# Linking Rivers in the Ganges-Brahmaputra River Basin: Exploring the Transboundary Effects

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## Introduction

Concerns over transboundary freshwater transfers have sparked increased research into international river basin cooperative management (e.g., see Beach et al. 2000; Biswas 2001; Dinar and Dinar 2000 and Just and Netanyahu 1998). A growing number of studies have focused on bilateral and multilateral cooperative water agreements as potentially efficient mechanisms (Bennett et al. 1998; Dinar and Wolf 1994; Just and Netanyahu 1998; Kilgour and Dinar 2001; Rogers 1993; Wolf 2005; Alexender et al. 2004). These studies also indicate that water transfers, the diversion of water from a water-surplus part of a river basin to one or more water-deficit areas, could prove a useful way of augmenting existing water-sharing treaties for an international river basin, especially when growing water demands threaten the long-term viability of the agreements. For example, Just and Netanyahu (1998) show that cooperation in international river basin management can be strengthened through 'linking' any agreement between the parties to an additional issue of mutual interest to the parties. Similarly, Bennett et al. (1998) demonstrate how issue linkage can facilitate agreement on a number of international river basin issues, and strengthen the enforceability of existing agreements.

The following article contributes to this literature by examining the scope for linking the existing bilateral agreement between India and Bangladesh on sharing water from the Ganges River to an additional provision allowing for mutually beneficial water transfers from the Brahmaputra River. The article provides a modelling framework for analyzing the bilateral decision to cooperate on such water transfers, which also provides the basis for analyzing the conditions under which both countries would agree to such transfers. Such a framework, although relying on the specific case of water sharing between India and Bangladesh, is potentially relevant to many other river basins where international cooperation in river basin management and water transfers may play a significant role.

To understand the importance of the Brahmaputra water transfer proposal to the existing bilateral agreement between India and Bangladesh on sharing water from the Ganges River, it is necessary to explore further the background to transboundary water sharing of the Ganges River.

The Ganges River originates in China, and along its 2,500 km long course, the river flows through northern India and passes through the state of West Bengal in India and then enters Bangladesh. In central Bangladesh, the Ganges is joined by the Brahmaputra and Meghna rivers before the combined flows empty into the Bay of Bengal (see Figure 1). In Bangladesh, which is the final downstream country along the Ganges, freshwater availability depends on the share of water diverted by India, which is the next country upstream. For many decades, India and Bangladesh failed to resolve issues of sharing the water of the Ganges River, particularly the dry season flow.[1] In 1996, a major treaty (The Ganges River Treaty) was signed between India and Bangladesh to resolve the water allocation dispute. The treaty was based on the existing flow of water in the Ganges River.

Unfortunately, however, the rapidly increasing populations of both India and Bangladesh are already leading to a shortage of surface water flows in the Ganges River relative to the rising demand.[2] However, while there is a shortage of flows in the Ganges to meet the future

**Figure 1.** Map of India and Bangladesh showing major rivers.

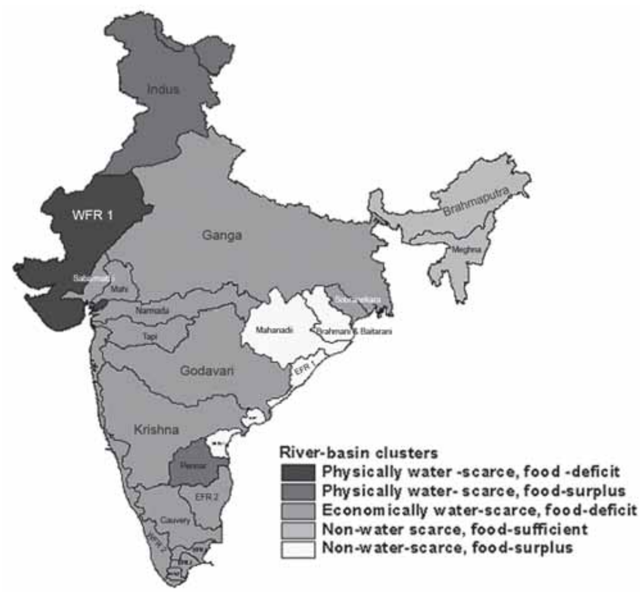

[1] For a complete history of the dispute between India and Bangladesh over sharing the water of the Ganges River, see Crow et al. (2000), Nishat and Faisal. (2000), Hossain (1998) and Khan (1996).

[2] As summarized by Shah (2002, pp. 40-41): "The flows at present available in the various tributaries and the main river are totally inadequate to meet the requirements of the remainder of the irrigation potential of about 41 million ha. The present population in the Ganges portion of India is about 400 million, and this is expected to increase to about 550 million by the year 2010. Consequently, the demand of water for various purposes, including domestic, municipal, livestock, and agriculture, will progressively increase every year." See also Amarasinghe et al. (2005), who examine the spatial variation of the available water resources (see Figure 2) and estimate that much of the peninsular river basin is water-scarce with the availability being less than 20 billion cubic meters (BCM). In comparison, the total annual water withdrawal estimate in India is 650 BCM.

requirements of both India and Bangladesh for water, there is likely to be a surplus of water available in the neighboring basin of the Brahmaputra River. For example, it is estimated that in-basin utilization of the Brahmaputra accounts currently for only 4 % of the available surface flow (Shah 2001). Thus, trans-basin transfers of water from the Brahmaputra to the Ganges has been proposed as a potential solution to the imminent water shortage in the Ganges River basin and as a means to forestall possible future water conflicts between India and Bangladesh.

There are good reasons why India is particularly interested in such a water transfer scheme. A significant part of the water resources of India lies in the Brahmaputra River, which is in a remote corner of the country and far from the areas where the demand for water is high (see Figure 2). The Brahmaputra River accounts for 29 % of the total runoff of all of India's rivers, representing a potential source of available water. Currently, India is planning to develop a National River Linking Project (NRLP) and divert surplus water from the Brahmaputra River to alleviate shortages in western and southern India (Iyer 2003). India intends to transfer water from Brahmaputra through a gravity link canal taking water from Jogighopa in India, and joining the Ganges River just above Farakka (see Figure 3). The link is proposed to transfer 43 billion cubic meters (BCM) of water from the Brahmaputra River, of which 15 BCM is to be transferred to the Ganges River at Farakka (Thakkar 2007). The augmented water at Farakka would then be shared between the peninsular river basins in southern India and water flows to the downstream of Ganges River in Bangladesh.[3]

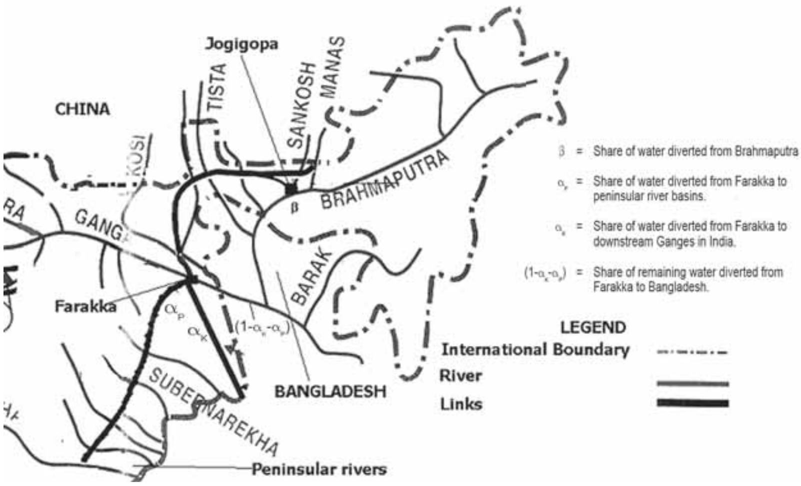
**Figure 2.** Spatial variation of available water resources in India's river basins.




*Source:* Amarasinghe (2005)

[3] The interlinking of rivers in peninsular India involves Mahanadi, Godavari, Krishna Cauvery and Pennar rivers.

**Figure 3.** Proposed river link from Brahmaputra (Jogigopa) – Ganges (Farakka).




*Source*: National Water Development Agency, Government of India

Under such a water diversion scheme, diversions from the Brahmaputra to the Ganges would, therefore, be made entirely within India.[4]

However, there are several concerns about such a proposal for the downstream country, Bangladesh. Diversions of large amounts of water, above a certain threshold level, from the Brahmaputra River upstream in India could disrupt the lean season flows and ecology of the downstream Brahmaputra River in Bangladesh.[5] Of particular concern is the increased likelihood of an environmental catastrophe in Bangladesh because of the salinity ingress that could arise from the depletion of water in the downstream Brahmaputra. There are also fears in Bangladesh that construction of a dam at Jogighopa would provide India an additional opportunity to control the entire amount of water flowing into Bangladesh, where currently nearly 20 million Bangladeshi small farmers depend on river water that flows through India for their cultivation.

On the other hand, if India diverts an amount of water below the threshold level, then Bangladesh could benefit, as the surplus water from Brahmaputra, which creates frequent floods, can be diverted to meet the excess demand of water in the Ganges River basin. Even in a normal

[4] In the past, India had made several attempts to persuade Bangladesh to agree to a proposal to augment the flow of water of the Ganges River at Farakka through transferring surplus water from the Brahmaputra River. Previously, India proposed constructing a 200-mile long canal that would transport the water to the Ganges at a point just upstream of the Farakka Barrage. However, this canal would have occupied 20,000 acres of agricultural land in Bangladesh. As a result, the Bangladesh Government rejected the Indian proposal. Hence, the current proposal by the Indian Government involves redesigning the construction of the canal, so that the transfer of water from Brahmaputra would take place entirely within Indian Territory. See Shah (2001).

[5] Bangladesh Government scientists claim that 10 to 20 % reduction in the water flow of Brahmaputra to the country could dry out great areas for much of the year (Rahman 2005).

year, about 20 % of the country is inundated, but in extreme years the area of inundation may rise up to 60 % (Ahmed et al. 2006). For example, the 1998 floods in Bangladesh covered more than two-thirds of the country and lasted 59 days, resulting in 918 deaths, the displacement of over a million people, and caused 2.04 million metric tonnes in rice crop losses (10.45 % of target production in 1998/99) as well as other economic damages (Ninno 2001). Thus diversion of surplus water would reduce the flood-related damage caused by the Brahmaputra in Bangladesh, while at the same time augment the flow at Farakka to ensure sufficient surface flow in the downstream Ganges River to meet the growing water needs of Bangladesh.

Unfortunately, the existing Ganges River Treaty contains no provisions to augment the flow of the Ganges River, through regional cooperation to transfer water from a separate river basin, such as the Brahmaputra. Thus India and Bangladesh would have to negotiate and sign a separate agreement to establish an appropriate sharing of the augmented flow of the Ganges River through water transfers from the Brahmaputra River. A key issue, therefore, is whether it is in the interest of both India and Bangladesh to agree mutually to such a water augmentation agreement.

To explore the implications of this issue, and thus the feasibility of such an international river basin agreement on water transfers, in the next section we develop a two-country river basin model of upstream-downstream water allocation, with the possibility of water augmentation. We show that water transfer from the Brahmaputra River could be mutually beneficial for both countries. However, the only possible motivation for the richer upstream country, India, to agree to transfer water to the poorer downstream country, Bangladesh, is political altruism: If there is a good political relationship between India and Bangladesh, then India could be altruistic towards Bangladesh and transfer more water downstream. Changes in the political altruism factor, however, could entice India to exercise unilateral diversion, in which case simulations predict that Bangladesh would incur large environmental damages.

## A Model of Water Sharing between India and Bangladesh

In this section, we develop a model of water allocation for the Ganges-Brahmaputra –peninsular river basin to assess the impacts of the additional supply of water from Brahmaputra on the benefits accrued to India and Bangladesh.

India and Bangladesh are represented in the model as superscripts by superscripts 1 and 2 respectively, while the Ganges and Brahmaputra and peninsular river basin are denoted by subscripts *G* and *B* and *P*, respectively.

Consider the amount of water available in the upstream Ganges (at Farakka) and the peninsular river basins in India as $W_G$ and $W_P$, respectively. Similarly, the flow of water of the Brahmaputra River in India at the point of diversion (Jogighopa)[6] is $W_B$. After the construction of the dam at Jogighopa, India has the opportunity to now determine the share of water ($\beta$) diverted from the Brahmaputra River. The proportion of water diverted from upstream Brahmaputra in India is $\beta$ and the remaining $(1-\beta)$ proportion flows in the downstream Brahmaputra River basin in Bangladesh. $\beta$ strictly lies between 0 and 1. We also assume that

[6] The point where India constructed a dam on the Brahmaputra River to divert water through a link canal.

the proportion of water allocated to Indian downstream of the Ganges River and peninsular river basin at the point of the diversion (Farakka) are $\alpha_G$ and $\alpha_P$, respectively.[7] The remaining water flows in the downstream Ganges to Bangladesh. The total supply of water in downstream Ganges River and peninsular river basin in India, respectively, are as follows:

$$S_G^1 = \alpha_G [W_G + \beta W_B] \quad \text{and} \quad S_P^1 = \alpha_P [W_G + \beta W_B] + W_P \tag{1}$$

The total supply of water in downstream Ganges River basin in Bangladesh is represented as

$$S_G^2 = (1 - \alpha_G - \alpha_P)[W_G + \beta W_B]; \tag{2}$$

while the total supply of water in downstream Brahmaputra River basin in Bangladesh is

$$S_B^2 = (1 - \beta) W_B \tag{3}$$

Every year Bangladesh incurs heavy losses from flood-related damages. Examples of such flood-related damages include loss of human life, loss of crops and damage of properties. There would be a reduction in flood-related damages after the diversion of surplus water from Brahmaputra. The flood-related damages incurred by Bangladesh, represented by $D$, were caused by surplus water in downstream Brahmaputra River and can by characterized by the following function:

$$D = D[(1 - \beta) W_B] \text{ For } \beta < \hat{\beta} \text{ with } D'(\beta) < 0, D''(\beta) < 0 \tag{4}$$

$$D = 0 \text{ for } \beta \geq \hat{\beta}$$

We assume that the damage caused by floods in the Brahmaputra Basin, $D$, decreases with the increase in the share of the diversion of water ($\beta$) to the Ganges Basin. We also assume that there would be no flood-related damage if the level of water diversion ($\hat{a}$) equals or exceeds a threshold level ($\hat{\beta}$).

The diversion of surplus water from Brahmaputra could initiate a process of environmental degradation in Bangladesh. If the share of water diverted from Brahmaputra exceeds a certain threshold level, we assume that the reduced water levels in the downstream Brahmaputra River could cause environmental losses. Less water in the downstream could disrupt fishing and navigation, and also could bring unwanted salt deposits into rich farming soil. More water diversion of silt-free water in the upstream could allow greater saline intrusion into Bangladesh, and change the hydraulic characteristics of the river. It could affect the ecology of the delta.

The environmental damage to Bangladesh can be expressed by the following function

$$L = 0 \text{ for } \beta < \tilde{\beta}$$

$$\text{and } L = L(\beta) \text{ for } \beta \geq \tilde{\beta} \text{ with } L'(\beta) > 0, L''(\beta) > 0 \tag{5}$$

[7] Under the case where there is no provision to transfer water $\alpha_P = 0$

We assume that if the share of water diversions by India in the upper Brahmaputra crosses a threshold level ($\tilde{\beta}$), there would be consequential environmental losses, which will further increase with the increase in the share of water diverted from the upstream Brahmaputra ($\beta$). Since such environment losses generally take place at a much higher share of water diversion, we assume that the threshold level for environmental damage ($\tilde{\beta}$)is higher than that of the threshold level, ($\hat{\beta}$) , above which there exists no flood control damage.

Water transfer from Brahmaputra may produce positive externalities in the form of additional benefits to India. The benefits mainly include hydropower generation, and navigation. The dam at the point of diversion (Jogighopa) could help India to generate hydroelectric power for the northeastern part of the country.[8] India can also use the link canal for navigational purposes, to connect the remote areas of the country in the northeast to the mainland. The benefits can affect India's welfare and may alter the water sharing allocation. The benefit function, $G$, is dependent on the total water transfer ($\beta W_B$). The additional benefits to India as a result of diversion of water from Brahmaputra River can be represented by:

$$G = G(\beta) \text{ with } G_1'(\beta) > 0, G_1'(\beta) > 0. \qquad (6)$$

India incurs the cost of constructing a dam on the upstream Brahmaputra to divert water and also to construct the interlinking canal. Transfer of water entails a high cost, which may include building storage dams, canals or pipelines. The presence of the transfer cost of water is crucial to the outcomes of the model. The marginal cost of diverting each unit of water is assumed to be convex, denoted by:

$$r(\beta) \text{ where } r'(\beta) < 0 \text{ and } r''(\beta) > 0 .^{9} \qquad (7)$$

Though initially India will incur a huge cost for the construction of dams, the unit cost will decline with the increase in the share of water diversion.

We assume the benefit function from water use for each country is concave and there exists an interior solution. Although both countries are likely to obtain multiple benefits from water use, we solely consider the production benefits of the only agricultural sector in our model, as nearly 70-80 % of the water is used for irrigation in the region. Consider the agricultural production in country $i$ ($i$=1, 2) and river basin $j$ ($j$=$G$, $B$, $P$) is $q^i_j(\omega, m)$ where $\omega$ is theconsumptive usage of water and $m$ is the vector of other inputs used in the agricultural production. The farmers in each country sell the crops at a vector of price $p$ ($i$=1, 2)[10] and the marginal cost of agricultural production is $c$.

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[8] India 's national water development agency, which is backing the interlinking of rivers scheme, has said it will divert enough water to produce 34,000 megawatts of hydroelectricity (Government of India 1999).

[9] As water flow in the Brahmaputra River, $W_B$ is deterministic, we assume the marginal cost of water transfer is independent on flow of water at Jogighopa.

[10] p is exogenously determined in the international market.

Prior to the inter-linkage of the rivers in two river basins, India's benefit function can be represented by the following equation:

$$B_0^{1} = (p - c)[q_G(\omega_G^{1}, \mathrm{m}^1) + q_P(\omega_P^{1}, m^1)]. \quad (8)$$

In the peninsular river basin, the physical water availability constraint is binding and the consumptive usage of water is determined by the available supply of water. The water constraint in the peninsular river basin, prior to transfer of water from Brahmaputra is $\omega^1_p = S^1_{\mathrm{p}} = W_p$

In the case of the Ganges Basin, if there is no treaty between India and Bangladesh, India diverts a share of water to meet its optimal water consumption needs.

India will determine the optimal share of water diversion upstream by choosing $\alpha$ to maximize its benefit function given in equation 8, and the constraint $\omega^1_G = \alpha W_G$ $\alpha \in (0,1)$.

The first order condition of the above problem can be represented as:

$$\left[(p - c)\frac{\partial q_G{}^1}{\partial \omega_G}\right] = 0 \quad (9)$$

The above expression implies that India's payoff will be maximized when the net marginal benefit of water consumption is equal to zero.

Suppose the solution to the above maximization problem is $\alpha_0{}^*$. Since $B^1$ $(W^1)$ is strictly concave, it follows that the slope of the benefit function with respect to the share of water diverted is positive for $\alpha < \alpha_0{}^*$, and conversely, is negative for $\alpha > \alpha_0{}^*$. Assuming that the consumptive usage of water is a fixed proportion of the available water, $\alpha$, a lower rate of water utilization would require a lower value of $\alpha$, thus under-utilization of water for a lower value of $\alpha$ will result in lower profit for producers. Similarly, over-utilization of water will ensure a lower profit $B^1{}_0 < B^1{}_0{}^*$ because of diminishing marginal productivity of water and the negative second-order profit condition. Given that there is no water sharing agreement; India will maximize its agricultural profit $B^1{}_0{}^*$ by diverting $\alpha_0{}^*$ share of water in the upstream and allowing the rest to flow downstream to Bangladesh.

The freshwater availability of the downstream country, Bangladesh, is dependent on the share of water diverted by the upstream country, India. Bangladesh's benefit from water would be:

$$B_0^{2} = (p - c)[q^2_G(\omega^2_G, m^2_G) + q^2_B(\omega^2_B, m^2_B)] - D(W_B) \quad (10)$$

As Bangladesh's water consumption in the downstream Ganges River basin is determined by India' optimal decision to share the water at Farakka, Bangladesh's problem would be only to maximise the agricultural benefits in the Brahmaputra Basin by choosing the optimal water consumption level, $\omega^{*2}_B$, in the latter basin.

In the scenario, where India has the opportunity to divert surplus water from Brahmaputra, the benefit function of India and Bangladesh can be represented as follows:

$$B^1 = (p - c)[q_G(\omega^1, m^1) + q_p(\omega^1, m^1)] + G(\beta) - r(\beta)\,\beta W_B \qquad \text{For India} \quad (11)$$

$$\begin{aligned} B^2 &= (p - c)[q_G(\omega^2, m^2) + q_B(\omega^2, m^2)] - D(\beta W_B) \text{ if } (\beta < \hat{\beta}) \qquad \text{For Bangladesh} \\ &= (p - c)[q_G(w^2, m^2) + q_B(w^2, m^2)] - \text{ if } (\hat{\beta} < \beta < \tilde{\beta}) \\ &= (p - c)[q_G(w^2, m^2) + q_B(w^2, m^2)] - L(\beta) \text{ if } (\beta > \tilde{\beta}) \end{aligned}$$

In such a situation, India will have the dual opportunity to divert water in both the Ganges and Brahmaputra river basin. India's problem would be to choose the share of diversion from the Ganges River at Farakka, $\alpha_G$, $\alpha_P$ and from the Brahmaputra River at Jogigopa, â, to maximize its benefit function $B^1$ as given in equation 11. The first order condition of the above problem can be expressed in terms of following equations:

$$(p - c)W_B \left[ \left\{ \frac{\partial(q_G{}^1)}{\partial(\omega_G{}^1)} \right\} (\alpha_G) + \left\{ \frac{\partial(q_P{}^1)}{\partial(\omega_P{}^1)} \right\} (\alpha_P) + \right] + \frac{\partial(G)}{\partial(\beta)} - \frac{\partial(r)}{\partial(\beta)} \beta + r\ (\beta) = 0 \tag{12}$$

$$(p - c) \left[ \left\{ \frac{\partial(q_G{}^1)}{\partial(\omega_G{}^1)} (W_G + \beta\ W_B) \right\} \right] = 0 \tag{13}$$

$$(p - c) \left[ \left\{ \frac{\partial(q_P{}^1)}{\partial(\omega_P{}^1)} (W_G + \beta\ W_B) \right\} \right] = 0 \tag{14}$$

Equation (12) suggests that the optimum share of water transferred from the Brahmaputra River will be chosen when the marginal benefits of increasing the share of water diverted in the downstream Ganges and peninsular river basin equals the marginal cost of the diversion of water from the Brahmaputra. Combining equations 13 and 14, we get

$$\frac{\partial(q_G{}^1)}{\partial(\omega_G{}^1)} = \frac{\partial(q_P{}^1)}{\partial(\omega_P{}^1)} \tag{15}$$

Equation 15 suggests that India would allocate water between the Ganges and Brahmaputra so that the marginal benefit of water consumption is equal in both river basins in India. It also implies that if the waters in the peninsular basin were relatively less endowed than the availability at Farakka before the transfer, then India would divert a lesser proportion of water in the downstream Ganges Basin than in the peninsular river basin. The optimal share of water diversion from the Brahmaputra, $\beta^*$ and water allocation at Farakka, $\alpha_G{}^*$, $\alpha_P{}^*$ can be determined by solving the first order conditions (12-14).

Bangladesh faces two possible regimes while maximizing its benefit function:

I. The constraint is binding $\omega^B = (1 - \beta)\ W_B$ implying that there is scarcity of water in the Brahmaputra River basin.

II. The physical water availability constraint is non binding $\omega^B \succ (1 - \beta)\ W_B$

If the water availability constraint is binding, then the optimal consumption of water of Bangladesh in the Brahmaputra River basin is $\omega^B = (1 - \beta^*)\ W_B$. In the absence of any water sharing treaty, Bangladesh's water consumption, $\omega^B$, depends on the optimal share of water diverted by India, $\beta$, and thus is influenced by India's domestic agricultural price and usage of other inputs. A rise in agricultural production subsidies in India, for instance, will increase the demand of water there. Higher consumption of water in the upstream country will thus affect the water consumption in the Brahmaputra River basin of Bangladesh. The benefit of Bangladesh under regime I will be $B^{*2}(\alpha_G, \alpha_P, \beta)$.

In this case, Bangladesh is left with no choice variables to maximise its benefit function. Bangladesh's benefits would be dictated by India's choice of the share of water diverted from the Ganges and the Brahmaputra river, respectively. As the marginal cost of water transfer decreases with the increase in the share of water diversion, India could divert more water from the Brahmaputra to meet the water demand of the Ganges and the peninsular basins and to cover the costs of water transfer. This may lead India to divert an optimal share of water from the Brahmaputra above $\tilde{\beta}$, which may cause an environmental loss in Bangladesh.

If the water availability constraint is non binding, then Bangladesh's optimal consumption of water would be $\omega^{*}_{B}{}^{2}$. The solution represents Bangladesh's desired demand of water, which approximates the profit maximizing optimal water consumption as in the case with no water scarcity in the Brahmaputra River basin. The solution suggests that the consumptive usage of water of Bangladesh in the Brahmaputra River basin is independent of the share of water diverted by India. The benefit of Bangladesh under this regime would be $\pi^{B}(\alpha_{G}, \alpha_{P}, \omega^{*}_{B})$.

## The Social Planner's Problem

In the presence of externalities, transboundary water allocation issues create a unique economic problem. In applying the definition of externality to international rivers, LeMarquand (1977) stated "An international river is a common property shared among the basin states." When water is shared by many countries, however, the problem of externalities takes a different dimension, because the river basins shared by more than one country cannot be easily planned and developed as a single unit unless all of the riparian countries agree. Only in a few cases has this been attempted, and a leading case, the Columbia River basin shared by Canada and the United States, yielded mixed results (Krutilla 1966; Roger 1993).

Several attempts have been made to develop general rules of international law to guide the sharing of water in transboundary settings (Helsinki Rules 1966; Helsinki Convention 1992; UN Convention 1996). The principles generally hinge on the notions of equality, reasonableness, and avoidance of harming one's neighbors. The fundamental goal is to achieve joint, optimum utilization of resources and avoidance of disputes over the shared water resource.

We assumed that there is a benevolent social planner who is in charge of the entire Ganges -Brahmaputra and peninsular river basin. According to the Coase Theorem (Coase 1960), the social planner will choose a water sharing allocation on the Pareto efficiency frontier – a water allocation, which is Pareto efficient. Choosing an allocation on the Pareto efficiency frontier is equivalent to maximizing the joint net benefits. The joint net benefits of the countries without altruism are represented by $Z = B^1 + B^2$.

The social planner's problem would be to choose an optimal share of water transferred from the Brahmaputra River through joint maximization of the benefit functions of both India and Bangladesh with respect to the water supply constraints (1-3). In the optimization exercise, the social planner also decides about the water allocation between the Ganges and peninsular river basin by choosing the variables $\alpha_{G}$ and $\alpha_{P}$.

The social planner's maximization problem is:

$$\max_{\beta,\, \alpha_1,\, \alpha_2} Z = B^1 = B^2 = (p - c)[q^1_G(\omega^1_G, m^1_G) + q^1_P(\omega^1_G, m^1_G) + q^2_G(\omega^2_G, m^2_G) + q^2_B(\omega^2_B, m^2_B)] + G(\beta) - r(\beta)\,\beta - D(\beta) - L(\beta) \qquad (16)$$

where $D(\beta) = 0$ for $(\beta > \hat{\beta})$ and $L(\beta) = 0$ for $(\beta < \tilde{\beta})$

The first order conditions results in the following equations:

$$(p - c)W_B \left[ \left\{\frac{\partial(q^1_G)}{\partial(\omega^1_G)}\right\}(\alpha_G) + \left\{\frac{\partial(q^1_P)}{\partial(\omega^1_P)}\right\}(\alpha_P) + \left\{\frac{\partial(q^2_G)}{\partial(\omega^2_G)}\right\}(1 - \alpha_G - \alpha_P) - \left\{\frac{\partial(q^2_B)}{\partial(\omega^2_B)}\right\} \right] \qquad (17)$$

$$+ \left[\frac{\partial(G)}{\partial(\beta)} - \frac{\partial(D)}{\partial(\beta)}\right] = \left[\frac{\partial(r)}{\partial(\beta)}\,\beta + r(\beta) + \frac{\partial(L)}{\partial(\beta)}\right]$$

$$(p - c)(W_G + \beta W_B)\left[\left\{\frac{\partial(q^1_G)}{\partial(\omega^1_G)} - \frac{\partial(q^2_G)}{\partial(\omega^2_G)}\right\}\right] = 0 \qquad (18)$$

$$(p - c)\left[\left\{\frac{\partial(q_P^1)}{\partial(\omega_P^1)}(W_G + \beta W_B)\right\} - \left\{\frac{\partial(q^2_G)}{\partial(\omega^2_P)}(W_G + \beta W_B)\right\}\right] = 0 \qquad (19)$$

Equation (17) suggests that the optimum share of water transferred from the Brahmaputra River will be chosen when the marginal benefits of increasing the share of water diverted in both India and Bangladesh equals the marginal cost of the diversion of water from Brahmaputra. The first term in the left hand side of the equation indicates the weighted net marginal benefit of the countries in agricultural productivity from a unit increase in the share of water diversion from the Brahmaputra River. In the Ganges River basin, the weights are the share of each country's augmented water flow at Farakka. The second term is an aggregate of India's marginal gain in additional benefits and that of Bangladesh's in flood control. The right hand side of the equation denotes the marginal cost of diverting the water from the Brahmaputra River and includes the marginal environment cost incurred by Bangladesh from an increase in the share of water diverted from Brahmaputra.

Equation 18 implies the social planner will allocate water between India and Bangladesh in the downstream Ganges River basin according to the marginal benefits of water of both countries. Equation 19 shows that at Farakka, the augmented Ganges River flow would be shared between Bangladesh in the downstream Ganges, and India in the peninsular river basins according to the marginal benefits of water.

Substituting equation 18 and 19 in equation 17, we derive the following equilibrium condition to determine the optimal shares of water allocation

$$\left[\frac{\partial(q^2_G)}{\partial(\omega^2_G)} - \frac{\partial(q^2_B)}{\partial(\omega_B^2)}\right] = \frac{\dfrac{\partial(r)}{\partial(\beta)}\,\beta + r(\beta) + \dfrac{\partial(L)}{\partial(\beta)} - \dfrac{\partial(G)}{\partial(\beta)} + \dfrac{\partial(D)}{\partial(\beta)}}{(p - c)\, W_B} \qquad (20)$$

The above equilibrium condition suggests that the difference between the marginal benefit of water consumption of Bangladesh in the Ganges River basin and in the Brahmaputra River basin is proportional to the difference between the marginal cost and additional benefit of water transfer from the Brahmaputra River. It also implies that, if the marginal cost of water transfer is greater than the marginal additional benefits like hydropower generational and flood control, then the social planner would compensate Bangladesh by providing more water in its downstream Brahmaputra.

Finally, solving the first order conditions as given in equations 17-19, the social planner determines the optimal share of water transfer from the Brahmaputra River, $\beta^{**}$, and the share of water to the Ganges downstream $\alpha_G^{**}$, and that for the peninsular river basins in India $\alpha_P^{**}$.

## Endogenous Risk and Environmental Losses of Bangladesh

It is imperative to assess the hypothesis whether diverting water above the threshold from the Brahmaputra River can create severe environmental damage in Bangladesh.[11] The risk of environmental damage depends on the amount of water diverted by India in upper Brahmaputra and the degree of self-protection used by Bangladesh to cover its losses. India who acts here like an emitter wants to minimize the probability of type I error, which is the probability of accepting the false null hypothesis that transferring water above the threshold will create severe environmental damage. While Bangladesh, whose role is like a receptor, in a typical environmental problem will try to minimize the probability of Type II error, which is the probability of rejecting the true null hypothesis that water diversion above the threshold level will not create severe environmental losses. Thus, for any stock of information the social planner faces a trade off between the Type I error and Type II error. As Bangladesh engages in self-protection it provides information about the linkage between the share of water transferred from Brahmaputra by India and the consequential environmental damage in India. The information will be valuable to the policymakers to assess the risk. We assume that both India and Bangladesh are risk neutral. Bangladesh is using $x$ degree of self- protection for environmental damage, while India is supplying $y$ proportion of water to Bangladesh in downstream Brahmaputra to control the environmental damage.

We assumed that the following restriction holds in the measure of environmental damage resistance and environmental damage control $0 < x < 1$ and $0 < y = 1 - \beta < 1$. We assumed the probability of making type I error is $P(x, y)$, while the probability of making type II error is $1 - P(x, y)$. We also presumed that:

$$P_x > 0,\ P_{xx} > 0,\ P_y > 0,\ P_{yy} > 0,\ P_{xx} P_{yy} - (P_{xy})^2 > 0 \tag{21}$$

It means that as Bangladesh reduces environmental damage through self-protection, the probability of accepting the false hypothesis (Type I error) will increase. Similarly, the probability of making type I error will increase if Bangladesh is having less damage due to the increase in the share of water diversions by India to downstream Brahmaputra. So, if environmental

[11] Here in this model we have used a framework developed by Crocker (1983).

damage resistance and environmental damage control are effective in reducing environmental losses, then the belief that water diversion above the threshold will create severe environment damage gets stronger. The restriction $P_{xx} P_{yy} - (P_{xy})^2 > 0$ suggests that the direct type I error effects of a change in environmental damage resistance or environmental damage control dominate the indirect effects of the change in Type II error.

Let the marginal cost of achieving a unit more of environmental damage resistance by Bangladesh be $d$, while the marginal cost of controlling a unit more of environmental damage by supplying more water downstream Brahmaputra be $w$. Both, for simplicity reasons, are assumed to be constant. So the total cost associated with the prospect of protecting the environment in Bangladesh is $dx+wy$. The additional environmental damage and control costs arising from the belief that water diversion above the threshold level will not create severe environmental loss is $L(\beta)=L(1-y)$ with the assumption $L_Y<0$. It means that as less water is flowing to the downstream Brahmaputra in Bangladesh, the environmental loss for Bangladesh will increase when further environmental protection is not adopted. The social planner's objective will be to minimize social cost with respect to the choice variable $x$ and $y$. The social planner's objective function can be stated as follows:

$$\min_{x,\, y} S(x, y) = dx+wy + L(y)\,[1 - P(x,y)] \qquad (22)$$

The policymaker by choosing the optimum $x$ and $y$ can generate information that reduces the likelihood of Type I and Type II error.

First order condition of the above problem results in the following equations

$$d = L(y)\, P_x \qquad (23)$$

$$w = L_y\, [P(x, y) - 1] + L(y)\, P_y \qquad (24)$$

Equation (23) suggests that at equilibrium the marginal cost of achieving a unit more of environmental damage resistance ($d$) by Bangladesh equals the marginal expected environmental damage for believing that that water diversion above the threshold level will not create environmental damage. Equation (24) can be interpreted by saying that the marginal cost of controlling a unit more of environmental damage ($w$) will be equal to marginal expected environmental damage for rejecting the true null hypothesis.

The cost minimizing solution to equation (22) is found by simultaneously solving equations (23) and (24). Thus the social planner's objective is to minimize the social cost with respect to the environmental damage resistance and environmental damage control and weigh the alternative truth standards by developing a burden sharing rule that will cause each country to generate information, which reduces the likelihood of Type I and Type II errors.

## Political Economy of Water Sharing

Given countries' increasing demand for water resources, there is limited scope for cooperation to resolve such transboundary water conflicts in a social planner's way. However, we know many upstream countries do care about the downstream country to a limited extent. This is evident from the number of international agreements on water sharing that have been signed, and many of which seem to be against the own interest of upstream countries. Since 1948, about 300 water agreements have been signed and negotiated between countries (Wolf et al. 2003). In most of the cases, for instance, water sharing agreements between Egypt and Sudan in 1959; Israel and Jordan in 1994; and India and Bangladesh in 1996, the issues of water sharing were resolved without provision of side payments or compensation from downstream countries. Using a political altruism model, we make an attempt to determine the water allocation between India and Bangladesh in the situation where India might recognize the welfare of Bangladesh and enforce its water claims. In a natural extension of the standard economic model, it is possible to explain the above phenomena, by allowing for altruism between countries. We assume that India incorporates some proportion of Bangladesh's benefit function in its net benefit function. Weights are the altruistic concerns, and are based on the political relationship between the two countries. If there is a good political relationship between India and Bangladesh, then India could be altruistic toward Bangladesh and divert more water. Political relations are crucial elements influencing the altruistic behavior of the countries, and we determine the optimal allocation of water sharing based on the political relationship between the two countries. The net benefit function of India $NB^1$ can be expressed as

$$NB^1 = B^1 + m^1 B^B \tag{25}$$

where $m^1$ is the parameter reflecting India's altruism towards Bangladesh. The value of altruism factor lies between 0 and 1. If $m^1 = 1$, India would play the role of a social planner; whereas if $m^1 = 0$, then India would not care about Bangladesh and engage in maximizing its own welfare. Given the net benefit function as specified in equation 25, India would choose the optimal share of water diversion from Brahmaputra and share of water allocation between Ganges and the peninsular river basins. The first order conditions are expressed as follows:

$$(p - c)W_B \left[ \left\{ \frac{\partial(q^1_G)}{\partial(\omega^1_G)} \right\} (\alpha_G) + \left\{ \frac{\partial(q^1_P)}{\partial(\omega^1_P)} \right\} (\alpha_P) + m^1 \left\{ \frac{\partial(q^2_G)}{\partial(\omega^2_G)} \right\} (1 - \alpha_G - \alpha_P) - m^1 \left\{ \frac{\partial(q^2_B)}{\partial(\omega^2_B)} \right\} \right]$$
$$- \frac{\partial(G)}{\partial(\beta)} + m^1 \frac{\partial(D)}{\partial(\beta)} = \frac{\partial(r)}{\partial(\beta)} \beta + r(\beta) + m^1 \frac{\partial(L)}{\partial(\beta)} \tag{26}$$

$$(p - c) \left[ \left\{ \frac{\partial(q^1_G)}{\partial(\omega^1_G)} \right\} - m^1 \left\{ \frac{\partial(q^2_G)}{\partial(\omega^2_G)} \right\} \right] = 0 \tag{27}$$

$$(p - c) \left[ \left\{ \frac{\partial(q^1_P)}{\partial(\omega^1_P)} \right\} - m^1 \left\{ \frac{\partial(q^2_G)}{\partial(\omega^2_G)} \right\} \right] = 0 \tag{28}$$

The first order conditions of the maximization problem would be similar to that of the social planner's maximization problem, but the marginal benefits of Bangladesh from water consumption would be weighted by India's altruism toward Bangladesh. Solving the first order conditions, we can derive the optimal share of water diversion from Brahmaputra, $\beta^{\pm}(m^1)$ and the water allocation at Farakka $\alpha_G^{\pm}(m^1)$, $\alpha_P^{\pm}(m^1)$. Also if $m^1 = 0$ then India would unilaterally divert water from Brahmaputra without caring about the loss of Bangladesh's welfare. The optimal share of water diversion from Brahmaputra $\beta^*$ and water allocation at Farakka, $\alpha_G^*$, $\alpha_P^*$, are determined in problem 11 where India diverts water unilaterally.[12] We investigated whether India would divert less water from the Brahmaputra if the political relationship between the two countries improves.

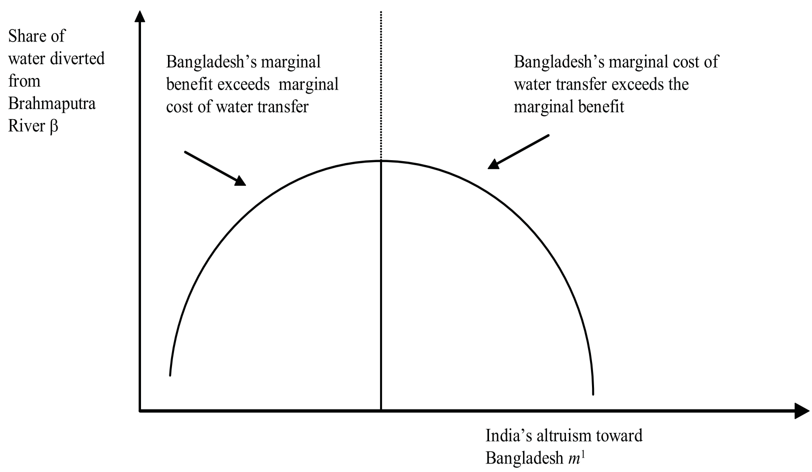
Using the implicit function theorem, we derived the effect of change in India's altruism on the share of water diversion from Brahmaputra.

$$\frac{\partial \beta}{\partial m^1} = -\frac{\dfrac{\partial^2 NB^1}{\partial \beta \partial m^1}}{\Delta} = -\frac{(p-c)W_B\left[\left\{\dfrac{\partial(q^2_G)}{\partial(\omega^2_G)}\right\}(1-\alpha_G-\alpha_P)-\left\{\dfrac{\partial(q^2_B)}{\partial(\omega^2_B)}\right\}\right]-\dfrac{\partial(D)}{\partial\beta}-\dfrac{\partial(L)}{\partial(\beta)}}{\Delta} \qquad (29)$$

$$\text{where } \Delta = \begin{bmatrix} \dfrac{\partial^2 NB^1}{\partial\beta^2} & \dfrac{\partial^2 NB^1}{\partial\beta\partial\alpha_G} & \dfrac{\partial^2 NB^1}{\partial\beta\partial\alpha_{P2}} \\ \dfrac{\partial^2 NB^1}{\partial\alpha_G\partial\beta} & \dfrac{\partial^2 NB^1}{\partial\alpha_G^2} & \dfrac{\partial^2 NB^1}{\partial\alpha_G\partial\alpha_P} \\ \dfrac{\partial^2 NB^1}{\partial\alpha_P\partial\beta} & \dfrac{\partial^2 NB^1}{\partial\alpha_G\partial\alpha_P} & \dfrac{\partial^2 NB^1}{\partial\alpha_P^2} \end{bmatrix} < 0$$

The matrix in the denominator of the right hand of equation 29 represents the second order condition of the maximization net benefit of India, which is negative. The numerator of the equation is the difference between Bangladesh's marginal benefit and the marginal cost of water diversion by India. If Bangladesh's marginal benefit of water diversion from Brahmaputra exceeds the marginal cost, then India will divert more water from Brahmaputra with the increase in level of altruism. On the other hand, if the marginal cost exceeds the marginal benefit, then India would divert less water with the increase in altruism. So we get a concave relationship between India's share of water diversion and the latter country's altruism towards Bangladesh.[13] The relationship is illustrated in Figure 4.

**Figure 4.** Relationship between share of water diversion from Brahmaputra and India's altruism.




[12] Similar results can be obtained by setting $m^1 = 0$ in the first order conditions (26-28).

[13] The concave relationship between Bangladesh and India's share of water diversion, and the latter country's altruism towards the former holds only for concave benefit function of Bangladesh.

## Why Bangladesh Could Reject India's Proposal?

If India is sufficiently altruistic then she could divert a share of water, which could make both countries better off. However, in the future, changes in political relationship between the two countries can worsen the degree of altruism that India offers to Bangladesh. If there is a hostile relationship between India and Bangladesh in the future, India could choose to unilaterally divert water from Brahmaputra, and make Bangladesh worse off in terms of its net benefit. In the model, we assume that India would not care about Bangladesh with a probability $\rho$. Given this uncertainly in political relationships, Bangladesh fears of loss in net benefits largely due to environmental losses in the Brahmaputra River basin. India may also unilaterally divert more water at Farakka and allow less water in the downstream Ganges in Bangladesh. Due to the risk of unilateral diversion of water from the river by India, Bangladesh may reject India's proposal of river linking.

If Bangladesh rejects India's proposal, it's expected benefit would be $E(B^2) = \rho B^2 (\alpha^1_0, \omega^{*2}_B) + (1\text{-}\rho)B^2 (\alpha(m^1), \omega^{*2}_B)$ where $\alpha^1_0$ is the share of water diverted by India unilaterally at Farakka, and $\alpha(m^1)$ is the share of water diverted by India given the political relationship. As India would divert less water in the upstream in the case where it cares about Bangladesh we have $\alpha(m) < \alpha^1_0$. Similarly, if Bangladesh accepts India's proposal of river linking, the expected benefit of Bangladesh can be represented as:

$E(B^2) = pB^2(\alpha^*_G, \alpha^*_P\ \beta^*) + (1\text{-}\rho)B^2 (\alpha^\pm_G, \alpha^\pm_P, \beta^\pm, m^1)$ where Bangladesh benefit

$B^2(\alpha^*_G, \alpha^*_P\ \beta^*)$ from water transfer is lower in the case of hostile political relationship than the benefit in the case $B^2 (\alpha^\pm_G, \alpha^\pm_P, \beta^\pm, m^1)$ where India cares about its welfare.

Assuming Bangladesh is risk neutral, then she may accept India's proposal if

$\rho[B^2(\beta^*, \alpha^*_G, \alpha^*_P) - B^2 (\alpha^1_0, \omega^{*2}_B)] + (1\text{-}\rho)[B^2 (\alpha^\pm_G, \alpha^\pm_P, \beta^\pm, m^1) - B^2 (\alpha(m^1), \omega^{*2}_B)] > 0$

The above expression can be simplified to:

$$\rho < \frac{[B^2 (\alpha^\pm_G, \alpha^\pm_P, \beta^\pm, m^1) - B^2 (\alpha(m^1), \omega^{*2}_B)]}{[B^2 (\alpha^\pm_G, \alpha^\pm_P, \beta^\pm, m^1) - B^2 (\alpha^*_G, \alpha^*_P, \beta^*)] - [B^2 (\alpha(m^1), \omega^{*2}_B) - B^2 (\alpha^1_0, \omega^{*2}_B)]} \quad (30)$$

The above inequality suggests that Bangladesh will accept India's proposal, if the probability of the hostile relationship is less than the ratio of Bangladesh's net benefit from water transfer under altruism to that of change in net benefit from altruism under water transfer.

In order to build the link between the two rivers, it is necessary for India to make Bangladesh agree to the proposal given in the existing international law of transboundary water sharing. Creating new sources to augment water supply requires large investments and effective institutions for allocating water. Implementation of these measures requires cooperation and coordination between regions.

India is optimistic about Bangladesh agreeing to the river linking proposal. We denote the probability that Bangladesh would accept India's proposal as $\upsilon$. We assume that the probability, $\upsilon$ is endogenous and depends on the expected political relationship between India and Bangladesh, and can be expressed as $\upsilon = \upsilon(E(m^1))$. As the probability is endogenous, India can take the opportunity to induce Bangladesh to accept the proposal of water transfer from Brahmaputra through insuring the loss in the latter country's benefit in the case of political uncertainty. Suppose India is willing to pay $a$ proportional of premium to $\theta$ an international insurance firm to protect against the risk of Bangladesh's loss of benefit due to future political uncertainties. The proportion of risk premium, $a$, India would pay lies between 0 and 1.The insurance firm would also insure that in case of environmental and economic loss due to excess water diversion, Bangladesh would get back $a$ proportion of loss in net benefits, $\Omega$ where $\Omega = B^2(\alpha^{\pm}_G, \alpha^{\pm}_P, \beta^{\pm}, m^1) - B^2(\alpha^{*}_G, \alpha^{*}_P, \beta^{*})$. In such a case Bangladesh's probability of accepting India's proposal would be greater with insurance and $\upsilon = \upsilon(E(m_1)) < \upsilon(E(m_1, a))$.

In the framework of a simple insurance model, we examine the equilibrium outcome in terms of the insurance premium that India would like to pay to maximize Bangladesh's chance of agreeing to the proposal, and thereby maximizing India's net benefit over an infinite period of time.

India's problem is to choose the value of the insurance premium $a$ so that it maximizes the following expected net benefit function of India.

$$H=(1-\upsilon(a, E(m))[NB^1(\alpha(m^1)]+\upsilon(a, E(m)\left\{\begin{array}{l}[NB^1(\beta^{\pm}, \alpha^{\pm}_G, \alpha^{\pm}_P, m^1)-a\theta)] \\ +\delta[\rho[(NB^1(\beta^{*}, \alpha^{*}_G, \alpha^{*}_P)]+(1-\rho)[NB^1(\beta^{\pm}, \alpha^{\pm}_G, \alpha^{\pm}_P, m^1)-a\theta]] \\ +\delta^2[\rho[(NB^1(\beta^{*}, \alpha^{*}_G, \alpha^{*}_P)]+(1-\rho)[NB^1(\beta^{\pm}, \alpha^{\pm}_G, \alpha^{\pm}_P, m^1)-a\theta]]\end{array}\right\}$$

where $\delta$ is the discount rate.

Simplifying the above expression we get,

$$H=(1-\upsilon(a, E(m)[NB^1(\alpha(m^1)]+\upsilon(a, E(m)\left\{NB^1(\beta^{\pm}, \alpha^{\pm}_G, \alpha^{\pm}_P, m^1)-a\theta)]\ \frac{1-\delta\rho}{1-\delta}\ +[(NB^1(\beta^{*}\ \alpha^{*}_G, \alpha^{*}_P)]\frac{\delta\rho}{1-\delta}\right\} \quad (31)$$

The first order condition can be represented as

$$\frac{\partial(H)}{\partial(a)} = -\frac{\partial\upsilon(a,\ E(m^1))}{\partial a}[NB^1(\alpha^{*})]+\frac{\partial\upsilon(a,\ E(m^1))}{\partial a}\ [[NB^1(\beta^{\pm}, \alpha^{\pm}_G, \alpha^{\pm}_P, m^1)-a\theta)]\frac{1-\delta\rho}{1-\delta} \quad (32)$$
$$+[(NB^1(\beta^{*}(\alpha^{*}_G, \alpha^{*}_P)]\frac{\delta\rho}{1-\delta}\ )]+\frac{\upsilon(a,\ E(m)}{1-\delta}[-\theta\ (1-\delta\rho)] = 0$$

where, $m^1 > 0$, $0 < a < 1$.

Solving the first order condition, India would determine optimal premium for the loss in net benefits due to political uncertainty. The first order condition suggests that India would choose to pay a proportion of the premium so that its marginal cost of influencing the probability of Bangladesh accepting the treaty is equal to the marginal benefit acquired from water transfer. However, India will not insure Bangladesh's loss if doing so is not expected to increase the net benefits of India. Thus although the overall gain to India from such a water augmentation might be reduced from paying such insurance, India would still benefit compared to the current situation without any water transfers from Brahmaputra. With both countries gaining, it is possible that they might negotiate successfully an international water transfer treaty with a provision of hedging the risk of political uncertainty using suitable insurance mechanism for environment loss.

## Simulation Results

In the past, limited analysis of water allocation of the optimal allocation of the Ganges and the Brahmaputra River basin based on actual data sets was conducted due to lack of data regarding water flow in the respective river basins.

As an alternative approach, we have used simulations to predict the outcomes of the theoretical model using the Latin Hypercube technique.[14] Using simulations, we attempt to determine the optimal allocation of the share of water by a social planner, and also in the case where India has the opportunity to divert water given the political relationship between the two countries.[15] The optimal water allocation has been computed by simulation using computer software 'RISK Optimizer'.[16]

We seek to illustrate how political relationship factors might have influenced the share of water diversion from Brahmaputra and the water allocation between India and Bangladesh.

In the simulation, we have assumed that the total flow of water in each river basin is subject to stochastic variability. The uncertainty in the flow of water can be attributed to environmental changes in the headwaters of the rivers such as deforestation and dwindling glaciers as a result of climate variability and change. As an example of stochastic dependence in the flow of water, low rainfall or a hot summer may simultaneously lower *W* and raise the marginal benefit of water for both the countries, thus, the flow of water, $W_{t\,i}$, at time period *t* in jth river basin *(j=G ,B)* can be represented by

$$W_{t\,i} = \overline{W} + \varepsilon_{t\,j}, \tag{33}$$

where $\overline{W}_i$ is the long run average flow of water of at the point of diversion and $\varepsilon_{jt}$ is the stochastic variable factor.

Simulation results in the model suggest that the stochastic factor, $\varepsilon_{jt}$, is best fitted with a lognormal distribution with zero mean and a known constant variance σ.[17] The variance of the distribution function of the uncertain element in the water flow provides a degree of information or knowledge about the flow of water in a given time period. We assume that both India and Bangladesh has the opportunity to access accurate water flow information, and know the true variance of the stochastic disturbance of the flow of water. The water allocation decision between the two countries depends on the uncertainty in the flow of water and, hence it is based on the degree of information about the flow of water.

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[14] Latin Hypercube sampling (Iman et al.1980) has been shown to require fewer model iterations to approximate the desired variable distribution than the simple Monte Carlo method. The Latin Hypercube technique ensures that the entire range of each variable is sampled. A statistical summary of the model results will produce indices of sensitivity and uncertainty that relate the effects of heterogeneity of input variables to model predictions.

[15] There is a caveat .Much of the benefit and cost functions are not fully based on empirical data and the outcome of the simulation may change substantially.

[16] RISKOptimizer is the simulation optimization add-in for Microsoft Excel®. It allows the optimization of Excel spreadsheet models that contain uncertain values. RISKOptimizer runs an optimization of simulations, finding the combination of adjustable cells that provides the best simulation results.

[17] Using Best Fit Software and empirical data, we determined the distribution function of the water flow of the Ganges.

We also assume that in the case where India diverts water from Brahmaputra and Farakka based on political relationship, the country's altruistic concerns for Bangladesh is also subject to uncertainty and follows a uniform and discrete distribution.

We make the problem more tractable by assuming a specific form of benefit functions of both countries. The specific benefit functions of India and Bangladesh are presented in Table 1. And the simulations results are shown in Table 2.

**Table 1.** Assumptions in the simulation.

| Parameters and Variables | Computation and Values | Explanation |
|---|---|---|
| India's political relationship with Bangladesh, $m^1$ | [0.1 0.9] ,$0<m^I<1$ | India cares more about itself than Bangladesh. $m^1$ follows uniform discrete distribution |
| Water flow of the Ganges at Farakka | $W^1_G = \overline{W}^1_G + \varepsilon_G$ where $\varepsilon_G$ follows lognormal (0, σ) $\overline{W}^1_G$ = 69 billion cubic meters(long-term average flow of water) σ = 12. | Derived from existing empirical data (Biswas 2001); used best fit software to derive the distribution |
| Water availability of Brahmaputra at Jogighopa | $W^1_B = \overline{W}^1_B + \varepsilon_B$ where $\varepsilon_B$ follows lognormal (0, σ) $\overline{W}^1_B$ = 537 billion cubic meters(long-term average flow of water) σ = 98. | Derived from existing empirical data (Crow 1995); used best fit software to derive the distribution |
| Water withdrawal in Cauvery and pennar river basin under current situation. | $\omega^1_P$ = 32 billion cubic meters | Derived from existing empirical data (Amarasinghe et al. 2005); used best fit software to derive the distribution |
| Agricultural benefit function of India $(\pi^1_G)$ in Ganges River basin | $\pi^1_G = .04(\omega)^{1/2}$ | The form of India's benefit function is based on the concavity assumption The quadratic benefit function is assumed for computational simplicity. Also we have taken into account each country's marginal productivity of water in each basin from Nasima (Chowdhury 2005) |
| Agricultural benefit function of India $(\pi^1_G)$ in Cauvery and Pennar River basins | $\pi^1_G = .03(\omega)^{1/2}$ | |
| Agricultural benefit function of Bangladesh $(\pi^1_G)$ in Brahmaputra | $\pi^1_G = .02(\omega)^{1/2}$ | |
| Agricultural benefit function of Bangladesh $(\pi^1_G)$ in Ganges River basin | $\pi^1_G = .03(\omega)^{1/2}$ | |
| Flood control damage function $D(\beta)$ in Brahmaputra River basin | $D = 0.4\ ([1-\beta)\ W_B]^{1/3} = 0$ for $\beta > .10$ | The form of Bangladesh's flood damage and environmental loss function and India's marginal cost of transfer water is based on the assumption and literature review |
| Environmental loss function $L(\beta)$ in Brahmaputra River basin | $L = 0.3\ [\beta W]^{1/3}$<br>$= 0$ for $\beta < k$<br>$k$ = [0.15,0.25] | |
| Marginal cost or water transfer | $r = 0.003\ (\beta W_B)^{-1/3}$ | |
| Share of water $\alpha$ according to Ganges Treaty | $\alpha = 0.5$ | |

**Table 2.** Simulation results.

| Decision Unit | Share of water diversion in percentage | | | Threshold level of environmental damage $\tilde{\beta}$ | Expected change in present total benefit from water transfer(percentage) per year | |
|---|---|---|---|---|---|---|
| | Ganges (India) $\alpha_G$ | Peninsular (India) $\alpha_P$ | Brahmaputra $\beta$ | | India | Bangladesh |
| Social | 40 | 23 | 12 | >15 | 43.61 | 41.01 |
| Planner | 39 | 22 | 10 | 10 | 42.31 | 42.9 |
| India with | 41 | 24 | 14 | >15 | 58.65 | 29.59 |
| average altruism | 43 | 25 | 10 | 10 | 48.87 | 27.19 |
| India without altruism | 40 | 36 | 22 | >10 | 93.98 | -102.07 |

*Source*: Authors' estimates

The simulation results suggest that in the case where the social planner decides about water allocation, the optimal share of water diverted from Brahmaputra could be between 10 to 12 % of the total availability of water of the Brahmaputra River at Jogighopa, and is below the threshold level of environmental damage of Bangladesh. The expected change in present discounted benefit from water transfer would be nearly the same for both countries.

In the case where India cares about Bangladesh with average altruism, India's expected benefit would increase more. But, India would still forgo substantial benefits to Bangladesh when the transfers are taking place under political altruism than the case where India has the opportunity to unilaterally divert water. However, India would forgo less if the threshold level of environmental damage is above 15 % of the total flow of Brahmaputra River.

The share of water allocation of the augmented water at Farakka for India would range from 61 % in the case of water allocation by a social planner to 76 % in the case where India has an opportunity to unilaterally divert water.

Bangladesh could incur a loss of up to 177 % if India diverts water unilaterally under a hostile political relationship. The expected change in benefits of Bangladesh would decline if India decides the water share based on a political relationship. Uncertainty in political relationships between India and Bangladesh could induce India to divert water unilaterally; and it could be one of the reasons for Bangladesh to reject India's proposal to transfer water from Brahmaputra, even though Bangladesh could be better off from a water transfer under a cooperative situation.

## Conclusion

In this paper we have attempted to analyze the effects of inter-linkage of the Ganges and Brahmaputra River basin on future water allocation between India and Bangladesh. From a social planner's perspective, we determined the optimal diversions of water from Brahmaputra. We also examined the endogeniety of risk of environmental losses in Bangladesh if India diverts a share of water above the threshold level from Brahmaputra River. Bangladesh can use self-protection as a means of resistance to environmental damage, while India can supply more water to downstream Brahmaputra River as a control measure to environmental damage. The social planner's objective will be to minimize social cost with respect to the environmental damage resistance and environmental damage control.

Assuming the structural forms of the benefit functions of both countries, we simulated the optimal allocation of water sharing and the associated expected change in benefits of the countries from water transfer. Results suggested that both countries could be better off if water is allocated according to the social planner's decision rule. Bangladesh would enjoy a substantial benefit from reduced flood damage in the Brahmaputra Basin and the augmented water flow in the downstream Ganges.

We also explored the situation where India cares about the welfare of Bangladesh. Using a political altruistic model, we determine the water allocation between India and Bangladesh. In the model we assume that if there is a good political relationship between India and Bangladesh, then India could be altruistic towards Bangladesh and divert more water in the downstream.

However, we recognize the risk in benefit loss of Bangladesh that could stem from the hostile political relationship between the two countries. In such case of political uncertainty, India has the opportunity to divert water unilaterally and Bangladesh could incur huge environmental damage that would outweigh its benefits from water transfer. We have derived the conditions under which Bangladesh could reject such an Indian proposal of river linking.

Given the international laws on water sharing, it is essential for India to make Bangladesh agree to such a proposal. We examined the conditions determining whether Bangladesh would accept such a supplemental water augmentation treaty, and also whether such an agreement can guarantee a potential Pareto improvement.

To induce Bangladesh to agree to such proposals, India may promise to insure some proportion of Bangladesh's environmental and agricultural loss if a hostile political situation induces India to divert water unilaterally in the future. Thus, although the overall gain to India from such a water augmentation might be reduced from paying such insurance, India would still benefit compared to the current situation without any water transfers from Brahmaputra. With both countries gaining, it is possible that they might negotiate successfully an international water transfer treaty with a provision of hedging the risk of political uncertainty using suitable mechanisms, without resorting to a less satisfactory 'victims pay' outcome (Bennett et al. 1998).[18]

[18] Bennett et al. (1998) point out that water diversion by the upstream country imposes unidirectional external costs on the downstream country, which leads to an unsatisfactory 'victims pay' outcome under a traditional game theory approach whereby the downstream country may need to bribe the upstream country to prevent such diversion from occurring.

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