. 3. Modeling framework.

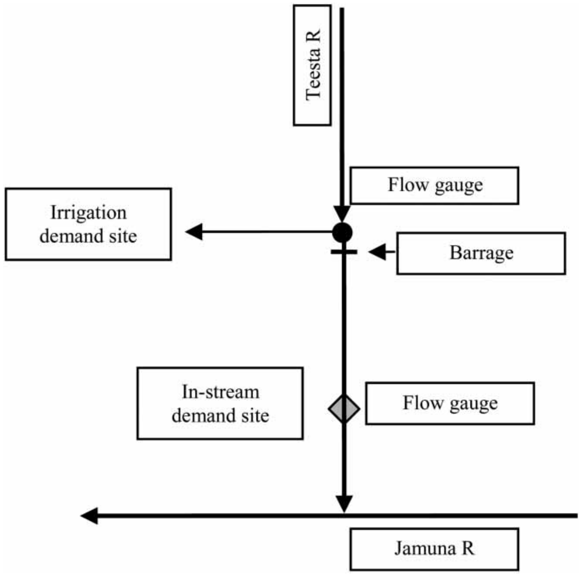

Fig. 4. Teesta River basin network at the study area.

(in-stream) demands vertically and the competitive (off-stream) demands horizontally. The time horizon for this is taken as 1 year, divided into monthly steps.

Components of the module

Economic module: establishing MB functions. The economic module establishes the relationship between stream flow and net economic benefit acquired from each water-use sector. A quadratic relationship between water-use benefit and stream flow (Equation (1)) is considered as the TB function for river water use, symbolizing a production function. A production function is often approximated using polynomials. In the case of a single input, such as stream flow, with a single output (i.e. crop production, fish production, boatmen's income), a quadratic production function, called the TB function hereafter, would reflect appropriately the usual shape of the relationship: while input use increases, output first increases then stabilizes and then finally decreases:

$$\mathrm{TB_u} = \beta_0 + \beta_1 \times \mathrm{flow}_i + \beta_2 \times \mathrm{flow}_i^2 \tag{1}$$

where $\mathrm{TB_u}$ is the TB of water use at a flow level i, β_0 is the constant and β_1, β_2 are the coefficients. The flow indicates mean monthly stream flow ($\mathrm{m^3\,s^{-1}}$). The first-order derivative of the TB function with respect to flow gives the MB function.

Irrigation water use. A water-crop production-function estimating crop yield in relation to varying levels of irrigation water availability or shortage was adopted as the basis for deriving a benefit function for irrigation water. Market-based valuation methods are more acceptable in this case (Hussain *et al.*, 2007), but researchers can apply several non-market techniques to value irrigation water because of the insufficient role the market itself plays in the case of irrigation water. In TIP, farmers pay a nominal fee of Tk 1,730 (about US$25) per hectare per year[2]. However, not all farmers have yet been brought under that payment system (BWDB, 2008). Considering the existing poorly operated irrigation water market in the TIP area, the RIM – the most widely used deductive technique – was employed to estimate the water value in this study for five different levels of water availability scenarios. Based on RIM, the total value of production (TVP) equals the opportunity cost of all the inputs (Agudelo, 2001) in a production process as expressed in Equation (2):

$$\mathrm{TVP} = \sum_i \mathrm{VMP}_i \times Q_i + \mathrm{VMP}_\mathrm{w} \times Q_\mathrm{w} \tag{2}$$

where TVP is the total value of the commodity produced; VMP_i is the value of the marginal product of input i; Q_i indicates the quantity of input i used in production; and w stands for irrigation water. Following Equation (2), VMP_w or the shadow price of water – indicating the maximum amount the farmer could pay for irrigation water and still cover the cost of production – can be obtained when the marginal value products of all inputs are considered the same as their market price. Market prices for agricultural inputs and outputs in June 2008 were used in the RIM analyses in this study. Information on input and output quantities from crop production were taken from the TIP evaluation report (BWDB, 2005).

Information related to the quantity of water applied or diverted to a specific crop or farm or to the entire TIP area was not available for this study. Irrigation water requirements for crops and the aggregated demand at the project level were estimated using the field water balance approach (Equation (3)) (Mohan *et al*., 1996) for lowland rice and CROPWAT model 4.3 (FAO, 1998) for the other, upland crops:

$$S_t = S_{t-1} + I_t - \mathrm{ET}_\mathrm{ct} + \mathrm{ER}_t - \mathrm{SP}_t \tag{3}$$

where S_t indicates storage at the end of time period t; S_{t-1} is the storage at the beginning of time period t; I_t refers to the applied irrigation during the period t; ET_ct is the actual evapotranspiration by the rice crop during the period t; ER_t refers to effective rainfall during the period t and SP_t indicates seepage and percolation (S&P) losses during time period t. A span of one day is the unit time period (t) in the fieldwater balance calculation. All the components of fieldwater balance are measured in mm.

Equation (3) itself takes into account the estimation of effective rainfall for the rice fields, whereas for the other crops, effective rainfall was estimated using the US Department of Agriculture soil conservation service method in CROPWAT modeling. Monthly irrigation requirements were estimated only for the months when an irrigation water supply is needed (November to April). Crop estimations also took into account that three different varieties of rice (*Aus*, *Aman*, *Boro*) and dry season crops such as cabbage, cauliflower, potato, tobacco, tomato and wheat need irrigation to produce a satisfactory level of yield.

The fieldwater balance method assumes that the paddy field can store additional rainfall up to the level of a field-bund (spillway). Given the typical local practices, the ponding depth in rice fields is assumed to be from 50 to 100 mm. S&P losses are considered to be 3 mm d^{-1} for the first 105 days based on local data (Institute of Water Modelling, 2003). Afterwards, a drained condition takes place

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[2] Tk indicates Taka, the national currency of Bangladesh. US$1.00 = Tk 68.96 in June 2009.

for 15 days, such that the total growth period of the rice crops is 120 days. Estimations also account for the water requirement for rice nursery (assumed to cover 5% of the rice area under cultivation) and land preparation (180 mm).

Two measures of irrigation water are of interest. The water-use requirement in the field (WRF) refers to the amount of irrigation water actually required at the field level, which includes the demands of evapotranspiration, S&P and land preparation, as well as requirements for maintaining ponding conditions in the case of rice. The model does not consider water requirements for leaching of salts or pre-irrigation. The water withdrawal requirement (WWR) from the source refers to the amount of water required to be withdrawn from the source, that is, the Teesta River. The ratio of WRF to WWR is the overall efficiency of the irrigation project, which is taken as 0.4 in this study. The estimated monthly WWRs were converted into flow with an appropriate conversion from their depth unit (mm) based on the water requirement for each crop in a specific month and considering the area irrigated for each crop.

Following RIM, the overall benefit from agricultural production using irrigation water in the TIP area was calculated for five different water availability levels (90, 80, 70, 60 and 50%) and by invoking the concept of yield responses to water stress. The TBs were distributed over the irrigation season uniformly and presented on a monthly basis. Water availability was further calculated as monthly flow averaged over 6 months of the irrigation season. This represents *flow* in Equation (1).

Yield response to water stress is quantified from the ratio of actual to maximum evapotranspiration (Equation (4)), as given by Doorenbos & Kassam (1979):

$$Y_{\mathrm{a}} = Y_{\mathrm{m}}\left[1 - k_{\mathrm{y}}\left(1 - \frac{E_{\mathrm{a}}}{E_{\mathrm{m}}}\right)\right] \tag{4}$$

where Y_{a} is the actual harvested yield (t ha^{-1}), Y_{m} is the potential yield (t ha^{-1}), k_{y} is the average yield response factor (non-dimensional) for the overall growth period and E_{a} and E_{m} refer to actual and maximum evapotranspiration (mm), respectively. The value of E_{m} is taken from the CROPWAT model's calculation.

Here, Equation (4) represents the yield response to water use, which is quantified by the yield response factor (k_{y}). Yield response relates relative decrease in yield ($1–Y_{\mathrm{a}}/Y_{\mathrm{m}}$) to relative evapotranspiration deficit ($1–\mathrm{ET}_{\mathrm{a}}/\mathrm{ET}_{\mathrm{m}}$). As noted in the Food and Agriculture Organization (FAO) Irrigation and Drainage Paper 33, this relationship is valid for upland crops. For lowland rice, Equation (5) was adopted, which expresses an empirical relationship based on experimental data from two contrasting rice-growing areas – central north India in the subtropics (≈21°–32° latitude) and Luzon (in the Philippines) in the tropics (≈14°–16° latitude) – and from a greenhouse study in Japan (Bouman & Toung, 2001). Water input to the rice field is controlled by reducing the depth of standing water to soil saturation or by alternate wetting/drying:

$$Y_{\mathrm{a}} = Y_{\mathrm{m}}\left(1 - \mathrm{e}^{-b(wi-300)}\right) \tag{5}$$

where Y_{a} and Y_{m} are the actual and potential yield (t ha^{-1}), respectively, b is the initial factor (water in this case) use efficiency or the initial slope (dimensionless value in the range of 0.00175–0.00275 based on potential yield and wi is the total water input (including irrigation water and effective rainwater, in mm).

The figure 300 in Equation (5) indicates the minimum amount of water input (in mm) for any yield at all.

In-stream water direct uses. Capture fishery and small-scale navigation are the two main and direct uses of in-stream water in the Teesta. Apart from biological factors, fish yield in a river critically depends on the river's hydrology, characteristics of flooded zones and fish migration routes (Welcomme, 1985). Yet a firmly established hydrological–ecological link is missing in contemporary literature on the subject (IWMI, 2005; Arthington *et al*., 2006). Along these lines, Bovee (1982) calculated the amount of micro-habitat available for different life stages of various particular species at different flow levels using the physical habitat simulation (PHABSIM) model. That model, however, fails to represent all the species' habitats in an integrated fashion.

Instead, overall habitat can be considered as a proxy for total fish production or catch and can easily be incorporated into further economic applications. The World Bank (2004) has demonstrated a habitat versus fish production relation for Cambodian Dai fisheries in which habitat is estimated according to a 'feeding opportunity index'. Baran *et al.* (2001) had previously modeled water levels and fish production for the Cambodian Dai fisheries using logarithmic water-level-to-catch relations. Ringler & Cai (2006) modeled an Arctan function between flow and fisheries benefits for the Mekong River. This research provides a background conspectus on flow, habitat and fish production interdependency.

The concept of a flow–habitat–fish production interrelation was further considered in valuing water for fishery use in the Teesta. As no data were available relating to fish production from the Teesta, a primary survey was designed and administered to the fishermen working at the study reach (Dalia to Kaunia); individual income data from the fishermen provided the basis for developing the benefit function. The value of fish production is considered equal to the sum of the fishermen's income for a certain time period (e.g. a month or a year). The study aimed to estimate only the short-run benefits that relate to operating costs of fishing efforts. It must be kept in mind, though, that the operating costs of the poorer fishing group at the study reach consist of the constituents' own labor and time. The opportunity costs of time and labor involved in small-scale fisheries were deemed insignificant because of the lack of alternative livelihood opportunities in the context of impoverished socioeconomic conditions in the study area, and consequently were not considered in the study.

For short-run and at-source valuations of water for inland water transport, all operating costs subtracted from the estimated gross benefits of water transport facilities yield economic benefits for water by navigational use (Gibbons, 1986). The short-run value would be justified owing to the high seasonality of navigation, where a negligible marginal value is realized in the high-flow period and a high value is realized in a marginal flow period. Water value for navigation on the Teesta was derived according to these principles. No data or information related to the number of boats and cargos plying in the Teesta were available from any secondary sources. Thus, as with the fishermen, a primary survey was administered to the boatmen and the group's income was considered to be the gross benefit from navigation. Here too the operating costs were considered to be zero, as most of the boats are manually operated.

Primary survey. A semi-structured primary survey was administered (in the local language) to the fishermen and boatmen along both the banks of the Teesta (study reach) in May and June 2008. In all, 97 fishermen and 23 boatmen were surveyed from a random selection of 11 of the 26 riparian unions at the study site. The questionnaire focused on two topics: socio-demographic data, with specific questions on each respondent's name, address, age, experience, education, gender, working days per week, family size and fishing mode (individual or group fishing, in the case of fishermen), and a detailed survey eliciting the individual respondent's dependency on river discharge and the variations of the respondent's daily income levels with the changes in river flow over the course of a year.

Estimating the TB from in-stream use required data from the total number of fishermen and boatmen working in the study area. Only the riparian unions were considered in the ultimate estimation. National demographic survey data (BBS, 2005) were used to obtain the number of households engaged in the fishery sector and the number of people engaged in transportation work at the union level. These data were adopted with a number of underlying assumptions: (1) fishermen or boatmen who were working at the Teesta study site in fact lived in the local riparian unions; (2) fishermen in these riparian unions were engaged only in capture fishery; and (3) only one person from each household was engaged in fishery work. These assumptions were validated by the socio-demographic information collected during the field survey. No information at all was available about the total number of boatmen at the study area; the total figure here was calculated proportionately from national and local data on transportation labor. At the union level, BBS (2005) reported the number of people working in the transport sector as a whole but did not differentiate them by specific transportation modes. The Bangladesh Labor Force Survey (2008) did provide the number of people engaged in different transportation modes including the motorized and non-motorized water transport sector for the entire country. Because the boats in the study area are mostly non-motorized, the proportion of the number of people working in inland water transport (non-motorized sector) to total number of people working in the transport sector was used to estimate the total number of boatmen at the study site, as shown in Equation (6):

$$\text{Boatmen}_{t,s} = \sum_{j} \text{PWT}_{\text{U}} \times \frac{\text{PWWT}_{\text{NM}}}{\text{PWT}_{\text{C}}} \tag{6}$$

where $\text{Boatmen}_{t,s}$ is the total number of boatmen at the study site, PWT indicates the number of people working at the transport sector, PWWT_{NM} is the number of people working in the watertransport non-motorized sector, U is the riparian union, C indicates the whole country, $j = 1, 2,..n$ is the number of riparian unions.

Optimization module

Equation (7) shows the objective function of the optimal water allocation model:

$$\begin{aligned} \text{Max\_Obj} &= \sum_{\text{m}} \text{CS}_{\text{o\_s}} + \sum_{n} \text{CS}_{\text{i\_s}} \\ &= \sum \text{CS}_{\text{irr}} + \sum (\text{CS}_{\text{fish+nav}}) \end{aligned} \tag{7}$$

where CS is consumer surplus and o_s and i_s represent, respectively, the summation of the spatially distributed all off-stream (m) and in-stream (n) sectors. The optimization is subject to hydrologic and environmental flow requirement constraints. The important features of the optimization are that it is deterministic in nature, spatially distributed and set on a monthly time step.

The flow balance at a node in the basin network is calculated as described in Equation (8):

$$\text{Flow}_{\text{d/s},t} = \text{Flow}_{\text{u/s},t} - \text{withdrawal}_t - \Delta Q_t \tag{8}$$

where ΔQ_t is the adjustment for any conveyance loss or gain in flow from an upstream point to the downstream for any time period t. This parameter is calculated by subtracting the upstream flow after irrigation diversion from the downstream flow on a monthly basis. The hydrologic flow balance is embedded within the optimization module. Flow data for a post-barrage period of 16 years (1991–2006) from the farthest upstream point (Dalia, above the barrage) to the lowest downstream point (Kaunia) of the study area were used in this analysis.

The model used to solve the optimization problem in this study is the computer model AQUARIUS developed by Diaz *et al.* (1997) which depicts temporal and spatial allocation of river flow among traditional and non-traditional in- and off-stream water uses in a basin. In this modeling, all water uses are represented by their MB functions. To determine water allocation between users, AQUARIUS considers the economic efficiency criterion, that is, reallocation of stream flow until the net marginal returns in all water uses are equal. The optimization problem was solved using sequential quadratic programming (SQP), starting with an initial feasible solution until the quadratic problem reached the optimal solution. The model was implemented using an object-oriented programming (OOP) language C + +, which runs on a personal computer using the Microsoft Windows operating system.

Results

MB functions

Irrigation water use. The total irrigation water requirement is estimated to be 1,890 mm, which corresponds to an average 136 $\text{m}^3\,\text{s}^{-1}$. Table 2 presents six different water availability scenarios including 100% and their corresponding monthly benefits gained from the agricultural production process estimated following the RIM.

The calculation is based on Equation (1). The TB function for irrigation water is derived where flow indicates water availability and benefit is monthly benefits as reported in Table 2. Equation (9) represents the TB function for irrigation water use. The TB is reported in million Taka (Tk):

$$\text{TB}_{\text{irr}} = -0.0146 * \text{flow}^2 + 8.1327 * \text{flow} - 247.97 \tag{9}$$

Figure 5 represents the MB function for irrigation water use, which is the first-order derivative of the TB function (Equation (9)).

Table 2. Benefits (10^6 Tk) imputed to irrigation water for different water availability levels.

	Water availability as % of total irrigation WWR					
	100%	90%	80%	70%	60%	50%
Irrigation water availability $\text{m}^3\,\text{s}^{-1}$ (mm)	136 (1,890)	122 (1,701)	109 (1,512)	95 (1,323)	81 (1,134)	68 (945)
TB per month	587	527	462	393	318	236

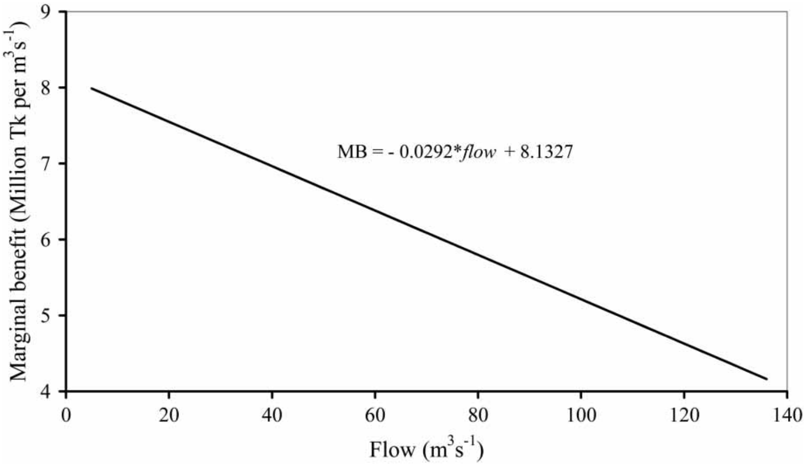


Fig. 5. MB function for irrigation water use for the Teesta River.

In-stream water use. Three seasons per year were identified in replies from respondents (91 fishermen, 21 boatmen) regarding income-related questions. The respondents gave their daily income for each season: dry or low-flow (December–March), wet or high-flow (June–September) and intermediate-flow seasons (April–May and October–November). The individual's daily income in a season was considered uniform over the entire season. Boatmen earned their highest income in the high-flow season, their lowest in the dry season. Three income values, therefore, are recorded for this group.

For the fishermen, four income values over three seasons were reported in the survey. The additional value was for the dry season, when, they explained, the catch is quite favorable. However, *very* dry conditions affect fishing adversely. Thus in December and January, the dry season, they earn the maximum for the year, whereas income falls to its lowest point in the driest month, which normally is February. The final dry season month, March, follows an income pattern similar to that of the April–May intermediate-flow season. Wet season months (June–September) also have relatively low income. Income then rises from October to November and reaches a peak in December and January.

An intercept indicating no benefit at a certain flow level is an obvious case and has been considered in earlier researches related to in-stream water use (e.g. for fishery, Baran *et al*., 2001; Ringler & Cai, 2006; for hydropower, Jager & Bevelhimer, 2007). Hence a no-income flow level was also part of the survey questionnaire, but no specific flow value could be derived. According to the boatmen, their income falls precipitously during severe low-flow conditions, as people usually walk to cross the river then. This usually happens for only few days in a year, most likely in February. Thus for navigation, no-income flow was considered to be the mean flow of the driest month, February (24 m^3 s^{-1}) in recent years (2000–06). The critical flow value for fishery was taken from a PHABSIM study for the Teesta River by Bari & Marchand (2006), which shows zero habitat for the river's main fish species (Boirali, *Aspidoparia morar*) at about 50 m^3 s^{-1} flow level, estimated from a monthly habitat duration curve.

The mean monthly flows of a post-barrage period of 16 years (1991–2006) were used to deduce the TB functions for fishery and navigation water uses. Table 3 presents the monthly or seasonal average daily income (calculated over the entire responding population) along with corresponding flows considered for developing the fishery benefit function; Table 4 presents the same for navigation. From

Table 3. Incomes and corresponding flow levels used to develop the fishery benefit function for the Teesta River.

Season Months in season	Dry December–January	February	March	Intermediate flow April–May, October–November	Wet June–September
Mean flow ($m^3 s^{-1}$)(1991–2006)	152	88	107	466	1,918
Individual fisherman daily income ($Tk\ d^{-1}$), avg. all respondents	207	54	123	123	73

A flow of 50 $m^3 s^{-1}$ is considered to result in zero benefit or no daily income at all for fishermen.

Table 4. Incomes and corresponding flow levels used to develop the navigation benefit function for the Teesta River.

Season Months in season	Dry December–March	Intermediate flow April–May, October–November	Wet June–September
Mean flow ($m^3 s^{-1}$)(1991–2006)	125	466	1,918
Individual boatman daily income ($Tk\ d^{-1}$), avg. all respondents	68	190	464

A flow of 24 $m^3 s^{-1}$ is considered to result in zero benefit or no daily income at all to boatmen.

920 fishing-engaged households, 920 fishermen were considered as the total number of fishermen and, using Equation (6), a total of 51 boatmen were found to be living at the study area.

The income values reported in Tables 3 and 4 were multiplied by the corresponding total number of fishermen and boatmen and the resultant totals were applied to the related flow values to develop the TB functions for fishery and navigation. The TB functions are reported in Equations (10a) and (10b). The principal income-generating in-stream water-use activity in the Teesta is capture fishery and it receives maximum benefit from dry season flow (December and January) and a smaller benefit in the wet season. Agriculture demands irrigation water over a single, longer interval, during the months from November to April. As for water use demand, in-stream water use benefits were calculated for the dry and intermediate-flow seasons with a flow level up to 500 $m^3 s^{-1}$. As both fishery and navigation uses are public and mutually non-competitive in nature and are estimated at a single node, the benefits are added vertically to achieve a single TB function for in-stream uses, as is presented in Equation (10c). The MB function for in-stream use is depicted in Figure 6:

$$TB_f = -151.8 \times flow^2 + 87795.6 \times flow - 4.36 \times 10^6 \tag{10a}$$

$$TB_n = -0.153 \times flow^2 + 730.12 \times flow - 3431 \tag{10b}$$

$$TB_{isu} = -151.95 \times flow^2 + 88525.7 \times flow - 4.37 \times 10^6 \tag{10c}$$

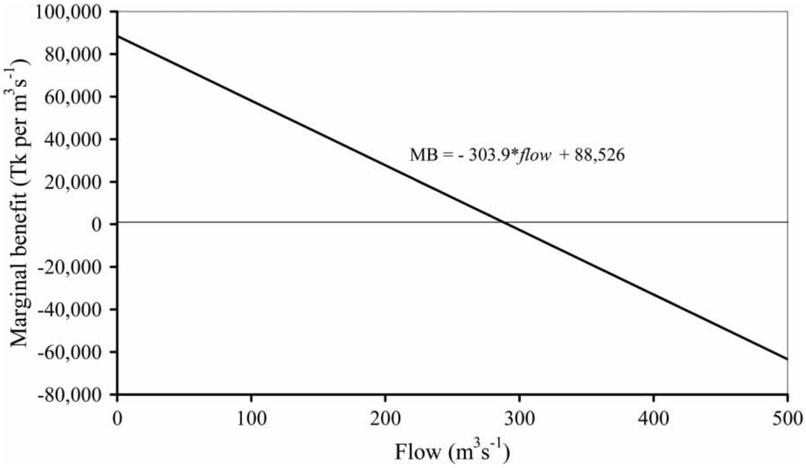


Fig. 6. Combined MB function of fishery and navigation water use for the Teesta River.

Optimal water allocation

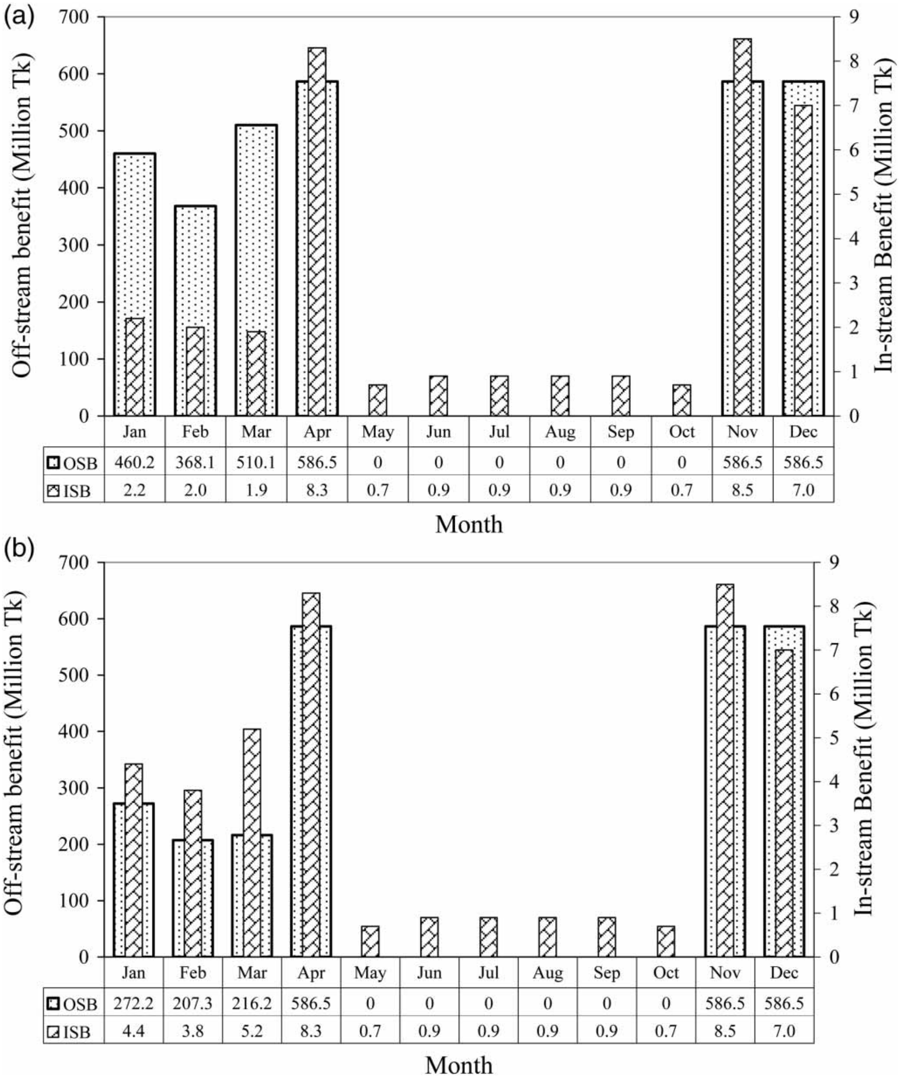
Table 5 presents the available mean monthly flow (Q) at Dalia for the 16 years of the post-barrage period (1991–2006), the monthly irrigation requirements for TIP and maximum possible irrigation diversion (90% of the available flow when irrigation demands are higher than the available flow) within current policy and practice. The downstream flow demand at Kaunia is considered the constraint and is estimated from the 'two-period parametric analysis' and RVA boundary setting, using IHA software. Pre-barrage flow data for the period 1967–90 were considered for defining the high and low RVA boundaries (Table 5).

The river network was assembled on a 'network worksheet' in the AQUARIUS modeling platform with two nodes for the two water users, that is, off-stream irrigation users and in-stream fishery and navigation users. Monthly irrigation demands and in-stream flow target (only low flow) at the downstream point along with inflow data were entered into the AQUARIUS model as physical data and coefficients of MB functions were entered as economic data. The model was run to maximize benefit

Table 5. Inflow in irrigation season to the Teesta Barrage at Dalia, irrigation demand, possible diversion and downstream flow (environmental flow) requirements at Kaunia for the Teesta.

Month	Dalia flow ($m^3\,s^{-1}$)	Irrigation demand ($m^3\,s^{-1}$)	Max. irrigation diversion ($m^3\,s^{-1}$)	Flow requirements at Kaunia ($m^3\,s^{-1}$) from RVA target: High	Low
November	252	166	166	460	250
December	125	194	113	279	149
January	69	134	62	200	118
February	61	161	55	168	119
March	70	128	63	190	134
April	174	27	27	315	199

without any constraint and optimal water allocation was sought when the consumer surpluses for both the off- and in-stream uses were maximized (economic efficiency). In another scenario, the model was run with the constraints of meeting the lower RVA target of in-stream flow requirement at the downstream node and the optimal benefits (environmental protection) were estimated. In the case of economic efficiency, the total irrigation and in-stream benefits were Tk 3,098.0 million and Tk 34.8 million, respectively. For maintaining environmental protection, the in-stream benefit increased by Tk 7.3 million, but irrigation benefit decreased to Tk 2,455.3 million. Results for the two cases are presented in Figures 7(a) and 7(b).



(a)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
▣ OSB	460.2	368.1	510.1	586.5	0	0	0	0	0	0	586.5	586.5
▨ ISB	2.2	2.0	1.9	8.3	0.7	0.9	0.9	0.9	0.9	0.7	8.5	7.0

(b)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
▣ OSB	272.2	207.3	216.2	586.5	0	0	0	0	0	0	586.5	586.5
▨ ISB	4.4	3.8	5.2	8.3	0.7	0.9	0.9	0.9	0.9	0.7	8.5	7.0

Fig. 7. (a) Optimal off- and in-stream water-use benefits without any constraint (economic efficiency) for the Teesta River. (b) Optimal off- and in-stream water-use benefits with the in-stream flow target at the downstream point Kaunia (with environmental sustainability) for the Teesta River.

Because available flow is location-specific and its allocation and benefit estimation for the water users were done for two locations (at Dalia and at Kaunia), a positive optimal water allocation to in-stream uses was observed in the dry months from December to March, even though the river flow is low during these months (Table 5). In this case, after allocating the entire flow (due to high MB for irrigation water use compared to in-stream uses) to the irrigation sector at the upstream node, some flow at the Kaunia downstream point was observed, due mainly to local flow and possible groundwater contribution to the river between the two locations, which resulted in this positive allocation and benefit from in-stream uses (Figures 7(a) and (b)).

Sensitivity analysis

Table 6 presents sensitivity analysis results for various parameters for the baseline optimization case. A reduction in total inflow by 25% reduces the off-stream and in-stream benefits by 16% and 26%, respectively, where economic efficiency is considered as the objective function. However, in this scenario environmental flow demands are impossible to satisfy. An increase in inflow by 25% increases both off- and in-stream benefits by 7% and 11.5%, respectively.

Changes in overall water-use benefits due to increase in irrigation efficiency were also investigated in this study. An improvement in irrigation efficiency to 0.5 and 0.6 (from a base case of 0.4) increased irrigation benefit by 9.5% and 10.8%, respectively. More water became available at the downstream node owing to improvement in irrigation efficiency and this resulted in higher in-stream benefits as well.

Reducing irrigated area by 25% reduced the irrigation benefit to Tk 2,582.9 million from the base case of Tk 3,098 million but increased in-stream benefit to Tk 37.3 million from Tk 34.8 million. However, expanding the irrigation area by 25% did not reduce in-stream benefit. This is because in the dry season, when both in- and off-stream users compete, flow in downstream node mainly depends on surface runoff and groundwater interaction, whereas almost all flow in upstream areas is diverted to irrigation.

In addition to the optimization results for various parameters, Table 6 presents the optimization results from considering environmental flow requirements at the downstream terminal point (Kaunia) in the study area. This table portrays the trade-offs between economic efficiency and environmental protection.

Table 6. Sensitivity analysis: off- and in-stream benefits (in million Taka) for various parameters.

		Off-stream benefit		In-stream benefit	
Parameter	Levels/values	Case A	Case B	Case A	Case B
Baseline		3,098.0	2,455.3	34.8	42.1
Inflow	75%	2,616.0		25.9	
	125%	3,320.2	3,182.6	38.8	40.5
Irrigation efficiency	0.5	3,391.9	2,815.0	36.5	42.1
	0.6	3,432.4	3,020.9	38.7	42.2
Irrigated area	75%	2,582.9	2,188.7	37.3	42.1
	125%	3,461.0	2,743.0	34.8	42.1

Case A: minimum environmental flow demand downstream is not considered.
Case B: minimum environmental flow demand downstream is considered.

Discussion and conclusion

Exploring the MB functions for in- and off-stream water uses for the Teesta, our model allocates water between competing demands based on these MB functions for various river water availability scenarios, in keeping with the criteria of economic efficiency and environmental protection. Because the MBs of irrigation water use are much higher than those of in-stream uses, water will mainly be allocated to the TIP. Maximizing economic benefit by allocating flow to irrigation often results in deterioration of natural environmental conditions. Optimal water allocation in this case is controlled by meeting environmental protection objectives, with a minimum in-stream flow constraint at the downstream point. However, this scenario results in a considerable reduction in overall benefits, by about Tk 635.4 million; that is, the irrigation benefit decreases by Tk 642.7 million, whereas the in-stream benefit increases by Tk 7.3 million compared to the baseline scenario.

It is worth noting in this context that the benefit from irrigation water explicitly indicates the benefit of diverted flow. The diversion requires a huge investment in infrastructure and high operation and maintenance costs, which have not been considered in the present analysis. Similarly, only direct uses of in-stream water were considered and indirect benefits from in-stream water flow, such as maintaining ecological integrity and diversity, water quality, sediment movement, esthetical value, groundwater recharge, recreation, amenity and so on, which may be appreciable, have not been included in the estimation of benefits. As about 1,000 people at the study site, who are very poor, critically depend on river flow for their livelihood, this statistic obviously carries very strong social and policy implications for maintaining or not maintaining river flow.

In the valuation of irrigation water, the hypothetical water stress applied at the field level was regarded as synonymous with deficit irrigation. Nevertheless, the economics and management of deficit irrigation have not been taken into account in the estimations of water value for the existing conditions in this study. Similarly, both in-stream and off-stream water uses depend on water quality, which was not considered in valuing water uses in this study.

One major challenge for the study was that, like off-stream use benefits, in-stream benefits cannot be ascribed to a discrete volume of water. Rather, the benefits depend on the flow and flow regime in the river. Hence, the MB functions for both off- and in-stream water uses were developed in terms of river discharge. This permitted comparison of the benefits of off-stream uses with in-stream uses. Because establishing MB functions for irrigation water flow proved to be a complicated process, we adopted a single measure, average irrigation-season flow, for the sake of simplicity. Thus, the irrigation benefit is calculated once, at the end of the season, when harvesting is done and distributed on a monthly basis over the growing period (Mullick *et al.*, 2011). Developing a monthly benefit function for irrigation water use, especially for a diverse cropping system, becomes quite challenging and could not be accomplished within the scope of this research.

Poor data availability for in-stream water uses also restricted the development of monthly benefit functions for fishery and navigation. The study assumes that for in-stream users, the level of income depends only on river flow, which is a seasonal phenomenon. Some seasonal but non-flow-dependent variations of income may exist, such as seasonal behavior of navigation clients or seasonal availability of fish and so on, and again these were not considered in the present study.

The estimated total and MBs of water use in the Teesta show an intriguing scenario in terms of the non-trivial relationship between in- and off-stream uses and informed trade-offs. The study provides a reasonable starting point for reconciling the competing needs of in-stream and off-stream water uses and may act as the basis for an informed policy decision, when adopting the water management system which intends to serve an impoverished clientele and at the same time to uphold environmentally sustainable water management standards. Despite facing challenges like poor data availability and quality, this study offers some methodological options for future research and recommends further field-level studies of water valuation and allocation.

References

Agudelo, J. I. (2001). The Economic Valuation of Water: Principles and Methods. Value of Water Research Report Series 5. IHE, Delft.

Arthington, A. H., Bunn, S. E., Poff, N. L. & Naiman, R. J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications 16*(4), 1311–1318.

Bangladesh Labour Force Survey (2008). *Labour Force Survey 2005–06*. Bangladesh Bureau of Statistics, Planning Division, Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka.

Baran, E., Zalinge, N. V., Bun, N. P., Baird, I. & Coates, D. (2001). *Fish Resource and Hydrobiological Modelling Approaches in the Mekong Basin*. ICLARM, Penang and the Mekong River Commission Secretariat, Phnom Penh.

Bari, F. M. & Marchand, M. (2006). *Introducing Environmental Flow Assessment in Bangladesh: Multidisciplinary Collaborative Research*. BUET-DUT Linkage Project, Phase III, Research Project No. 2. BUET, Dhaka.

BBS (2005). *Statistical Year Book*, *Community Series (Lalmonirhat*, *Nilphamari*, *Rangpur)*. Bangladesh Bureau of Statistics, Planning Division, Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka.

Bouman, B. A. M. & Toung, T. P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management 49*(1), 11–30.

Bovee, K. D. (1982). A Guide to Stream Habitat Analysis Using the Instream Flow Incremental Methodology. Instream Flow Information Paper 5. U.S. Fish and Wildlife Service FWS/OBS – 78/33.

BWDB (2005). *Impact Evaluation Report on Teesta Barrage Project (Phase-I)*. Directorate of Project Evaluation, Bangladesh Water Development Board, Dhaka.

BWDB (2008). *Teesta Barrage Prokolpo* (in Bengali). Bangladesh Water Development Board, Northern Region, Rangpur.

Cai, X. (2008). Implementation of holistic water resources: economic optimization models for river basin management – reflective experiences. *Environmental Modelling & Software 23*(1), 2–18.

Cai, X., McKinney, D. C. & Lasdon, L. S. (2003). Integrated hydrologic-agronomic-economic model for river basin management. *Journal of Water Resources Planning Management 129*(1), 4–17.

Diaz, G. E., Brown, T. C. & Sveinsson, O. (1997). AQUARIUS: A Modeling System for River Basin Water Allocation. General Technical Report RM-GTR-299. U.S. Department of Agriculture, Forest Services, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Doorenbos, J. & Kassam, A. H. (1979). Yield Response to Water. Irrigation and Drainage Paper no. 33, Food and Agriculture Organization, Rome, United Nations.

FAO (1998). *CROPWAT 4*. Windows Version 4.2. Developed by Clarke, D., Smith, M. & El-Askari, K., Food and Agriculture Organization, Rome, United Nations.

Gibbons, D. C. (1986). *The Economic Value of Water*. Resources for the Future, Washington, DC.

Griffin, R. C. (2006). *Water Resource Economics: The Analysis of Scarcity: Policies and Projects*. MIT Press, Cambridge, MA.

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R. & Howitt, R. E. (2009). Hydro-economic models: concepts, design, applications and future prospects. *Journal of Hydrology 375*(3–4), 627–643.

Hollinshead, S. P. & Lund, J. R. (2006). Optimization of environmental water purchases with uncertainty. *Water Resources Research 42*(8), W08403.

Hussain, I., Turral, H., Molden, D. & Ahmad, M. (2007). Measuring and enhancing the value of agricultural water in irrigated river basins. *Irrigation Science 25*, 263–282.

IWM (2003). Command Area Development of Teesta Barrage Project: Phase 1, Development of Decision Support Services Using Mathematical Modelling Technique and Photographic Survey, Mapping and Development of Interactive Information System. Final Report, Volume 2. Review of Irrigation Systems and Management. IWM, Dhaka.

IWMI (2005). *Environmental Flows: Planning for Environmental Water Allocation*. Water Policy Briefing, Issue 15. International Water Management Institute, Colombo.

Jager, H. I. & Bevelhimer, M. S. (2007). How run-of-river operation affects hydropower generation and value. *Environmental Management 40*(6), 1004–1015.

Khan, T. A. (1996). Management and sharing of the Ganges. *Natural Resources Journal 36*(3), 455–479.

Lund, J. R., Cai, X. & Characklis, G. W. (2006). Economic engineering of environmental and water resource systems. *Journal of Water Resources Planning and Management 132*(6), 399–402.

McKinney, C. D., Cai, X., Rosegrant, M., Ringler, C. & Scott, C. A. (1999). Integrated Basin-Scale Water Resources Management Modeling: Review and Future directions. SWIM Research Paper No. 6. International Water Management Institute, Colombo.

Mohan, S., Simhadrirao, B. & Arumugam, N. (1996). Comparative study of effective rainfall estimation methods for lowland rice. *Water Resources Management 10*(1), 35–44.

Molden, D. (2007). *Water for Food*, *Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. International Water Management Institute, Colombo and Earthscan, London.

Moore, M. (2004). Perception and Interpretations of Environmental Flows and Implications for Future Water Resources Management: A Survey Study. MSc Thesis, Linkoping University, Sweden.

Mullick, M. R. A., Babel, M. S. & Perret, S. R. (2011). Discharge-based economic valuation of irrigation water: evidence from the Teesta River, Bangladesh. *Irrigation and Drainage 60*(4), 481–492.

Poff, N. L., Allan, J. D., Palmer, M. A., Hart, D. D., Richter, B. D., Arthington, A. H., Rogers, K. H., Meyer, J. L. & Stanford, J. A. (2003). River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment 1*(6), 298–306.

Rahman, M. M. (2009). Integrated Ganges basin management: conflict and hope for regional development. *Water Policy 11*(2), 168–190.

Richter, B. D., Baumgartner, J. V., Wigington, R. & Braun, D. P. (1997). How much water does a river need? *Freshwater Biology 37*(1), 231–249.

Ringler, C. & Cai, X. (2006). Valuing fisheries and wetlands using integrated economic-hydrologic modeling—Mekong River Basin. *Journal of Water Resources Planning and Management 132*(6), 480–487.

Rosegrant, M. W., Ringler, C., McKinney, D. C., Cai, X., Keller, A. & Donoso, G. (2000). Integrated economic-hydrologic water modeling at the basin scale: the Maipo River Basin. *Agricultural Economics 24*(1), 33–46.

Scatena, E. (2004). A survey study of methods for setting minimum instream flow standards in the Caribbean Basin. *River Research and Application 20*(2), 127–135.

Smakhtin, V., Revenga, C. & Doll, P. (2004). A pilot global assessment of environmental water requirements and scarcity. *Water International 29*(3), 307–317.

Wang, L., Fang, L. & Hipel, K. W. (2008). Basin-wide cooperative water resources allocation. *European Journal of Operational Research 190*(3), 798–817.

Ward, F. A., Booker, J. F. & Michelsen, A. (2006). Integrated economic, hydrologic and institutional analysis of policy responses to mitigate drought impacts in the Rio Grande Basin. *Journal of Water Resources Planning and Management 132*(6), 488–502.

Welcomme, R. (1985). River Fisheries. FAO Fisheries Technical Paper no. 262, Food and Agriculture Organization (FAO), Rome, United Nations.

World Bank (2004). *Mekong Regional Water Resources Assistance Strategy: Modelled Observations on Development Scenarios in the Lower Mekong Basin*. The World Bank, Vientiane.

Young, R. A. (1996). Measuring the Economic Benefits for Water Investments and Policies. World Bank Technical Paper no. 338. The World Bank, Washington, DC.

Young, R. A. (2005). *Determining the Economic Value Of Water: Concepts And Methods*. Resources for the Future, Washington, DC.