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Interdependence in Water Resource Development in the Ganges: An Economic Analysis

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Abstract

It is often argued that the true benefits of water resource development in international river basins are undermined by a lack of consideration of interdependence in water resource planning. Yet it has not been adequately recognized in the water resources planning literature that overestimation of interdependence may also contribute to lack of progress in cooperation in many systems. This paper examines the nature and degree of economic interdependence in new and existing water storage projects in the Ganges River basin based on analysis conducted using the Ganges Economic Optimization Model. We find that constructing large dams on the upstream tributaries of the Ganges would have much more limited effects on controlling downstream floods than is thought and that the benefits of low-flow augmentation delivered by storage infrastructures are currently low. A better understanding of actual and prospective effects of interdependence not only changes the calculus of the benefits and costs of different scenarios of infrastructure development, but might also allow riparian countries to move closer to benefit sharing positions that are mutually acceptable.

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Introduction

It is now widely accepted that water resource development in international river basins is a highly interdependent process (Biswas, 2004; Serageldin, 1995). For example, large infrastructure projects upstream in a river basin may have significant impacts on both the quantity and the quality of water reaching downstream riparian countries and thus may affect economic benefits derived from water resource development throughout the river basin. Similarly, large infrastructure projects downstream risk foreclosing future opportunities for development upstream (Salman, 2010). This interdependence may evolve in complex ways over time due to effects of climate change, population increase, and economic growth, all of which may increase competition for water resources (Jeuland, 2010; Pahl-Wostl, 2007). Lack of attention to interdependence in water resource planning and development has resulted in project designs that deliver smaller net economic benefits to riparian countries than expected. Failure to account for interdependencies and externalities can create daunting challenges to cooperation regarding natural resources in many arenas, not only water in international river basins (Barrett, 1994; Ostrom *et al.*, 1999).

Although the economic issues associated with water resource development in international river basins are often misspecified due to underestimation of the complexities of interdependence, it may not be true that the impacts of such interdependencies will always be large. In fact, overestimation of the impacts of interdependence among riparian countries in international river basins may also be damaging, for several reasons. First, overestimating the effects of interdependence among countries sharing water resources can fuel unrealistic expectations regarding equitable distribution of the benefits from cooperation. In the Ganges basin, for instance, there is a widely held perception that India would benefit substantially, in terms of flood reduction, from the construction of large dams in the Himalayas in Nepal (Sadoff *et al.*, 2012; World Bank, 2012). These anticipated benefits, if overestimated, could in turn create unrealistic expectations regarding appropriate compensation or cost-sharing arrangements among riparian neighbors along the Ganges.

Second, overestimation of interdependence may generate unfounded concerns among downstream riparians. For example, Bangladesh has generally been wary of upstream development because of potential impacts on the availability of water downstream. These impacts might prove to be smaller than expected if interdependence were not in fact as high as is often assumed.

Third, overestimation of the effects of interdependence may adversely affect the timing and prioritization of water resource development projects across sectors. For example, misperception of potentially high levels of interdependency could lead to decisions to hold back development in certain sectors due to the perceived trade-offs. In this way, opportunities for benefiting from such developments may be lost or delayed.

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Importantly, most prefatory analyses of new infrastructure in river basins continue to focus primarily on hydrological and geographical considerations and their physical effects, with insufficient economic valuation to assess their net effects on integrated water resource systems (Harou *et al.*, 2009; Jeuland, 2010). Lacking accurate, reliable economic analysis, a riparian country may decide to play down or overstate its position in interdependent water resource development projects according to its own geographical position. It may also act strategically according to such projects' perceived or actual impacts on current conditions, which are by definition poor, incomplete indicators of future project performance. Thus the results of an information deficit can lead to unrealistic perceptions of the extent of interdependence present in such projects, perceptions that may become significant, unnecessary obstacles to realizing opportunities for cooperation. In this context, early and accurate economic analysis of water resource development options may contribute to the establishment of a shared understanding of the degree of interdependence that will be involved, as well as a more realistic forecast of the net economic effects of cooperation.

This paper examines the nature and degree of economic interdependence in water resource projects along the Ganges, using the Ganges Economic Optimization Model (GEOM). The objective of this nonlinear, constrained optimization model is to maximize the total annual system-wide economic benefits generated by releases of water from a set of assumed infrastructure facilities. Although there is a general sense that the development of multipurpose infrastructure in the Himalayan region would yield significant economic benefits to riparian countries throughout the basin, there is also some expectation that trade-offs among potential uses for stored water could be very large. There is also no common understanding among the riparians about the relative values of hydropower, flood control, and dry season flow augmentation in the various regions that comprise the basin. Thus the determination and equitable distribution of benefits from such projects is a matter of significant concern and contention among policy makers.

The research summarized in this paper focused on three questions: (1) What are the relative magnitudes of the economic values of hydropower, flood control, and low-flow augmentation from water resource development in the Ganges? (2) Are there significant trade-offs among hydropower, flood control, and low-flow augmentation resulting from water resource development in the Ganges, in economic terms? (3) How sensitive to varying assumptions of economic value are the relative sizes and trade-offs from hydropower, flood control, and low-flow augmentation delivered by Ganges water resource development options?

To address these questions, we conducted a careful review of existing information on the development of Ganges water resources, and developed the GEOM mathematical model to explore the impacts of potential new hydropower infrastructures. Using the GEOM, we find that the potential economic benefits of new hydropower generation from developing the full suite of new investments described could reach US$7-8 billion annually. This is significantly greater than the current hydropower benefits produced in the Ganges basin (about $2.5 billion). We also find that the economic trade-offs among hydropower, low-flow augmentation, and flood control objectives are very modest. Moreover, our findings show that although flood damages in the Ganges basin are presently substantial, the construction of upstream multipurpose water storage would not have a large effect on peak flows in the Ganges (particularly in wet years); that is, the economic value of reduced flood losses associated with these infrastructure development scenarios would be small. As for the trade-off between the two main downstream uses – irrigation in the Ganges plain and low-flow augmentation passing through to Bangladesh – we show that the optimal allocation between these two uses is highly sensitive to their relative economic values: if the economic value of low flows in Bangladesh is high, the GEOM allocates less water upstream for irrigation, and vice versa.

Our findings have several significant implications for improving the prospects of cooperation among riparian countries in the Ganges basin. First, our finding that construction of large dams upstream in Nepal would have limited effects on flood control downstream may prompt renewed consideration of options to develop smaller dams that focus primarily on hydropower benefits instead of seeking complex deals on large and potentially controversial dams that had been expected to deliver significant flood or irrigation benefits. Second, the fact that there is little trade-off between hydropower production and downstream water uses means that increases in irrigation in Nepal and India or low-flow augmentation in Bangladesh do not come at the expense of significant amounts of hydropower, i.e., hydropower production is relatively insensitive to changes in the economic value of water to downstream users. In this sense, downstream riparian countries (India and Bangladesh) need not fear that the operating rules of new hydropower projects developed upstream in Nepal will adversely affect or even foreclose their own development options. Third, the riparians can utilize economic analysis to better understand the nature of inter-dependency in this system, and to develop a common and shared understanding of the net benefits from Ganges basin cooperation.

The paper begins with a summary of relevant background information on the Ganges, after which we present themathematical description of the GEOM. We then report detailed results and conclusions.

Background

Previous studies relevant to the economic analysis presented here can be broadly classified into two categories. The first pertains to optimization and game-theoretic analyses of various potential water resource development pathways in the Ganges basin and of the distribution of the benefits they deliver to the affected riparian countries (Bhaduri & Barbier, 2003; Rogers, 1969, 1993). The second concerns the value of water in its various uses, as well as the value of hydropower. Some studies in the latter group attempt to estimate the marginal productivity of water in crop production in the expansive irrigation schemes located in the Ganges plain (e.g., Molden *et al.*, 2001). Surprisingly little economic valuation has been done of floods in India and Bangladesh (see Somanathan, this issue, for an exception), of ecosystem services in the Ganges–

Brahmaputra–Meghna delta in Bangladesh, or of the marginal productivity of water for uses other than agriculture.

The Ganges was one of the first river systems investigated using systems analysis and basin-wide assessments tools. Rogers (1969) used a linear programming model to analyze the benefits to India and Bangladesh (at that time, East Pakistan) of water resources development in the lower Ganges and Brahmaputra rivers, in terms of flood control, power production, and irrigation. Though constrained by severe data limitations and the omission of upstream riparians such as Nepal or Bhutan, the analysis suggested the possibility of significant net benefits to both India and East Pakistan from infrastructure development, even though the gains to be had from joint operation and budgeting for new projects appeared limited. In subsequent work, Rogers (Rogers, 1993) expanded the analysis into a three-person game that included Nepal and added the option (favored by India) of water transfer from the Brahmaputra to the Ganges. The new analysis showed that the collective gains from cooperation could reach 24%, and that four-fifths of these gains would result from coordination of infrastructure investments. An important finding was that most of the cooperative benefits would accrue downstream, to India and Bangladesh, as a result of those two countries' joint projects. (The investments considered for Nepal, however, were rather limited from the outset.)

The other game-theoretic analyses of the benefits of alternative development strategies in this region have come from a more recent series of analyses by Bhaduri and Barbier (2007; 2008a, b). These largely focus on long-standing conceptions regarding the value of water transfers from Nepal to downstream riparians during low-flow periods, or from the Brahmaputra to the Ganges (Crow *et al.*, 1995; Iyer, 2003; Verghese, 1999). This collective work suggests, first, that India would be capable of consuming any additional water transferred from Nepal to the downstream system. Second, the authors argue that altruism, that is, concerns other than simple welfare maximization within India, is the primary explanation for why India has allowed flow-through of water to Bangladesh during the dry season in the form of the Ganges Water Sharing Agreement, without requiring compensation (Bennett *et al.*, 1998).[1] The implication is that further altruism would be required in order for Bangladesh to benefit from additional dry season flow augmentation (Bhaduri & Barbier, 2008b). Third, transfer of water from the Brahmaputra could deliver net benefits in Bangladesh if India is altruistic, because flood protection gains would outweigh decreases in water availability. But if India's altruism were low or nonexistent, and India unilaterally diverted flow to the Ganges, welfare in Bangladesh would sharply decrease (Bhaduri & Barbier, 2007). Fourth, Bangladesh could attempt to purchase water directly from Nepal to augment its Ganges inflows, but India might still choose to consume that water if the marginal value of the water exceeded what Bangladesh was willing to pay. In the latter case, a

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[1] In their model, Bhaduri and Barbier use a formulation with interdependent utility functions to allow for altruism. Note that this formulation accommodates pure altruism, or caring about the welfare of the other for its own sake, as well as altruism for political, economic, and/or other perhaps self-interested reasons.

grand coalition of Nepal, India, and Bangladesh could make every riparian better off, but only if India and Bangladesh had altruistic concerns (Bhaduri & Barbier, 2008a).

Also relevant to our analysis are several studies of the marginal value of water and hydropower in the Ganges basin and wider region. For example, Rogers et al. (1998) obtained values of US$0.02 in Haryana (some of which lies at the northwest end of the Ganges basin), and Dhawan (1988) estimates the net income from water to be US$0.03 in the basin itself. In the wider region, a range of estimates obtained from various studies that employed a variety of methodologies – marginal water productivity estimation, average net benefits associated with a unit of water, and stated willingness to pay – span from US$0.02 to $0.05, (Abbie *et al.*, 1982; Chandrasekaran *et al.*, 2009; Gasser, 1981; Molden *et al.*, 2001). Higher estimates, reaching $0.12 per unit, were obtained for water delivered at the canal level (Molden et al. 2001).

Several topics relating to water use in the region are noteworthy but only indirectly relevant to the analysis presented here. The economic literature contains estimates related to the value of water quality and flood protection in the Ganges basin. Markandya and Murty (2004) used contingent valuation and revealed preference data to show that the nonuse benefits of cleaning up the Ganges in India dominate use benefits. For present purposes these estimates of the value of improved water quality have only limited relevance, as GEOM does not model wastewater treatment and pollution control investments. In addition, shifting the flow of water seasonally would likely have very minor effects on water quality in the most polluted reaches in India (World Bank, 2012). We are aware of no work estimating the value of enhanced low flows for ecosystem service provision in Bangladesh. Similarly, a few studies consider the value of, or willingness to pay for, flood protection in the Ganges delta (Brouwer *et al.*, 2009; Islam & Braden, 2006; Thompson & Sultana, 1996), but the GEOM indicates that the reduction of flood peaks in the Ganges would be very modest even with the largest-scale development of upstream storage in Nepal considered (World Bank, 2012).

Energy values for non-peak power based on the long-run marginal cost of alternative power sources in the region (coal and natural gas) vary between US$0.05 and $0.08/kW-h (Banerjee, 2006; Gautam & Karki, 2004; Limbu & Shrestha, 2004; Tongia & Banerjee, 1998). Our calculations of the benefits from hydropower production are informed by these estimates.

Methods

The Ganges Economic Optimization Model (GEOM)

The objective of GEOM is to maximize the total annual economic benefits generated by the system through releases of water from a set of assumed infrastructure facilities. The total annual economic benefits are the sum of four components: (1) the economic value of hydropower production from new and existing dams; (2) the economic value of irrigation water for the cultivation of agricultural crops; (3) the economic value of reduced flood losses; and (4) the economic value of incremental low flows to Bangladesh, above the minimum release at the Farakka Barrage in India as specified in the Farakka Treaty of 1996.

This model is similar to the Nile Economic Optimization Model (NEOM) that was previously developed and used to explore different combinations of infrastructure developments in the Nile basin (Guariso & Whittington, 1987; Thomas & Revelle, 1966; Whittington *et al.*, 2005). As with NEOM, users of GEOM can explore the consequences of building various new dam projects and test the sensitivity of results to hydrological flows (using low-flow, average, and high-flow years). Users can also impose minimum flow restrictions in critical stretches of the river to ensure environmental flows, or can require certain urban or agricultural demands to be prioritized (for example, flows to Calcutta or crops in Bangladesh). Finally, users can alter river channel capacities to reflect changes in river geomorphology or the effects of enhanced embankment protection (assuming there are no breaches).

While GEOM focuses exclusively on these economic values, it is not intended to suggest that these are the only values to be considered in the development of multipurpose infrastructure in the basin. The Ganges is a river of enormous cultural, religious, and social significance, and these values also must be a central consideration. Ecosystem sustainability; economic loss due to resettlement; recreation and tourism; navigation; municipal and industrial water supplies; and equity concerns within and across borders should all be factors in development decisions. The economic dimensions we do include are just one important part of the decision calculus surrounding infrastructure development and water allocations in the basin.

GEOM is formulated as an annual, nonlinear, constrained optimization problem with a monthly time step. It determines the annual pattern of water allocations that maximize the system-wide economic benefits from hydropower, agriculture, flood reduction, and downstream low flows. It calculates the economic benefits by type of water use and by country. Minimum flows in specific upstream reaches of the river and at the Farakka Barrage are imposed in GEOM as constraints on river flow. In the analyses presented here, for example, upstream minimum flows must be sufficient for all municipal demands to be satisfied, and downstream flows must be at least in accordance with the flow minima specified in the Farakka treaty between India and Bangladesh.

The Ganges system is characterized in GEOM as a network of nodes and links (Figure 1). There are five basic types of nodes: reservoirs, irrigation withdrawals, flood outflows, flood returns, and intermediate nodes. The model includes 29 existing storage reservoirs (all but one of which are in India), plus 23 potential new dams. All of these hypothetical new dams and the reservoirs behind them are in Nepal, with the exception of the proposed Pancheshwar Dam site on the Mahakali River, which is a border river shared by India and Nepal.[2] Most of these reservoir nodes allow storage of inflows up to reservoir capacity, beyond which flows spill downstream.

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[2] The Mahakali River runs north to south, with the right (western) bank in Indian territory and the left (eastern) bank in Nepal. The border runs down the center of the river, such that approximately half of the main dam and reservoir would lie in each country.

However, three of the new dams are run-of-the-river hydropower projects without water storage. Reservoir releases determine hydropower production and the amount of water available for downstream uses, and influence the peak flows in their tributaries and in the main stem of the Ganges.

[FIGURE 1 ABOUT HERE]

There are 34 irrigation nodes in GEOM, some of which in reality correspond to very large command areas served by irrigation canals. Some of these command areas currently are only partially irrigated with surface water due to constraints on water delivery. In GEOM at these nodes water is removed from the river system and partitioned into four components. The first portion of this water is used to satisfy irrigation water demands for crops grown in the command areas (this amount of water is estimated based on crop-water requirements for different areas obtained from the FAO CROPWAT model). The second component is for losses to nonproductive evapotranspiration from canals and fields; our analysis assumes this portion to be equal to 60% of the water actually used by crops (the first component), or 30% of the water diverted to irrigation areas. The third portion of diversions – 20% overall, or 40% of the crop-water requirement – is assumed to flow back into the Ganges system via return flows. Finally, GEOM allows additional diversion of water into groundwater recharge when the canal capacity is not fully utilized. This recharge water is not lost to the system; GEOM adds it to storage in groundwater reservoirs beneath each irrigation node. This stored groundwater can then be pumped (at a cost) and used throughout the year to help meet irrigation water demands when surface flows are insufficient. The water balance for groundwater reservoirs only incorporates flows out of the GEOM surface water system and does not include “green water” recharge, that is, recharge from local precipitation and infiltration.

GEOM also includes eight flood outflow nodes. Seven are located on the northern Ganges tributaries (Yamuna, Upper Ganga, Ghagara, Rapti, Gandak, Bagmati, and Kosi), one is on the main Ganges. At these flood outflow nodes, monthly flows in excess of natural river channel capacities leave the river network and cause flood damages. A fraction of these river spills are then assumed to return to the river at flood return nodes, which are located just downstream of the flood outflow nodes. The other intermediate nodes in GEOM account for inflow (that is, where runoff enters the system), confluence (where multiple rivers meet), and distribution (where a river splits). In total, 77 of the model nodes receive inflows from local catchments.

[FIGURE 2 ABOUT HERE]

Figure 2 illustrates the water balance to irrigation nodes, including nonproductive evaporation losses, seepage to local groundwater, delivery of surface water to irrigated fields, and return flows to the river system. The various flow variables Q are all decision variables in the model.

GEOM’s mathematical objective function is expressed as

$$\boldsymbol{Maximize\ Z = \sum_k p^h \cdot H_k^m + \sum_j p^{irr} \cdot I_j^m + p^l \cdot L^b - \sum_k F_k^m - \sum_j c^g \cdot G_j^m,} \qquad \text{(I)}$$

where

Z = total economic benefits (in millions of US$);

p^h = economic value of hydropower (US$/kW-h);

$\boldsymbol{H_k^m}$ = Annual hydropower generated in project at node k (in GW-h/yr);

p^{irr} = economic value of irrigation water (US$/m^3);

$\boldsymbol{I_j^m}$ = volume of irrigation water delivered to area j, in state/country m (in millions of m^3);

p^l = economic value of low flows (US$/m^3);

$\boldsymbol{L^b}$ = volume of low flows to Bangladesh during the lean season (January–May), above the Farakka Treaty minimum (in millions of m^3);

F_k^m = economic cost of exceeding channel capacity at node k, in state/country m (in millions of US$);

c^g = cost of pumping recharged groundwater (US$/m^3); and

$\boldsymbol{G_j^m}$ = volume of recharged groundwater pumped to area j, in state/country m (in millions of m^3).

The model uses a monthly time step t and determines the value of the decision variables that yield the highest outcome of the objective function Z. This model-determined pattern of water releases and allocations to water users is subject to constraints on flow continuity in the river, water balance and partitioning at irrigation nodes, river channel capacity, low-flow and municipal/ industrial water requirements, groundwater and surface water storage capacity, installed hydropower capacity, irrigation water requirements, and land availability. There is also a requirement that all “reservoirs” (including those for groundwater) end the year at the same level as where they began, though the optimal initial levels are determined by the model. A detailed presentation of the mathematical form of these constraints is included in Appendix A.

GEOM also incorporates several other important features. First, technological and demand management interventions (lining of canals, investments in drip irrigation, incentives for enhanced recharge, etc.) can be assessed by altering the irrigation and municipal water delivery parameters that influence efficiency: ρ_j, r_j, and λ_k, which specify how releases to water delivery canals are partitioned between productive ET, non-productive ET, and return flows. Similarly, the effects of changes in cropping and intensity can be simulated by altering assumptions about crop-water requirements in different areas using the CROPWAT and CLIMWAT tools applied to new cropping patterns, or other procedures for estimating water demands (FAO, 1998).

Second, the economic value associated with irrigation using Ganges water is obtained by multiplying the quantity of irrigation water by the marginal product of water p^{irr}. We adopt this formulation recognizing that the current marginal productivity of water in the Gangetic plain is low (Abbie *et al.*, 1982; Dhawan, 1988; Gasser, 1981; Molden *et al.*, 2001; Rogers *et al.*, 1998). Pumping costs from use of groundwater (parameter c_j^g, which can be varied based on the depth to groundwater in area *j*) are subtracted from these benefits as well; thus the model only uses groundwater if the value of water outweighs these extra pumping costs. By systematically varying the marginal product of water in sensitivity analysis (that is, giving more or less value to the agricultural component of the model), we can see whether water allocations are sensitive to assumptions about the value of water.

Third, GEOM seeks to minimize flood damages. Unfortunately, the damages μ_k associated with overbank spills at different locations are unknown at this time. Thus, much as with, agriculture, where we varied the weighting parameter p^{irr} in the objective function, here we study the effect of this value of μ_k on the optimal water allocations determined by the model. This allows us to examine whether trade-offs exist between the flood control and hydropower or agriculture objectives.

Finally, GEOM includes an additional parameter p^l that allows us to explore the implications of different economic values of water during the low-flow period in Bangladesh for optimal water allocations. This parameter is used to value incremental flows above the Farakka Treaty minimum, which is the status quo for minimum low flows to Bangladesh.

Scenario analysis

GEOM was used to explore the potential impacts of four scenarios, each with different combinations of new infrastructure projects. The hydrological year used in the base case is the year 2000, for which the overall runoff into the Ganges was 502 BCM, compared to an average of 508 BCM over the ten-year period 1999–2008 (range 460–545 BCM). None of the major river tributaries had exceptional hydrology in 2000.

The consequences of constructing different sets of upstream storage infrastructures are measured relative to a baseline “state of the world” that closely resembles current conditions. It is not possible to characterize precisely the present situation of Ganges water management, because the amount and pattern of surface water withdrawals for different basin irrigation schemes in India are unknown. Instead, we estimate overall crop-water requirements in different irrigation schemes from state-level data for the major crops in the existing mix, accounting for local climatic conditions and the differing cropping intensities in irrigated areas within Bangladesh, India, and Nepal.[3] Thus instead of constraining irrigation water withdrawals according to existing surface water demands in the basin, the model solves for the theoretical area of land that should be irrigable given existing cropping patterns, yields, market prices, and water use at the field-level according to the irrigation water partitioning parameters.

The four illustrative scenarios examined are as follows:

1. Existing storage and flow regulation projects (status quo, baseline case)
2. The three proposed Himalayan mega-dams: Pancheshwar Dam on the Mahakali/Sarda River bordering India and Nepal, Chisapani Dam on the Karnali River in Nepal, and the Kosi High Dam on the Kosi River in Nepal
3. Only building smaller dams and run-of-the-river projects in the Himalaya in Nepal, of which we include 20 (only the largest among a long list of possible projects)
4. All major proposed dams included in 2 and 3 above.

Sensitivity analysis was conducted to explore the effects of several modeling assumptions on the results`: (1) varying the relative economic value of low flows to Bangladesh; (2) varying the economic value of irrigation water; and (3) testing the effects of low-, average, and high-flow years on both physical and economic outcomes in different portions of the basin. To assess the effects of differing assumptions in terms of the first two points, we constructed nine cases representing all low, medium, and high combinations of the economic value of water to irrigation and downstream low-flow augmentation (Table 1).

[TABLE 1 ABOUT HERE]

The basic parameter assumptions used in our analysis are presented in Table 2. A discussion of the sources of data used to parameterize the model is presented in Appendix B.

[TABLE 2 ABOUT HERE]

Results

The economic benefits of hydropower from the 23 new dam projects considered in this study are estimated to range from US$3-8 billion per year, depending on the infrastructure scenario (Table 3). The upper end of this range includes the full suite of hydropower investments, which produce $7 billion to $8 billion annually above the current hydropower benefits produced in the basin (about $2.5 billion). These values are gross (they do not include the $1-2 billion/yr annualized costs shown in Table 3) and correspond to the assumption that 25% of power produced could be sold as peaking power in India to yield an average power value of $0.1/kW-h. If the energy from these dams were not used for peaking purposes, anticipated benefits would

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[3] Japan International Cooperation Agency 1985; Bangladesh Bureau of Statistics (BBS) 2004; Indiastat 2005.

be reduced by about 25%. On the other hand, if the dams could be operated to supply greater than 25% peaking power, the benefits would be proportionally higher.

[TABLE 3 ABOUT HERE]

The magnitude of irrigation and low-flow augmentation benefits downstream of the infrastructure projects are more difficult to assess because they depend directly on the assumed valuation parameters. In the medium value case (marginal productivity of water equal to US$0.05/m^3), these reach $2.8 billion; but they range from $0.3 billion (lowest value case) to $5.5 billion (highest value). On the one hand, the estimates of the marginal value of increased surface water irrigation presented in the baseline medium case ($0.05) would appear to be much higher than the current very low value derived from irrigation water in India and Nepal. On the other hand, in the future agricultural modernization and increased returns to water could change this picture dramatically.

Also, although flood losses in the Ganges basin are significant, our findings suggest that the construction of upstream multipurpose water storage would have a limited effect on peak flows in the Ganges (particularly in wet years); thus the economic value of reduced flood losses associated with these infrastructure development scenarios will be small (Table 4). On the tributaries, and particularly in the Gandak River, the reduction in peak flows is somewhat larger. Nonetheless, because of the extensive embankments now existing along the Gandak and other tributaries, flood losses are unlikely to be significantly reduced through the development of new, large-scale upstream infrastructure investments. Improved flood management will require a sharpened focus on forecasting and warning systems, as well as localized hard and soft responses (World Bank, 2012).

[TABLE 4 ABOUT HERE]

Analysis of trade-offs

We find that for the most part, the economic trade-offs among hydropower, irrigation, and flood control objectives are small. This is because there is little difference in the optimal water release pattern for hydropower production and downstream water supply needs; the storage in the upstream dams considered is relatively small compared to annual flows. Both these objectives are best served by storing peak flows to achieve steadier, increased dry-season releases, and flood control is limited regardless of how operating rules are designed, because water quickly fills even the largest dams that could be built in the system once the monsoon season begins. There is a trade-off in the quantity of water used for irrigation in the Ganges plain versus low-flow augmentation in delta [Sundarbans], but it is unclear whether this trade-off is economically significant given the current low marginal benefit associated with surface water irrigation in the plains and the unknown economic value of low-flow augmentation in Bangladesh.

Not surprisingly, the optimal water allocations --and economic benefits of irrigation in the Ganges plain and of dry season flow augmentation in Bangladesh-- are sensitive to varying assumptions about their relative economic value (Table 5). Given the difficulty in predicting the economic value of incremental changes for these uses, the precise nature of these trade-offs is difficult to assess at this time.

[TABLE 5 ABOUT HERE]

When low economic values are specified for both irrigation water and low flows (which is consistent with the limited economic information available on these use categories at this time), the economic benefits from the Himalayan dams are limited to hydropower and some modest expansion of surface water irrigation in Nepal and India. In this case, the downstream economic consequences of hydropower development for India and Bangladesh are very limited. One implication of this low economic value case is that the benefit-sharing calculus between Nepal and India for hydropower development is in fact much simpler than previously assumed. The economic benefits from Himalayan dams are almost solely due to hydropower generation (95%). If this is the case, India and Nepal should be able to negotiate fairly straightforward power development and trade agreements that also recognize any modest co-benefits in agriculture and flood management.

When low economic value is assigned to irrigation water but high value to environmental flows, Bangladesh, India, and Nepal all gain from the construction of the Himalayan dams. Nepal and India primarily share the benefits of hydropower generation (assuming the excess power produced in Nepal is exported to India), and Bangladesh benefits from low-flow augmentation (increased environmental flows). Therefore, theoretically Bangladesh and India should be willing to share in the costs of building the Himalayan dams. Bangladesh could invest a modest amount to ensure valuable low-flow augmentation, and India could invest primarily as part of a power trade agreement. Alternatively India could pay Nepal more for hydropower received, and Bangladesh could compensate Nepal annually for what would effectively be a “payment for environmental services” agreement.

When high economic value is assigned to irrigation water but low value to environmental flows, about 10-12 billion cubic meters (BCM) would be allocated for new irrigated schemes in Nepal. Given the poor availability of spatially specific data on agricultural productivity in the basin, GEOM assumes that the value of water in agriculture to India and Nepal is the same. If irrigation values are high and differentiated between countries, the economically optimal distribution of these flows to different schemes and riparian countries will change.

Importantly, the scenario in which high values are assigned to both irrigation water and low-flow augmentation reflects the current mindset of most stakeholders in the basin. It is widely assumed that irrigation water and low-flow augmentation are extremely valuable to both Bangladesh and India (Sadoff *et al.*, 2012). Furthermore, many believe that flood control from upstream dams in the Himalaya would be extremely valuable for the whole system (Salman and

Uprety 2002; Huda and Shamsul 2001; Onta 2001). Our background research on the economics of water use in the basin (reviewed above) suggests the opposite. In other words, water has very low productivity in the irrigation schemes in the Ganges plain, such that the benefits from additional supply to Indian agriculture would currently be quite small (though this could change over time).

Our sensitivity analyses also provide new information on the trade-offs between managing water for hydropower, irrigation, flood control and downstream low-flow augmentation in the Ganges basin. There appears to be little trade-off between hydropower production on the one hand, and downstream irrigation and/or low-flow augmentation on the other: hydropower producers and all of the downstream users would like monsoon flows to be smoothed and to see dry season flows increase. In fact, hydropower benefits decrease very little (by about 5%) even when the economic value of water in irrigation and in downstream Bangladesh is assumed to be \$0.1/m^3 (Figure 3). This is because flood waters are stored behind hydropower dams during the flood season, and released gradually over the course of the year, which enhances dry season flows and thus meets the objectives of both water uses.

[FIGURE 3 ABOUT HERE]

That there is little trade-off between hydropower production and downstream water uses simply means that increases in irrigation in India or low-flow augmentation in Bangladesh do not come at the expense of significant amounts of hydropower. Figure 4 illustrates the small trade-off between hydropower production and water uses in irrigation and in Bangladesh for the nine combinations of downstream economic values, and across infrastructure combinations.

[FIGURE 4 ABOUT HERE]

There is clearly a trade-off, however, between the two downstream uses examined, irrigation water usage and low-flow augmentation in Bangladesh, because consumption of water in irrigation in India precludes low-flow augmentation downstream in Bangladesh (Figure 5). If the economic value of low flows in Bangladesh is high, GEOM allocates less water to irrigation, and vice versa. This is consistent with the results presented in Table 5, which shows that increasing infrastructure development can allow both surface water irrigation and low-flow augmentation to increase relative to the status quo. With full infrastructure development (all Nepal dams, existing & proposed), about 35 BCM/yr of additional dry season water would become available, and this amount could be shared among these two competing uses. In reality, of course, actual usage will be determined not only by the relative economic values of water to different users, but also by political, cultural, and social considerations.

[FIGURE 5 ABOUT HERE]

GEOM was also used to test the sensitivity of the results to low- and high-flow years. Running GEOM with the hydrology for wet and dry years revealed, as expected, that the incremental value of hydropower produced by our infrastructures increases with flows in the basin. A “typical” dry year in the Ganges basin corresponds to a reduction in hydropower generation from the three proposed mega dams in Nepal of about 16%, and a reduction of 11% for full infrastructure development. The reduction is lower if all dams are assumed to be built, because the new, smaller dams are spread over a larger spatial area, and the driest years in particular tributaries rarely coincide. On the other hand, the incremental value of dams to irrigation and low flows in Bangladesh increases somewhat (by about 2%) in a dry year, because extra storage provides higher incremental dry season flows when water stress increases. Overall incremental annual benefits thus decrease by 8% to 10% in a typical low-flow year.

In a wet year, hydropower production does not change appreciably compared to an average year (increases by just over 1% with full development), because of the limited storage capacity in the Himalayan dams. The economic benefits of the dams for providing irrigation and low-flow augmentation in such years also decrease compared to an average year (by 8% and 17% for full and 3-dam development scenarios, respectively), because there is less demand for this additional water.

Concluding Remarks

It is often argued that the true benefits from water resource development in international river basins are undermined by a lack of consideration of interdependence in water resource planning. Yet it has not been adequately recognized in the water resources planning literature that overestimation of interdependence may also contribute to lack of progress in cooperation in many systems. Among riparians in the Ganges basin, a widely held belief that dams in Nepal would produce large downstream benefits for India creates expectations of commensurate compensation. This study finds that constructing large dams on the upstream tributaries of the Ganges may in fact have much more limited effects on controlling downstream floods than is thought, and that the benefits of low-flow augmentation delivered by storage infrastructures is currently low (though modernization of irrigation systems in India and Nepal could alter this). A better understanding of actual and prospective effects of interdependence not only changes the calculus of the benefits and costs of different scenarios of infrastructure development, but might also allow riparian countries to move closer to benefit-sharing positions that are mutually acceptable.

Overestimation of the effects of interdependence may also present obstacles for cooperation in international river basins more generally, because overestimation may needlessly aggravate concerns of downstream riparian countries regarding the effects of proposed large upstream infrastructures. In the Ganges basin, for example, Bangladesh has been wary of development initiatives taken by India and Nepal because of their potential impacts on the availability of water during the dry seasons.

On the one hand, our study finds that there is little trade-off between hydropower production and downstream water uses, because increases in irrigation in India or low-flow augmentation in Bangladesh do not come at the expense of significant amounts of hydropower. This suggests that the level of interdependence among different water uses is not as high as is commonly assumed. On the other hand, there is a clear trade-off between irrigation uses in Nepal and India and low flow reaching Bangladesh. A better understanding of the true effects of interdependence between these alternative uses, and of their relative values to participating riparians might help the participating countries to reach more mutually acceptable water-sharing deals and might allay some of the concerns that arise from misperceptions of a high degree of interdependence.

The marginal economic value of water in different uses plays a significant role in determining the nature and degree of interdependence in water resource development in international river basins. A potential obstacle for cooperation in international river basins therefore might be that interdependence is often conceptualized in hydrological and geographical terms. As a result, a riparian country may decide to either downplay or inflate the notion of the interdependence in water resource development projects depending on its own geographical location and position relative to large water resource development projects.

Whatever their origin, misperceptions of the manner and degree of interdependence in transboundary water resources development projects may become serious obstacles to realizing opportunities for cooperation. Our results show that the economic value of different water uses plays an instrumental role not only in shaping the nature of interdependence but also in determining optimal allocations of water resources.

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Tables and Figures

Table 1. Assumptions of irrigation and low-flow values in GEOM

Economic value	**Low**	**Medium**	**High**
Value of low flows to Bangladesh above the Farakka minimum for Jan-May (US$/m^3)	US$0.00/m^3	US$0.05/m^3	US$0.10/m^3
Value of water in irrigation (US$/m^3)	US$0.01/m^3	US$0.05/m^3	US$0.10/m^3

Table 2. Base case parameter assumptions and/or sources for the infrastructure development scenarios

Parameter description	Symbol	Units	Status quo scenario (current conditions)
Hydropower			
Value of hydropower	p_h	US$/kW-h	0.1
Installed power generation capacity of reservoir	H_k^{cap}	MW	Data from various sources (see data source documentation for details)
Minimum operating head in hydropower reservoirs	$\epsilon_{k,t}^{min}$	m	
Tailwater level for reservoirs	tw_k	m	
Storage-to-head conversion factor for reservoirs	ϑ_k	m/mcm	
Storage capacity of reservoirs Dead storage of reservoirs	S_k^{cap} ds_k	mcm mcm	
Agriculture			
Return flow from node *k*	λ_k	None	0.2
Marginal product of water in irrigation	p^{irr}	US$/m^3	0.01
Total irrigable land in area *j*	$land_j$	'000 hA	Existing data (see documentation for details)
Crop-water requirements	$CWR_{j,t}$	mcm/1000 hA	CROPWAT values
Cost of pumping groundwater	c_j^g	US$/m^3	0.02
Floods			
Channel capacities for flood nodes	Q_k^{max}	mcm/month	See notes
Cost of excess flow at node *k*	μ_k	US$/mcm	500
Return fraction of flood spills	z	None	0.2
Low flows			
Value of lean season flows in excess of Farakka treaty minimum to Bangladesh	p^l	US$/m^3	0
Other			
Municipal and industrial demand	$WS_{k,t}$	mcm/month	Existing data
Minimum flow to Calcutta	$Q_{Calcutta}$	mcm/month	1285 (Feb-May) 2935 (otherwise)
Minimum flow to Bangladesh	$Q_{Bang,t}$	mcm/month	1285 (Feb-May) 2570 (otherwise)

Table 3. Range of GEOM outcomes for the infrastructure scenarios

	Status Quo	3 proposed large dams	20 proposed smaller dams	All dams (existing & proposed)
1. Additional hydropower				
a. Production (TW-h/yr)	25.3	45.5	26.4	101
b. Value (billions of US$/yr)	2.5	4.6	2.7	10.1
2. Low-flow augmentation in irrigation				
	83	28	34	121
a. Volume of water (BCM/yr)	N/A	1.4	1.7	2.0
b. Incremental value above status quo (billions of US$/yr)				
3. Low-flow augmentation in Bangladesh				
a. Volume of water (BCM/yr)	N/A	4.8	9.0	15.4
b. Incremental value above status quo (billions of US$/yr)	N/A	0.24	0.45	0.77
4. Reduction in monsoon season flows (%)				
a. Ganges at Farakka	-	7	8	12
b. Kosi at Chatra	-	7	7	14
c. Ghagara d/s Rapti inflow	-	11	6	17
d. Gandak at India/Nepal border	-	1	22	20
5. Infrastructure costs				
a. Capital cost (billions of $US)		15.3	19.1	34.4
b. Annualized capital cost (billions of $US/yr)		0.8	1.0	1.9

Note: Assumes that the marginal value of additional water in irrigation and that the marginal value of additional low flows in Bangladesh are both US$0.05/$m^3$. Annualized capital costs are calculated by assuming a 5% discount rate and 50-year time horizon.

Table 4. Percent reductions in peak flow in the Ganges main stem and major tributaries resulting from the infrastructure scenarios

		Infrastructure scenario		
Hydrology	**River**	**+3 dams**	**+ Small Dams**	**+ All dams**
Dry year	Kosi	11	11	22
	Ghagara	18	6	22
	Gandak	1	27	27
	Ganges main stem	6	8	11
Average year	Kosi	7	7	14
	Ghagara	11	6	17
	Gandak	1	22	20
	Ganges main stem	7	8	12
Wet year	Kosi	6	6	9
	Ghagara	11	8	15
	Gandak	1	24	24
	Ganges main stem	4	6	9

Table 5. Nine cases of rrrigation and low-flow outcomes for different water values with full infrastructure development

Value of irrigation water ($/m3)	Outcome	Value of low-flow augmentation ($/m3)		
		0.01	0.05	0.10
0.01	Additional surface water irrigation (BCM/yr)	38	0	0
	Additional low flow to Bangladesh (BCM/yr)	6	35	37
0.05	Additional surface water irrigation (BCM/yr)	38	38	25
	Additional low flow to Bangladesh (BCM/yr)	5	16	25
0.10	Additional surface water irrigation (BCM/yr)	38	38	38
	Additional low flow to Bangladesh (BCM/yr)	5	16	19

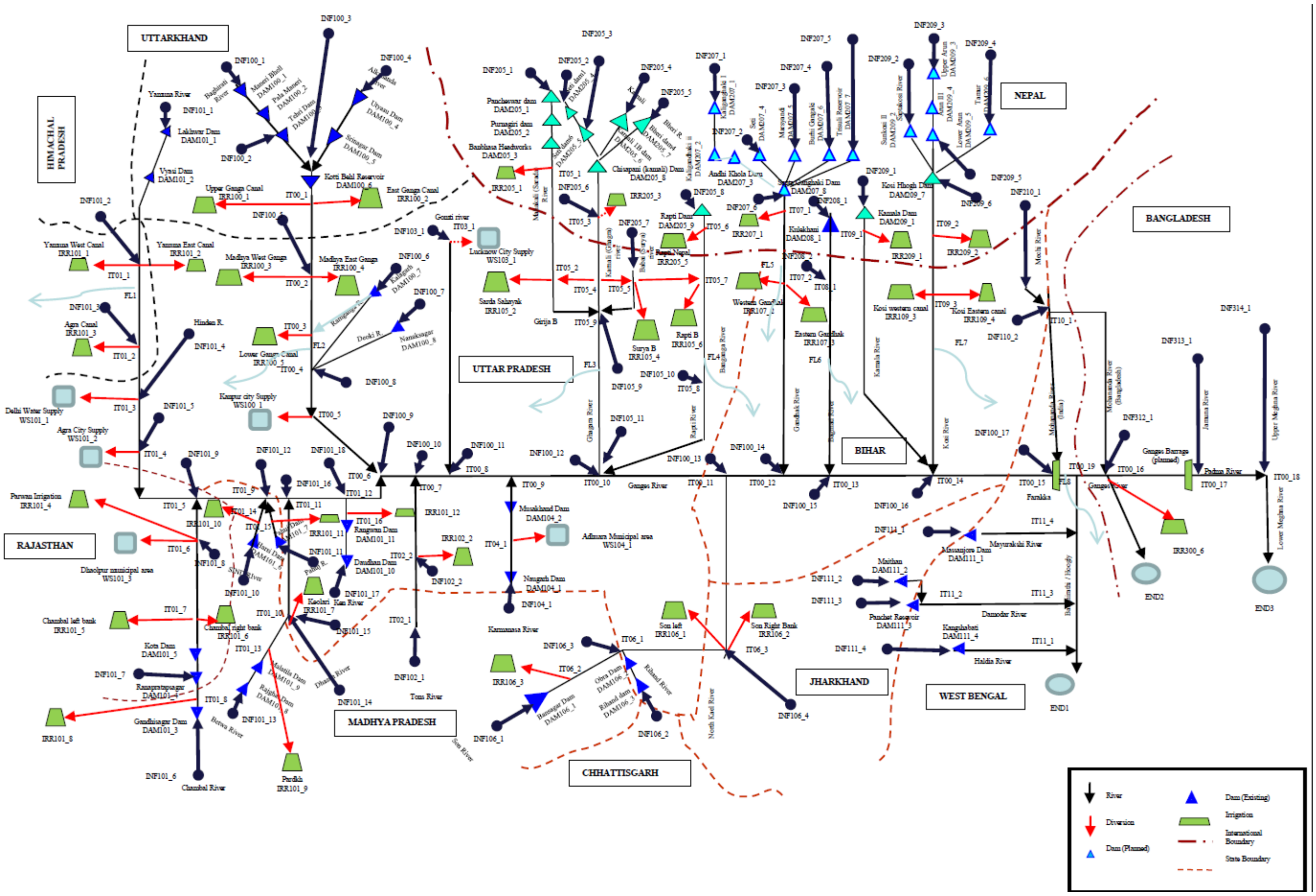
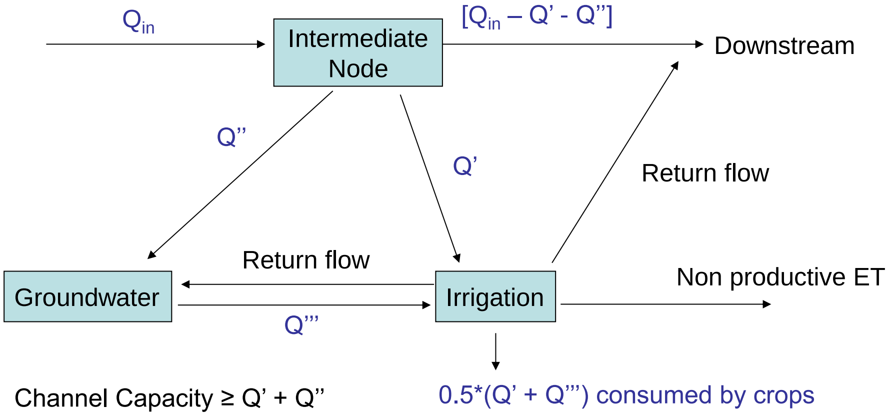
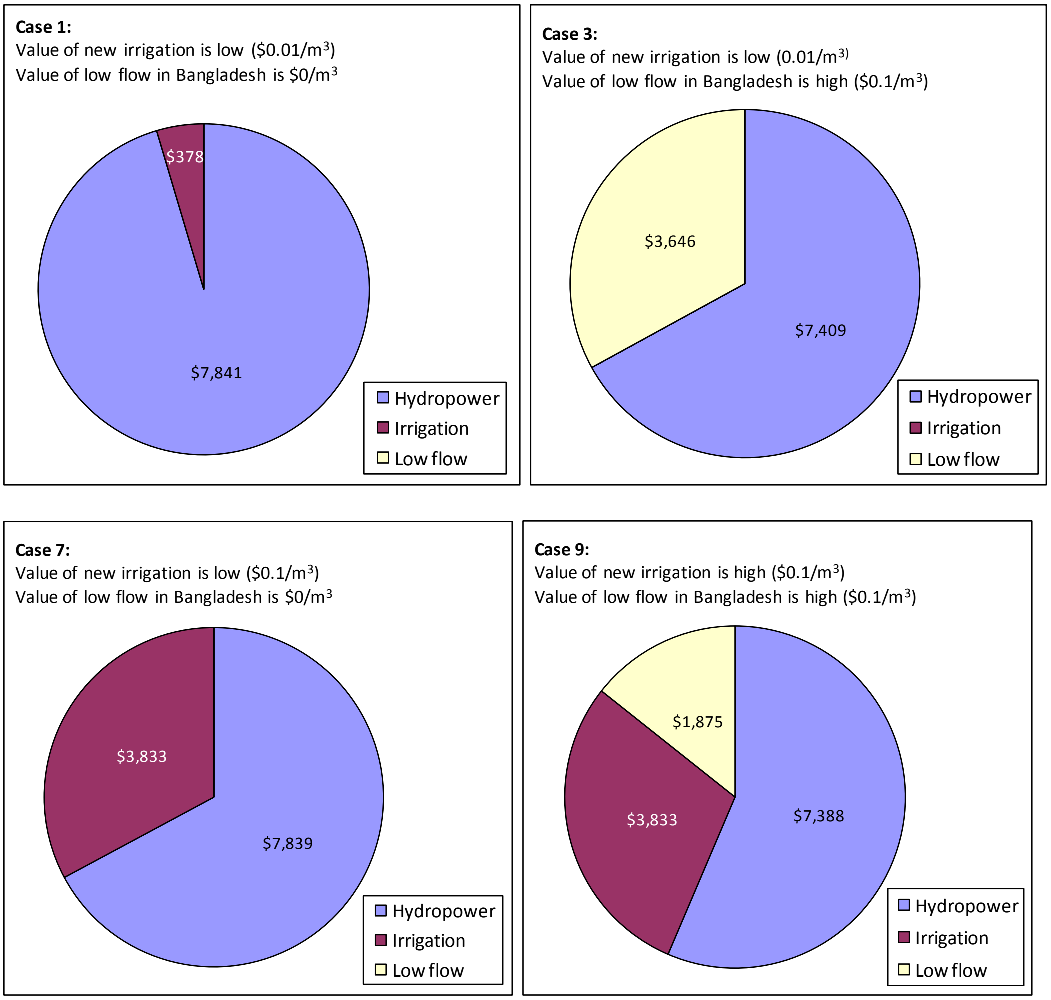


Figure 1. "Simplified" Schematic of the Ganges Basin Models (Water Systems and Economic Optimization Models)



<u>Key Assumptions</u>: 1) Return flows (20% overall)
2) Crop-water requirement (50%)
3) Losses to non-productive evaporation (30%)
4) Zero net change in groundwater storage over year

Figure 2. Water Balance to Irrigation Nodes



Case 1:
Value of new irrigation is low (\$0.01/m^3)
Value of low flow in Bangladesh is \$0/m^3

Case 3:
Value of new irrigation is low (0.01/m$^{3)}$
Value of low flow in Bangladesh is high (\$0.1/m^3)

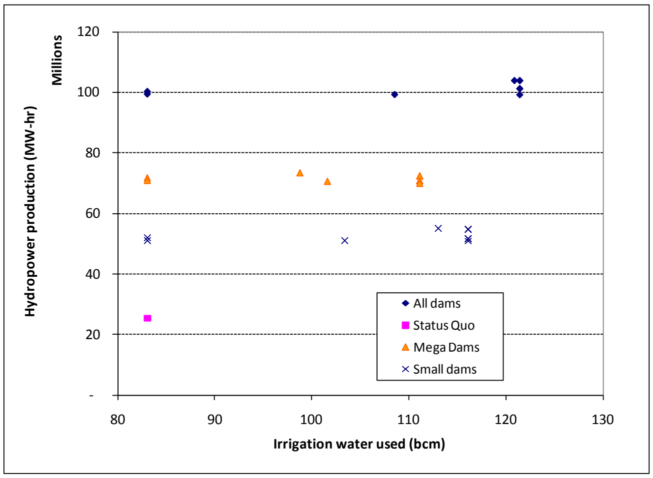
Case 7:
Value of new irrigation is low (\$0.1/m^3)
Value of low flow in Bangladesh is \$0/m^3

Case 9:
Value of new irrigation is high (\$0.1/m^3)
Value of low flow in Bangladesh is high (\$0.1/m^3)

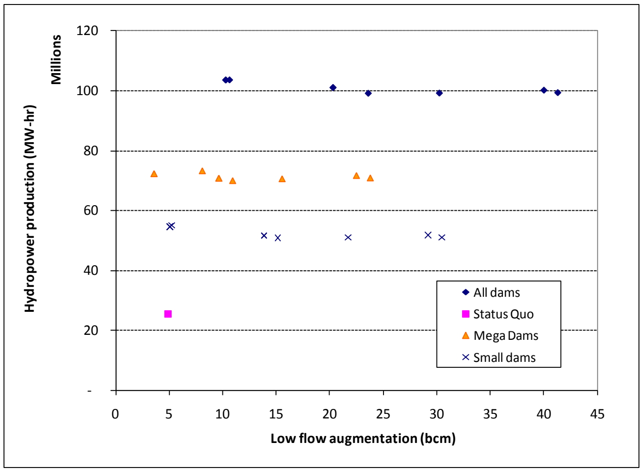
Economic benefits above the status quo by type, for four different low-low, low-high, high-low, and high-high combinations of economic values of additional irrigation in Nepal/India and low flows in Bangladesh

Figure 3. Economic Benefits for Four Scenarios of Irrigation and Low-flow Values

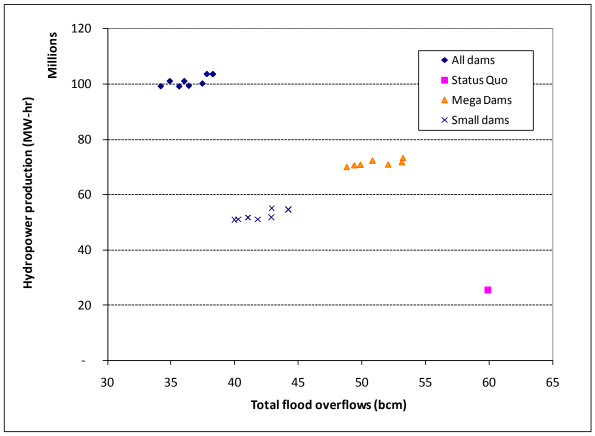
Figure 4: Trade-offs between Water Uses



A



B



C

Trade-offs between Hydropower Production and Irrigation Water Usage (Panel A), Low-flow Augmentation in Bangladesh (Panel B), and Overbank Flows during the Flood Season (Panel C)

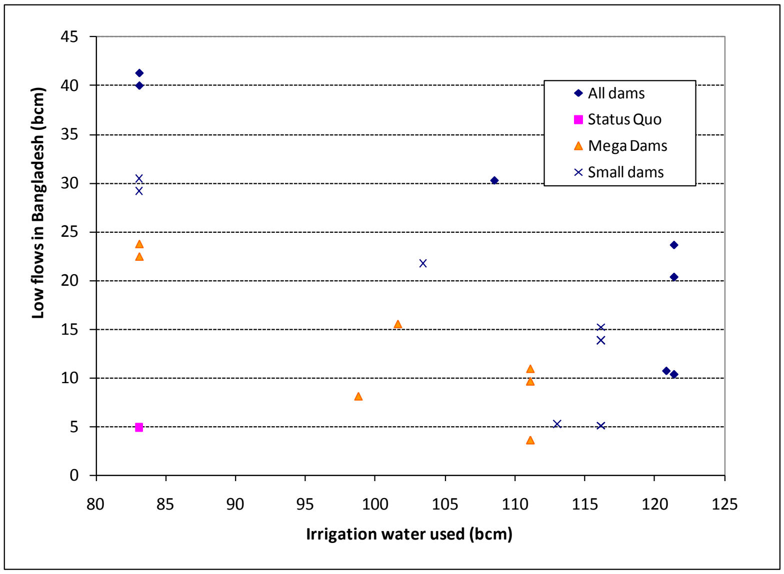


Figure 5. Trade-off between Irrigation Water Usage and Low-flow Augmentation

Appendix A. Ganges Economic Optimization Model (GEOM): Detailed Formulation

The mathematical model is expressed as:

$$Maximize\ Z = \sum_k p^h \cdot H_k^m + \sum_j p^{irr} \cdot I_j^m + p^l \cdot L^b - \sum_k F_k^m - \sum_j c_j^g \cdot G_j^m\ ; \tag{1}$$

subject to the following constraints:

<u>River flow continuity constraints</u>

a. Regular intermediate nodes:

$$Q_{k,t}^{inflow} + Q_{k-1\to k,t} = Q_{k\to k+1,t} - Q_{k\to j,t}^{Irr} - Q_{k,t}^{ws} \tag{2}$$

Storage reservoirs:

$$Q_{k,t}^{inflow} + Q_{k-1\to k,t} + S_{k,t-1} = Q_{k\to k+1,t} + S_{k,t} - Q_{k\to j,t}^{Irr} - Q_{k,t}^{ws} \tag{3}$$

b. Intermediate nodes with flood constraint

$$Q_{k,t}^{inflow} + Q_{k-1\to k,t} = Q_{k\to k+1,t} - Q_{k\to j,t}^{Irr} - Q_{k,t}^{ws} + flood_{k,t} \tag{4}$$

c. Intermediate nodes downstream of flood nodes:

$$Q_{k,t}^{inflow} + Q_{k-1\to k,t} + z \cdot flood_{k-1,t} = Q_{k\to k+1,t} - Q_{k\to j,t}^{Irr} - Q_{k,t}^{ws} \tag{5}$$

d. Farakka:

$$Q_{k,t}^{inflow} + Q_{k-1\to k,t} = Q_{Calcutta,t} + Q_{Bang,t} \tag{6}$$

<u>Irrigation node water balance</u>

a. Channel capacity constraint:

$$Q_{k\to j,t}^{Irr} \le Q_j^{cap} \tag{7}$$

b. Partition of surface flow to field and groundwater (net of canal evaporation ρ_j and canal return flows r_j):

$$Q_{j,t}^{Irr} + Q_{j,t}^{Gw} = \left(1 - r_j\right) \cdot Q_{k\to j,t}^{Irr} \tag{8}$$

<u>Groundwater storage assumptions</u>

a. Groundwater storage balance $S_{j,t}^{Gw}$ at time t:

$$S_{j,t}^{Gw} = S_{j,t-1}^{Gw} + Q_{j,t}^{Gw} - Q_{j,t}^{Pump} \tag{9}$$

b. Groundwater end storage requirement:

$$S^{Gw}_{j,t=0} = S^{Gw}_{j,t=12} = \Delta \qquad (10)$$

Irrigation water usage

a. Flow to surface water schemes, including recharge and non-productive evaporation, and net of return flows:

$$Q^{Irr}_{k\rightarrow j,t} = \rho_j \cdot (1 - r_j) \cdot CWR_{j,t} \cdot A_j \qquad (11)$$

b. Crop-water requirement for irrigation schemes:

$$Q^{Irr}_{j,t} + Q^{Pump}_{j,t} = CWR_{j,t} \cdot A_j \qquad (12)$$

Annual amount of recharge pumped to node *j* from groundwater (in millions of m^3)

$$G^m_j = \sum_t Q^{Pump}_{j,t} \qquad (13)$$

Land constraint

$$A_j \leq land_j \qquad (14)$$

Annual volume of irrigation water consumed at node *j* (in millions of m^3)

$$I^m_j = \sum_t CWR_{j,t} \cdot A_j \qquad (15)$$

Hydropower generation

a. Annual power generation in project at node *k*, in state/country *m*

H^m_k = annual hydropower generated in project at node *k* (in GW-h/yr)

$$= \varphi \cdot \sum_t \epsilon^{net}_{k,t} \cdot R_{k,t} \text{ and} \qquad (16)$$

b. Net head in hydropower reservoir at node *k* in month *t* (in meters)

$$\epsilon^{net}_{k,t} = \left[\epsilon^{min}_{k,t} + \theta_k \cdot (S_{k,t} - ds_k)\right] - tw_k \qquad (17)$$

c. Installed hydropower capacity constraint

$$0 \leq H_{k,t} \leq H^{cap}_k \qquad (18)$$

Reservoir storage constraints

a. Live storage capacity:

$$ds_k \leq S_{k,t} \leq S^{cap}_k \qquad (19)$$

b. End storage constraint:

$$S_{k,t=0} = S_{k,t=12} \qquad (20)$$

Flood damage penalty

Total annual penalty (cost) F^m_k of exceeding channel capacities at node *k*, in state/country *m* (US$)

$$F^m_k = \mu_k \cdot \sum_k \sum_t (Q_{k,t} - Q^{max}_k) = \sum_k \sum_t flood_{k,t} \qquad (21)$$

Flood constraint

$$Q_{k,t} \le Q_k^{max} \tag{22}$$

Low-flow constraints

a. General:

$$Q_{k,t} \ge Q_k^{min} \tag{23}$$

b. For Bangladesh:

$$Q_{Bang,t} \ge \; Q_{Bang,t}^{min} \tag{24}$$

c. Supplemental lean season flows to Bangladesh above Farakka minimum

(in millions of m^3):

$$L^b = \sum_{t=1}^{5}(Q_{Bang,t} - \; Q_{Bang,t}^{min}) \tag{25}$$

Satisfy all municipal and industrial water demands

$$Q_{k,t}^{ws} \le (1-\lambda_k) \cdot WS_{k,t} \tag{26}$$

Non-negativity constraints

$$Q_{k-1\to k,t}, Q_{k\to k+1,t}, Q_{k\to j,t}^{Irr}, flood_{k,t}, R_{k,t}, S_{k,t}, S_{j,t}^{Gw}, Q_{j,t}^{Gw}, A_j \; \ge 0 \tag{27}$$

where the decision variables are:

$Q_{k,t}^{inflow}$ = local runoff into node *k* in month *t* (mcm);

$Q_{k-1\to k,t}$ = flow from all connected upstream nodes *k-1* to node *k* (mcm);

$Q_{k\to k+1,t}$ = flow to all downstream node(s) *k+1* from node *k* (mcm);

$Q_{k\to j,t}^{Irr}$ = flow to irrigation area *j* from node *k* in month *t* (mcm);

$Q_{j,t}^{Irr}$ = volume of surface water satisfying crop-water requirements in area *j* at time *t* (mcm);

$Q_{j,t}^{Pump}$ = water pumped from groundwater onto fields in irrigation area *j* at time *t*;

$Q_{j,t}^{Gw}$ = volume of recharge into groundwater below irrigation scheme *j* in month *t* (mcm);

$R_{k,t}$ = release from hydropower project *k* in month *t* (mcm);

$Q_{k,t}^{ws}$ = municipal and industrial water demand from node *k* in month *t* (mcm);

$S_{j,t}^{Gw}$ = storage in groundwater at irrigation scheme *j* at the beginning of month t (mcm);

$S_{k,t}$ = storage in reservoir *k* at time *t* (mcm);

A_j = land irrigated in area *j* (in 1000 hA);

$flood_{k,t}$ = flood spill at node *k* (mcm);

and the model parameters are:

p_h = value of hydropower (US\$/kW-h);
p^{irr} = economic value of irrigation water (US\$/m^3);
p^l = economic value of low flows (US\$/m^3);
c_j^g = cost of pumping recharged groundwater in area *j* (US\$/m^3);
$Q_{Calcutta,t}$ = minimum flow towards Calcutta in month *t* (mcm);
$Q_{Bang,t}^{min}$ = minimum flow towards Bangladesh in month *t* (mcm);
Q_j^{cap} = irrigation canal capacity for area *j*;
Q_k^{max} = maximum channel capacity at node *k* (mcm);
Q_k^{min} = minimum flow required at node *k* (mcm);

Δ = initial groundwater storage at irrigation schemes;
S_k^{cap} = storage capacity of reservoir at node *k* (mcm);
$S_{k,t=0}$ = initial storage in reservoir at node *k* (mcm); and
$S_{k,t=12}$ = storage in reservoir at node *k* at the end of the year (mcm);
z = fraction of flood spills returning to the river at node *k*;
ρ_j = adjustment for field irrigation efficiency at area *j* (assumed to be 2, or 50% irrigation delivery efficiency at all irrigation nodes);
r_j = irrigation return flow fraction from area *j* (assumed to be 20% from all areas);
λ_k = return flow from municipal and industrial demand at node *k* (assumed to be 20% from all nodes);
$CWR_{j,t}$ = crop-water requirement for mix in area *j* in month *t* (mcm/1000 hA);
$land_j$ = total irrigable land in area *j* (thousands of hA);
$\epsilon_{k,t}^{min}$ = minimum operating head in hydropower reservoir at node *k* (m);
φ = unit conversion constant = $2.41 \cdot 10^3$ (kg /s^2-mcm) (assumes turbine efficiency is 0.9);
ϑ_k = storage-to-head conversion factor for reservoir *k* (m/mcm; assumed to be linear);
ds_k = dead storage in reservoir *k* (mcm);
tw_k = tailwater level for reservoir *k* (m);
H_k^{cap} = installed power generation capacity of reservoir at node *k* (MW);
μ_k = cost of excess flow at node *k* (US\$/mcm); and
$WS_{k,t}$ = municipal and industrial demand at node *k* in time *t* (mcm).

The model uses a monthly time step *t* and determines the value of the decision variables $R_{k,t}$ (release from reservoir *k*), $S_{k,t=0}$ (initial storage in reservoir *k*), $S_{k,t}$ (storage in reservoir *k*), $S_{j,t}^{Gw}$ (storage in groundwater under irrigation area *j*), $Q_{k\rightarrow j,t}^{Irr}$ (withdrawal for irrigation from node *k*), $Q_{j,t}^{Gw}$ (volume of groundwater pumped out for irrigation in area *j*), A_j (land irrigated in area *j*), $flood_{k,t}$ (flood spill from node *k*), that yield the highest outcome of the objective function *Z.* The constraints ensure conservation of water (continuity) at the different types of nodes, restrict storage and hydropower generation capacity in reservoirs according to dam design features, force withdrawals of irrigation water to be consistent with crop-water requirements and land constraints, and require satisfaction of low-flow and urban water supply requirements. Return flows from irrigation and municipal and industrial water supplies are assumed to be 20% (i.e., λ_k = 0.2 for all k); similarly the return flows from all irrigation schemes are assumed to be 0.2. There is also a requirement that reservoirs (including those for groundwater) end the year at the same level as where they began, though the optimal initial level for each surface water reservoir is determined by the model (intial groundwater storage levels are fixed). The model can be solved on a personal computer with the General Algebraic Modeling System (GAMS), using the Nonlinear Programming MINOS solver.

Appendix B. Ganges Economic Optimization Model (GEOM): Details of Data Sources

A. Inflow data

As stated in the Methods section, GEOM includes 77 nodes that receive inflows from local catchments. The flows were simulated using a NAM rainfall-runoff model developed at the Institute of Water Modeling (IWM) in Bangladesh. The model uses a Digital Elevation Model (DEM) that was developed from land-level data from SRTM90 from the Consultative Group for International Agriculture Research (CGIAR). The rainfall-runoff model was calibrated using a combination of sources: satellite precipitation data (TRMM; data are missing for 2003) and rain gauge data (Department of Hydrology and Meteorology, Kathmandu); Indian Meteorological Department (online); and daily hydrological flow data for tributaries in Nepal (Department of Hydrology and Meteorology, Kathmandu). Snowmelt in the Himalaya was simulated using the degree-day method. Hydrological flow data for the Indian tributaries and the Ganges in India are not publically available. The rainfall-runoff model could therefore not be fully calibrated for India. The data used are for the period 1998-2008.

IWM already had detailed calibrated NAM rainfall-runoff models for Bangladesh (meteorological data from the Bangladesh Water Development Board), which were used without modification.

Inflows from the IWM model were aggregated to a monthly time step and grouped according to GEOM'S inflow nodes. For the Brahmaputra and Meghna basins, over which the rainfall-runoff model has not been calibrated carefully, runoff based on historical inflows to the Padma and Lower Meghna (where these rivers join with the Ganges in Bangladesh) were used instead of simulated runoff. GEOM can be run using any of the available years of inflows, which are stored in the spreadsheetIWM_Inflows_Feb_2010.xls.

B. Reservoir data

Data on existing and potential dams and associated reservoirs have been collected from a variety of sources. Much of the data on existing dams in India comes from the National Register of Large Dams (Central Water Commission, 2009). These data have been supplemented with information from sources such as *Hydrology and Water Resources of India* (Jain *et al.*, 2007) and various online sources including Departments of Irrigation for individual Indian states (listed below, at Agriculture) and, for the Hooghly–Damodar system, from the Damodar Valley Corporation website (http://www.dvcindia.org/index.htm); these cover existing and potential projects. The sources for different types of information have been identified more clearly in the spreadsheet Modeling_Database.xls.

For Nepal, the data on potential projects are primarily from three sources: the National Water Plan for Nepal (Singh, 2003), the National Electricity Authority's listing of potential large projects exceeding 100MW (Nepal Electricity Authority, 2008), and the Nepal Hydropower Database (Nepal Hydropower Association, 2009).

There are no feasible surface water storage projects in Bangladesh.

C. Agricultural data

1. Surface water irrigated command areas

The quality of the data on surface water irrigation schemes is inconsistent, with the largest problems having to do with information on India. Due to the insufficiency of reliable water supply, there is a large gap between the official developed potential published by the Government of India and the actual area irrigated using surface water, which varies seasonally and annually. In GEOM we have tried to reflect the developed potential area using the land constraint and to allow the model to irrigate as much of the land as it can to grow a particular mix of crops (see below).

For India, the developed potential by state was obtained from several sources: Indiastat data from the National Irrigation Census of the Ministry of Water Resources and work by Narayanmoorthy (2006). An attempt was then made to allocate this potential among the different irrigation schemes in the model, taking into account information obtained from the existing canal capacities (provided by IWM, spreadsheet IWM_Existing_Diversion_Capacity.xls; data from various sources) and cross-checked against online information from the following state Water Resources or Irrigation departments:

- Jharkhand: http://www.jharkhand.gov.in/new_depts/water/water_fr.html
- Madhya Pradesh: http://www.mp.gov.in/wrd/
- Uttar Pradesh: http://irrigation.up.nic.in/diversion_projects.htm
- West Bengal: http://www.wbgov.com/portal/banglarmukh/Government/Departments/DepartmentListPortletWindow?action=e&windowstate=normal&mode=view

The following state agriculture department web sites did not provide reliable data:

- Bihar: http://wrd.bih.nic.in/
- Haryana: http://hid.gov.in/
- Himalchal Pradesh: http://hpiph.org/
- Rajasthan: http://waterresources.rajasthan.gov.in/2irrig.htm

The India data is summarized in the spreadsheet Land Constraints Irrigation.xls.

For Bangladesh, the relevant irrigation schemes are in the Ganges Dependent Area; data were obtained from the Institute for Water Modeling in Dhaka (see Irrigation_projects_OGDA.doc).

For Nepal, the data on potential irrigated area come from a recent district survey of agriculture and irrigation potential (Center for Engineering Research and Development, 2007). The data were roughly aggregated into basin-level irrigation potential, to correspond with the schemes in the model. Tthese data and calculations are summarized in the spreadsheet Land Constraints Irrigation.xls.

2. Crop mix

   For India, the crop mix data were obtained from Indiastat and are available by district. We used the state-level averages (see file India State District irrigated area by crop.xls). Data were not available for Jharkhand state; the years selected are 2005-6 for most states except Uttar Pradesh (2003-4). Only 3-5 major crops were put into the crop mix for each state.

   For Bangladesh, the data on irrigated crops by area are for 2002-3 and were obtained from the Bangladesh Bureau of Statistics Agriculture Wing (see file BBS 1979_2003 Irrigated crops area.xls). We also have data for other cropping years going back to 1979-80. The crops are *Aus, Aman,* and *Boro* rice; wheat, potato, vegetable; and other, comprised of other cereals, pulses, oil seeds, sugarcane, cotton, and any other minor crops.

   For Nepal, data on the crop mix were taken from the Kosi Master Plan without modification.

3. Cropping schedules

   Cropping schedules for India and Bangladesh were obtained from crop planting schedules monitored by the US Department of Agriculture for those countries. See http://www.fas.usda.gov/remote/aus_sas/crop_information/calendars/clndr_jan.htm#India. These data have been downloaded to the file Cropping_schedules.doc.

   Cropping schedules for Nepal have been taken from the Kosi Master Plan without modification.

4. Crop-water requirements

   Crop-water requirements were calculated using the FAO's CROPWAT software. The FAO climate data were obtained from CLIMWAT for meteorological stations nearest the different irrigation schemes in the model. To be conservative, precipitation data for India were then adjusted to reflect the fourth driest of five years of available district-level data (see India Rainfall_data_statedistrict.xls) monthly rainfall rather than average monthly rainfall. For Bangladesh, dependable rainfall was used from an annex to the IWM National Water Management Plan report (see NWMP_annexC_Irrigation.doc). Crop-water requirements were then calculated for each irrigation scheme using the state-level crop mix and schedules obtained above.

D. *Channel capacities*

The channel capacities for seven Ganges tributaries and the main Ganges come from a series of studies on river geomorphology conducted in India. These results are summarized in Table A1.

Table A1. Channel capacities presented in the literature (locations used in GEOM are **bold**)

River	**Location**	**Channel capacity** (mcm/month)	**Source** (year)
Yamuna	**U/s Agra Canal**	**8554**	Jain and Sinha (2003b)
Upper Ganga	Hardwar	15034	Jain and Sinha (2003b)
	Fategarh	**19912**	Roy and Sinha (2007)
	Ankinghat (d/s Garra)	25194	Roy and Sinha (2007)
Ghagara	**D/s Girija Barrage**	**18144**	Jain and Sinha (2003b)
Rapti	**D/s Rapti Barrage**	**6480**	Jain and Sinha (2003b)
Gandak	Dumariaghat	13608	Sinha (1998)
	Triveni	**32400**	
Bagmati	**Dhengbridge**	**2851**	Jain and Sinha (2003a)
	Hayaghat	2255	
Kosi	**Baltara**	**14904**	Sinha (1998)
Main Ganges	Farakka	82944	Jain and Sinha (2003b)

E. Municipal and industrial demands

The municipal and industrial demands for surface water included in the model are currently limited and should be verified (Table A2). There are many large cities along the Ganges, and they probably consume surface water supplies.

Table A2. Municipal and industrial demands in GEOM

Node	**City**	**Monthly demand (mcm)**
WS100_1	Kanpur	5
WS101_1	Delhi	60
WS101_2	Agra	5
WS101_3	Dhaolpur	5
WS103_1	Lucknow	0.5
WS104_1	Adhaura	5