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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.

Keywords: Economic optimization; Ganges; Interdependence; International river basins

Introduction

It is now widely accepted that water resource development in international river basins requires careful consideration of the interdependencies between water withdrawals of users, wastewater discharges and irrigation returns flows, and the operation and construction of different types of infrastructure (Serageldin, 1995; Biswas, 2004). 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. This interdependence may evolve in complex ways over time owing to effects of climate

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change, population increase and economic growth, all of which may increase competition for water resources. Failure to consider interdependence in water resource planning and operation of water resources infrastructure has resulted in project designs that deliver smaller net economic benefits to riparian countries than would be possible from a systems perspective. Failure to account for interdependencies and externalities can make cooperative management of all types of natural resources difficult, 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 mis-specified owing to underestimation of the interdependence involved, it is a misperception that the impact of such interdependencies will always be large. In fact, overestimation of the impact of interdependence among riparian countries in international river basins also may hamper prospects for water resource development and for cooperation, for several reasons. First, overestimating the effects of interdependence can fuel unrealistic expectations among participating countries regarding the magnitude and distribution of the benefits of cooperation. In the Ganges basin, for instance, there is a widely held perception in Nepal that India would benefit substantially, in terms of both flood reduction and water for irrigated agriculture from the construction of large dams in the Himalaya (World Bank, 2012; Sadoff *et al.*, 2013). These anticipated benefits, if overestimated, could in turn create unrealistic expectations among negotiators regarding equitable cost and benefit-sharing arrangements among riparian neighbors along the Ganges.

Second, overestimation of interdependence may cause unjustified anxiety and fear among riparians about making a 'bad' deal in the absence of information about its potential impact. For example, Nepal may be concerned that it lacks the information to estimate the benefits to India and Bangladesh from upstream reservoirs in the Himalaya and will thus not receive its fair share of the benefits from the construction of multipurpose reservoirs on its territory.

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 owing to the perceived trade-offs and the need to take full advantage of opportunities for multipurpose benefits. Opportunities to benefit from relatively simple, straightforward projects may be lost or delayed.

Importantly, many plans for new infrastructure in river basins focus primarily on hydrological and geographical considerations and their physical effects, with insufficient attention paid to the economic value of these physical outcomes (Harou *et al.*, 2009; Jeuland, 2010). Lacking accurate, reliable economic analysis, a riparian country may decide to play down or overstate its interests in international water resource development projects. Thus lack of information about the economic consequences of infrastructure projects located within a water resources system can lead to unrealistic perceptions of the extent of interdependence present in it, 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 benefits of cooperation.

This paper examines the nature and degree of economic interdependence in new and existing water storage projects in the Ganges River basin, 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 release of water from a set of assumed infrastructure facilities. Although there is a general sense that the development of multipurpose water storage infrastructure in the Himalayan region would yield significant economic benefits for riparian countries throughout the basin, there is also an expectation that trade-offs between potential uses for stored water could be very large. There is no common understanding among the riparians about the relative values of hydropower, flood control and dry season flow augmentation outcomes from such projects. Thus the size and distribution of their benefits is a matter of significant concern and contention among policy makers in India, Nepal and Bangladesh.

Our research focused on three questions: (1) What are the relative magnitudes of the economic benefits from hydropower, flood control and low-flow augmentation from water resource development in the Ganges? (2) Are there significant economic trade-offs from hydropower, flood control and low-flow augmentation resulting from water resource development in the Ganges? (3) How sensitive are the sizes of hydropower, flood control and low-flow augmentation outcomes to varying assumptions about their relative economic values and what are the trade-offs between them?

How we addressed these questions through applications of the GEOM and what the results revealed are described in the following discussion. After a review of background information, we present a detailed mathematical description of the GEOM. We then report results and conclusions.

The analysis detailed below finds that the potential gross economic benefits[1] of new hydropower generation from developing the full suite of new hydropower investments described could reach US$7–8 billion annually. This is significantly greater than the current hydropower benefits produced in the Ganges basin (about US$2.5 billion). We also find that the economic trade-offs from hydropower, low-flow augmentation and flood control objectives are very modest. Our findings also show that 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 value: if the economic value of low flows in Bangladesh is high, the GEOM allocates less water to India for irrigation and vice versa.

Our findings have several significant implications for improving the prospects of cooperation between riparian countries in the Ganges basin. First, our finding that construction of large dams upstream in Nepal would have a limited effect on flood control downstream and would be of limited benefit to irrigated agriculture in India given present conditions, may prompt both Nepal and India to concentrate on jointly developing dams for hydropower generation instead of seeking elusive deals designed to take full account of multipurpose benefits. Second, the fact that there is little trade-off between hydropower production and downstream water use means that increases in irrigation in India or low-flow augmentation in Bangladesh do not come at the expense of significant amounts of hydropower, that is, 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 foreclose their own development options. Third, the riparians can utilize economic analysis to understand the nature of interdependency in this system better and to develop a common and shared understanding of the benefits from Ganges basin cooperation.

[1] All benefit numbers are gross benefits; capital costs (total and annualized) in Table 3 are for reference relative to these benefits.

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 paths in the Ganges basin and of the distribution of the benefits they deliver to the affected riparian countries (Rogers, 1969, 1993; Bhaduri & Barbier, 2003). 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 (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 joint financing of 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 quite 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 & 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; Verghese, 1999; Iyer, 2003). 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)[2]. 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 to the Ganges 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 non-existent and

[2] 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.

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 water availability during periods of low flows, but India might still choose to consume that water. In the latter case, a 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).

There have been several studies of the marginal value of water in agriculture and on the value of hydropower in the Ganges basin and wider region. For example, Rogers *et al*. (1998) obtained values of US$0.02/m^3 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/m^3 in the basin itself. In the wider region, a variety 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 – range from US$0.02 to 0.05/m^3 (Gasser, 1981; Abbie *et al.*, 1982; Molden *et al.*, 2001; Chandrasekaran *et al.*, 2009). Higher estimates, reaching US$0.12/m^3, were obtained for water delivered at the canal level (Molden *et al*., 2001).

The economic literature also contains some estimates related to the value of water quality and flood protection in the Ganges basin. Markandya & Murty (2004) used contingent valuation and revealed preference data to show that the non-use 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 be likely to have very minor effects on water quality in the most polluted reaches in India (World Bank, 2012). A few studies consider the value of, or willingness to pay for, flood protection in the Ganges delta (Thompson & Sultana, 1996; Islam & Braden, 2006; Brouwer *et al.*, 2009), 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). We are aware of no work estimating the value of enhanced low flows for ecosystem service provision in Bangladesh.

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 US$0.08/kW-h (Tongia & Banerjee, 1998; Gautam & Karki, 2004; Limbu & Shrestha, 2004; Banerjee, 2006). Our estimates of the benefits of hydropower production are informed by these estimates.

Methods

The Ganges Economic Optimization Model

The objective of the GEOM is to maximize the total annual economic benefits generated by 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 Ganges Treaty of 1996.

This model is similar to the Nile Economic Optimization Model (NEOM) which was previously developed and used to explore different combinations of infrastructure developments in the Nile basin (Whittington *et al.*, 2005). As with the NEOM, users of the 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 the GEOM focuses exclusively on a specific set of economic outcomes, 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 must also be a central consideration. Ecosystem sustainability, social losses caused by 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 maximizes 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 1996 Ganges Treaty between India and Bangladesh.

The Ganges system is characterized in the 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 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[3]. Most of these reservoir nodes allow storage of inflows up to reservoir capacity, beyond which flows spill downstream. 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 use and influence the peak flows in their tributaries and in the main stem of the Ganges.

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 owing to constraints on water delivery. In the GEOM water is removed at these nodes 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 (the amount of water required per unit of cropped area is estimated based on crop-water requirements for different areas

[3] 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.

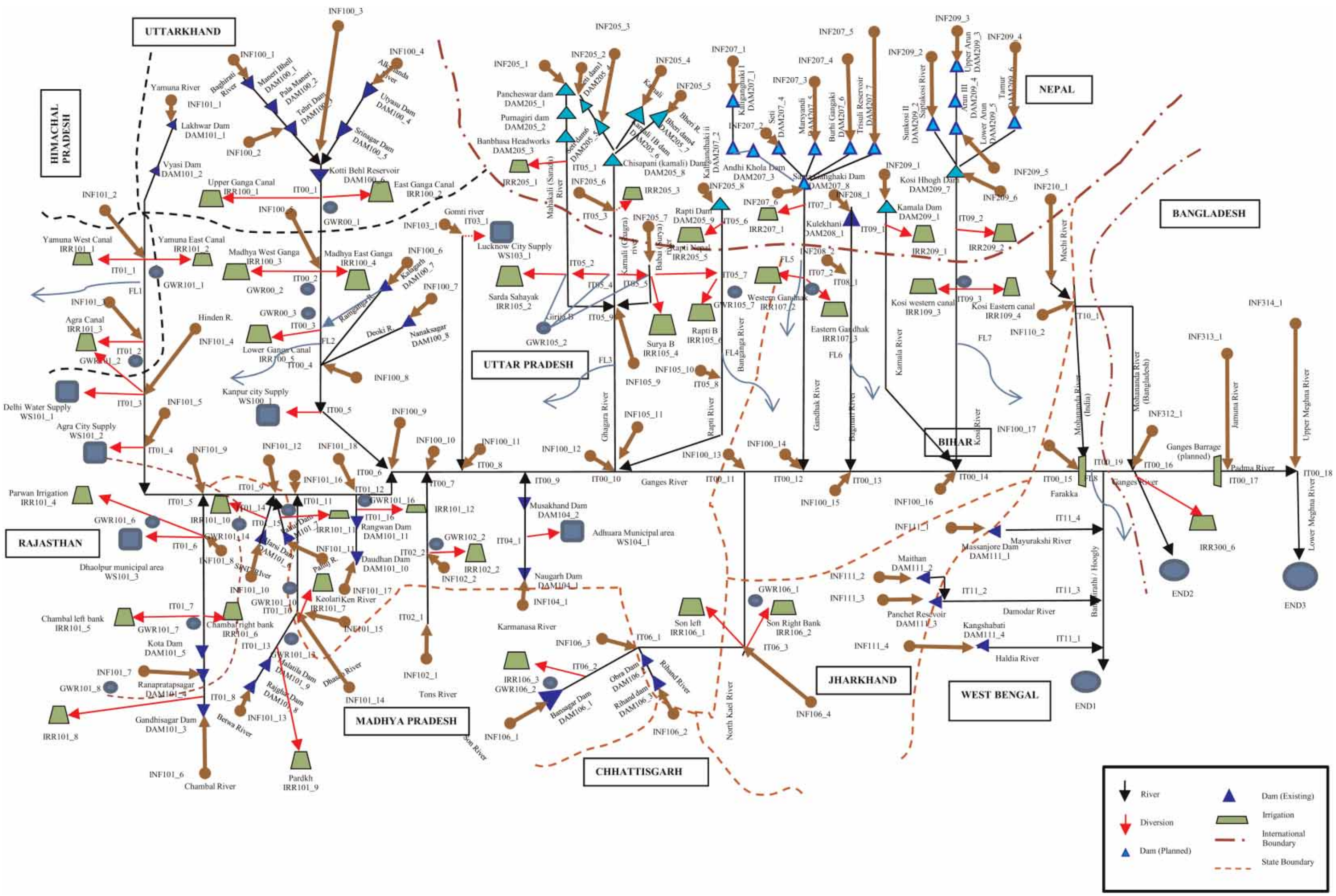

Fig. 1. ‘Simplified’ schematic of the Ganges basin models (water systems and economic optimization models).

obtained from the Food and Agriculture Organization (FAO) CROPWAT model). The second component is for losses from non-productive evapotranspiration (ET) 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 directly to groundwater from local precipitation and infiltration. Taking these four components of the water balance at irrigation areas into consideration, the model attempts to allocate as much surface water as required by these command areas (i.e. it attempts to meet the full crop-water requirement for the areas in question), subject to constraints on water availability and the balancing required by the other economic values included in the objective function.

Figure 2 illustrates the water balance for irrigation nodes, including non-productive 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.

The 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 damage. 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 the 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.

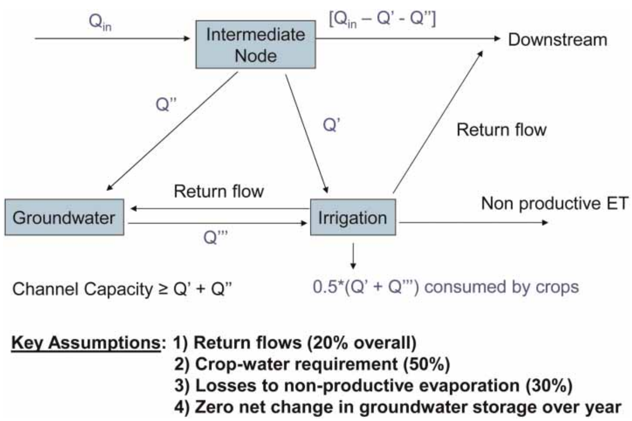

Fig. 2. Water balance for irrigation nodes.

GEOM's mathematical objective function is expressed as:

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

where Z = total economic benefits (in millions of US$); p^{h} = economic value of hydropower (US$/kW-h); H_k^m = annual hydropower generated in project at node k (in GW-h/yr); p^{irr} = economic value of irrigation water (US$/m^3); I_j^m = volume of irrigation water delivered to area j, in state/country m (in millions of m^3); p^{l} = economic value of low flows (US$/m^3); 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 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 the constraints of 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, although the optimal initial levels are determined by the model. A detailed presentation of the mathematical form of these constraints and how the economic outcomes of the objective function are obtained is included in Appendix A (available online at http://www.iwaponline.com/wp/015/003.pdf).

The GEOM also incorporates several other important features. First, technological and demand management interventions (lining of canals, investment 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 demand (FAO, 1998).

Second, the economic value associated with irrigation using Ganges surface 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 (Gasser, 1981; Abbie *et al.*, 1982; Dhawan, 1988; Rogers *et al.*, 1998; Molden *et al.*, 2001). Pumping costs associated with groundwater use (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 (i.e. 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, the GEOM seeks to minimize flood damage. Unfortunately, the damage μ_k associated with overbank spills at different locations is 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 varying the extent of damage caused by peak flows on the optimal water allocations determined by the model (see Appendix A for additional details of this calculation). This allows us to examine whether trade-offs exist between the flood control and hydropower or agriculture objectives, even if we cannot determine the precise cost of flood losses.

Finally, the GEOM includes an additional parameter p^1 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 1996 Ganges Treaty minimum for releases from Farakka, which is the *status quo* for minimum low flows to Bangladesh.

Scenario analysis

The GEOM was used to explore the potential impact 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 (billion cubic meters), compared to an average of 508 BCM over the 10-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 sub-national 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[4]. Then, instead of constraining irrigation water withdrawals according to existing surface water demands in the basin, the model endogenously solves for the theoretical area of land that is irrigable given the specified value of irrigation water and accounting for the other uses of water that generate value in the objective function.

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 of the possible

[4] JICA (1985); BBS (2004); Indiastat (2005).

combinations of low, medium and high economic values of water in irrigation and downstream low-flow augmentation (these values are summarized in Table 1).

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 (available online at http://www.iwaponline.com/wp/015/003.pdf).

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

	Value of low flows to Bangladesh above the Farakka minimum for Jan–May (US$/m^3)		
	Low (0.00 US$/m^3)	Medium (0.05 US$/m^3)	High (0.10 US$/m^3)
Value of water in irrigation (US$/m^3)			
Low (0.01 US$/m^3)	Case 1	Case 2	Case 3
Medium (0.05 US$/m^3)	Case 4	Case 5	Case 6
High (0.10 US$/m^3)	Case 7	Case 8	Case 9

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

Parameter description	Symbol	Units	*Status quo* scenario (current conditions)
Hydropower			
Value of hydropower	p_h	US$/kW-h	0.1
Installed power generation capacity of reservoir	cap	MW	Data from various sources (see data source documentation for details)
Minimum operating head in hydropower reservoirs	min	m	
Tailwater level for reservoirs	tw_k	m	
Storage-to-head conversion factor for reservoirs	θ_k	m/mcm	
Storage capacity of reservoirs	cap	mcm	
Dead storage of reservoirs	ds_k	mcm	
Agriculture			
Return flow from node *k*	λ_k	None	0.2
Marginal product of water in irrigation	p^{irr}	US$/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	g	US$/m^3	0.02
Floods			
Channel capacities for flood nodes	max	mcm/month	See notes
Cost of excess flow at node *k*	μ_k	US$/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	min	mcm/month	1285 (Feb–May) 2935 (otherwise)
Minimum flow to Bangladesh	min	mcm/month	1285 (Feb–May) 2570 (otherwise)

Results

The economic benefits of hydropower from the 23 new dam projects considered in this study are estimated to range from US$3 to 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 US$7 billion to US$8 billion annually above the current hydropower benefits produced in the basin (about US$2.5 billion). These values correspond to the assumption that 25% of power produced could be sold as peaking power in India to yield an average power value of US$0.1/kW-h. If the energy from these dams were not used for peaking purposes, anticipated benefits would 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.

The magnitude of irrigation and low-flow augmentation benefits downstream of the infrastructure projects depend directly on the assumed parameters. In the medium value case (marginal productivity of water in irrigation and low-flow augmentation equal to US$0.05/m^3), these reach US$2.8 billion, but they range from US$0.3 billion (lowest value case) to US$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 (US$0.05) would appear to be much higher than the current very low unit value derived

Table 3. Range of GEOM outcomes for the infrastructure scenarios.

	Status quo	3 proposed large dams	20 proposed smaller dams	All Nepal dams (existing & proposed)
1. Additional hydropower:				
a. Production (TW-h/yr)	25.3	45.5	26.4	101
b. Value (billions US$/yr)	2.5	4.6	2.7	10.1
2. Low-flow augmentation in irrigation:				
a. Volume of water (BCM/yr)	83	28	34	121
b. Incremental value above *status quo* (billions of US$/yr)	N/A	1.4	1.7	2.0
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 US$/yr)	N/A	0.24	0.45	0.77
4. Reduction in monsoon season flows (%):				
a. Ganges at Farakka	–	7	8	12
b. Kosi at Chatra	–	7	7	14
c. Ghagara d/s Rapti inflow	–	11	6	17
d. Gandak at India/Nepal border	–	1	22	20
5. Infrastructure costs:				
a. Capital cost (billions US$)		15.3	19.1	34.4
b. Annualized capital cost (billions 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. Calculations assume a 5% discount rate and a time horizon of 50 years.

from irrigation water in India and Nepal. On the other hand, in the future agricultural modernization and increased returns for 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 on 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 by the construction of new, 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).

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 included in the GEOM 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 the delta (Sunderbunds), 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 of predicting the economic value

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 irrigation and low-flow outcomes for different water values with full infrastructure development.

		Value of low-flow augmentation (US$/m^3)		
Value of irrigation water (US$/m^3)	Outcome	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

of incremental changes for these uses, the precise nature of these trade-offs is difficult to assess at this time.

When low economic values are specified for both irrigation water and low flows (which is consistent with the limited economic information available for 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 when it is received and Bangladesh could pay Nepal annually for what would be effectively a ‘paying for environmental services’ type of agreement.

When high economic value is assigned to irrigation water but low value to environmental flows, about 10–12 BCM would be allocated for new irrigated schemes in India and Nepal. Given the poor availability of spatially specific data on agricultural productivity in the basin, the 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 unit 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. 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 (although this could change over time).

Our sensitivity analyses also provide new information about 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 US$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 downstream water uses.

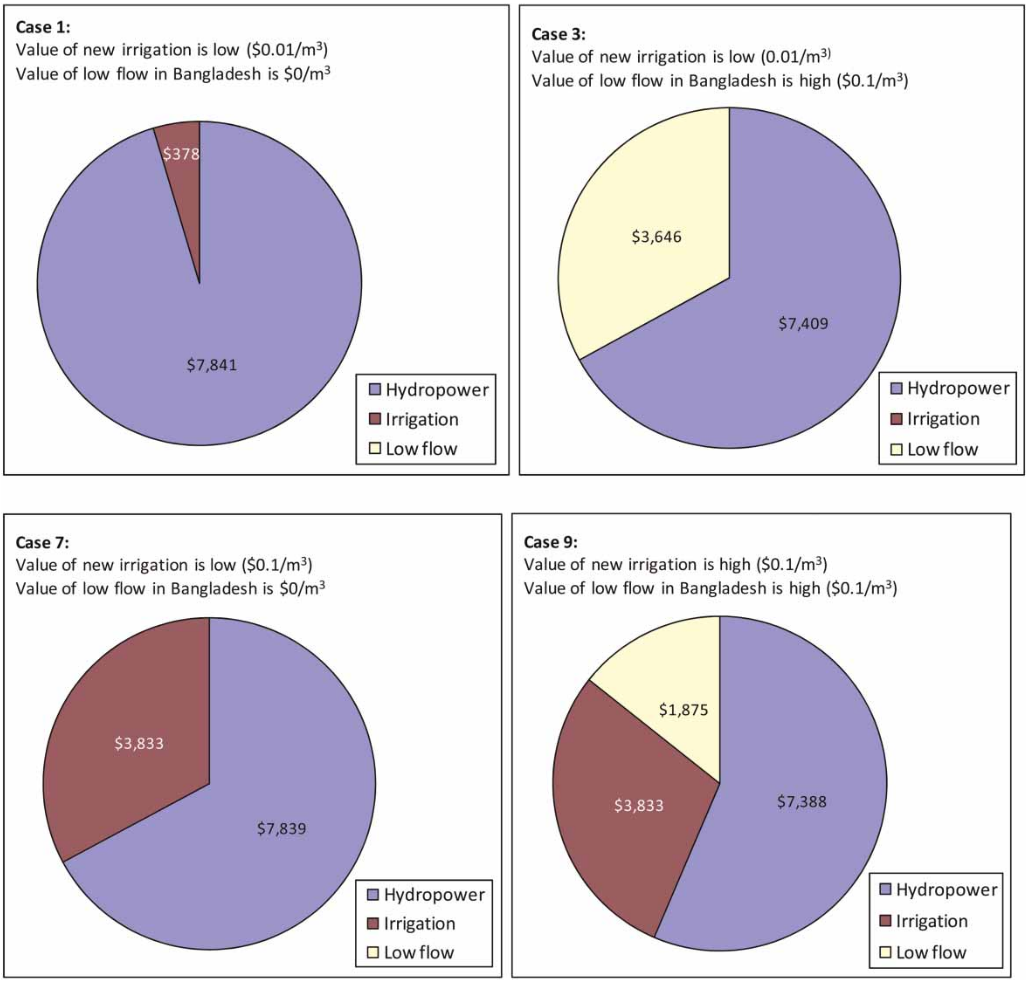

Fig. 3. Economic benefits above the *status quo* by type, for four different low-low (case 1), low-high (case 3), high-low (case 7) and high-high (case 9) combinations of economic values of additional irrigation in Nepal/India and low flows in Bangladesh.

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.

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 show 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 and proposed), about 35 BCM/yr of additional dry season water would become available and this amount could be shared between these two competing downstream 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.

The GEOM was also used to test the sensitivity of the results to low- and high-flow years. Running the 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 8–10% 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 in 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 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. 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 (although modernization of irrigation systems in India and

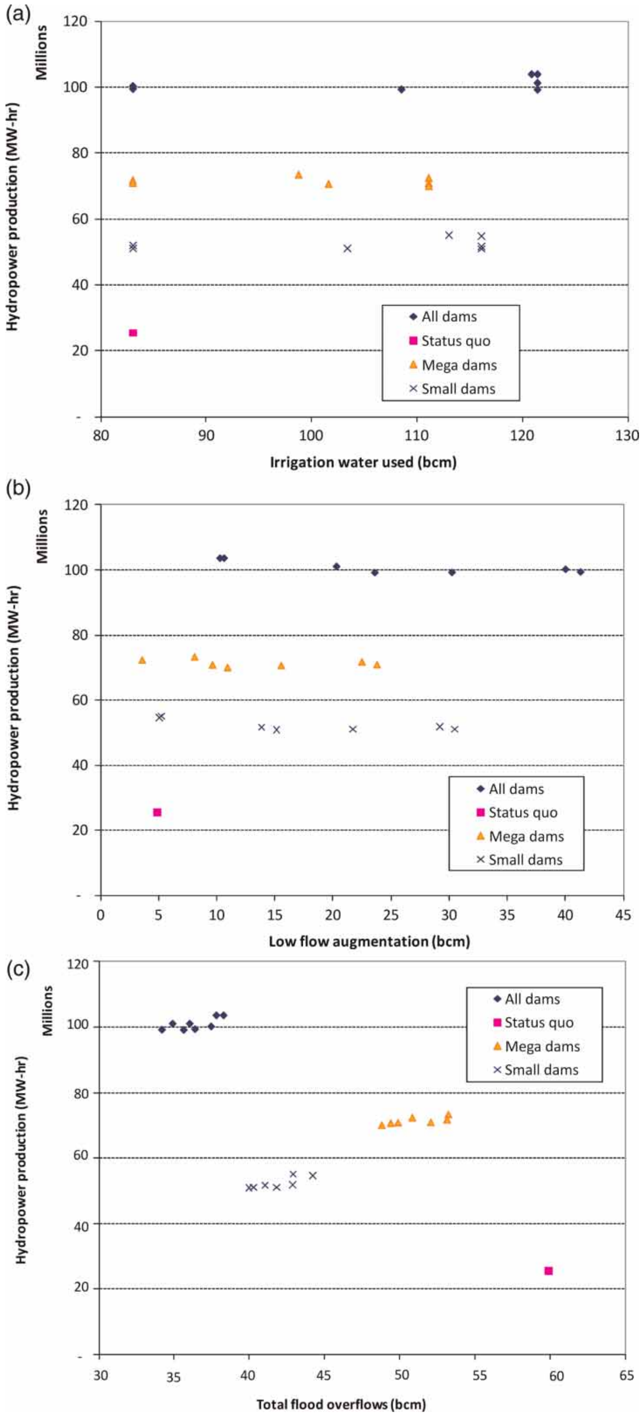

Fig. 4. Trade-offs between hydropower production and irrigation water usage (a), low-flow augmentation in Bangladesh (b) and overbank flows during the flood season (c).

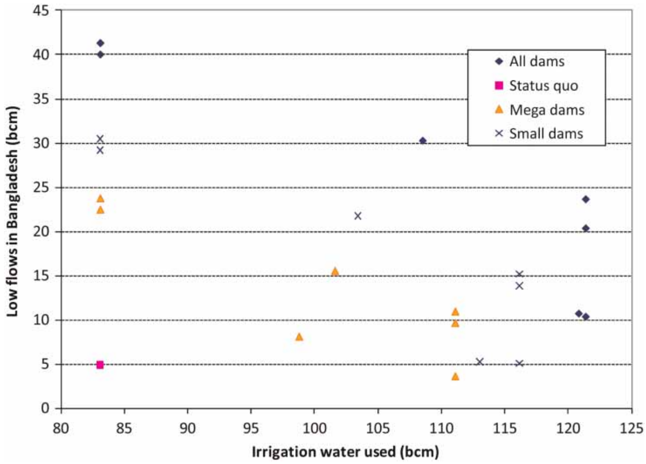

Fig. 5. Trade-off between irrigation water usage and low-flow augmentation.

Nepal could alter this). A better understanding of the 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 rationalize the anxiety and fear 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 impact on the availability of water during the dry season at Farakka. 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 between hydropower and other 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 benefit-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 terms of power asymmetries induced by hydrological locations. As a result, a riparian country may decide either to downplay or to inflate the notion of the interdependence of water resource development projects depending on its position on the river and relative to the sites of large potential water resource development projects.

Whatever their origin, misperceptions of the manner and degree of interdependence in transboundary development projects may become large 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. It is essential to have a realistic understanding of how such economic values affect water allocations and the economic returns from infrastructure investments before assumptions about the nature and implications of interdependence are made.

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