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A critical review of the Ganges Water Sharing arrangement

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Abstract

The 1996 Ganges Water Sharing Treaty was an important breakthrough in solving disputes over sharing Ganges water between India and Bangladesh. This study evaluates cooperation reflected in the Treaty by performing a quantitative analysis on available water sharing data. The study recognized that inaccurate projection of future flow and the obligation of allocating guaranteed 991 m^3/s flows perpetuate the ongoing water sharing conflicts. The provision of guaranteed minimal flow alternately to India and Bangladesh during critical periods leads to frequent occurrences of low-flow events. Results indicated that the Treaty underestimated the impact of climate variability and possibly increasing upstream water abstraction. Statistical analysis of the post-Treaty data (1997–2016) also indicated that 65% of the time Bangladesh did not receive its guaranteed share during critical dry periods with high water demand. It is advised to project the reliable water availability using a combination of modelling and improved observation of river flows. In addition, the condition of minimum guaranteed share should be removed to reduce the frequency of low-flow events in future. Although our analyses show a number of weaknesses, the Treaty could still enhance the future regional cooperation if some adjustments are made to the current terms and conditions.

Keywords: Farakka Barrage; Ganges Water Sharing Treaty; Regional cooperation; Transboundary rivers; Water conflicts

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Introduction

A transboundary river basin represents a combined hydrologic and geographic unit shared by two or more countries. River basins that cross international boundaries account for an estimated 60% of global freshwater flow and are also home to approximately 40% of the global population (McCaffrey, 2003; Giordano *et al.*, 2014). According to the Oregon State University's Transboundary Freshwater Dispute Database (TFDD), 286 transboundary river basins cover almost half of the ice-free land surface on the earth (Petersen-perlman *et al*., 2017). Transboundary water bodies offer precious ecosystem services to humans such as food and energy production, flood mitigation and pollution control. Riparian states often have different needs and divergent views on the ownership, distribution and utilization of transboundary water resources. The growing pressure on freshwater availability, coupled with increasing hydrologic variability due to climate change, leads to higher potential for water-induced conflicts across terrestrial boundaries (De Stefano *et al.*, 2017). Research has shown that the likelihood and intensity of potential transboundary conflicts can best be reduced by regional cooperation along with adequate legal and institutional frameworks, and a joint planning and management approach (Yoffe *et al*., 2003; Dinar *et al.*, 2015).

Climate change could potentially further complicate the transboundary conflicts due to changes in water availability and potentially increased scarcity of freshwater resources in future. The socio-economic disparity as well as power asymmetries between the riparian countries also becomes an influential catalyst to promote hydro-political tensions over transboundary waters (Wolf *et al*., 2003; Zeitoun & Warner, 2006). For instance, overexploitation by an upstream hydro-hegemonic country in absence of transboundary institutional mechanisms can lead to severe water scarcity in downstream countries with potential impacts on ecosystems and livelihoods. Therefore, transboundary water management provides a framework for dialogues and negotiations between riparian countries to overcome such disputes by promoting cooperation (Giordano *et al.*, 2014).

In South Asia, the sensitivity of water conflict gradually increased because of the over-extraction of the rivers due to the growing pressure on water, food and energy (Wolf, 1998). To illustrate the transboundary water interaction processes in South Asia, a classic case would be the conflict in the Ganges–Brahmaputra–Meghna (GBM) basin. The GBM river system is the third largest freshwater outlet to the world's oceans, being exceeded only by the Amazon and the Congo River systems (Chowdhury & Ward, 2004). Within the GBM river system, 54 common rivers cross the border between upstream India and downstream Bangladesh. Only one of these rivers, the Ganges, is subject to a bilateral agreement between the two countries (Nishat & Faisal, 2000).

When India commissioned the Farakka Barrage (just upstream of the India–Bangladesh Border) on the Ganges in 1975, the dry season flow into Bangladesh reduced significantly. This eventually resulted in a dispute over the sharing of the dry season flow between the two countries. After a series of negotiations, India and Bangladesh signed a 30-year Ganges Water Sharing Treaty (referred as 'the Treaty' in this paper) in 1996 to share the dry season flow of the Ganges (GWT, 1996). The Treaty has been operationalized uninterruptedly and has completed 20 years of its 30-year tenure, leaving numerous new challenges and unresolved issues between the riparian countries.

Most of the earlier works on Farakka Barrage disputes and the 1996 Treaty implications have typically been conducted to present the historical and political perspectives, and to critically examine the legal aspects of the mechanisms of implementing the Treaty (Crow *et al*., 1995; Hossain, 1998; Salman & Uprety, 1999; Nishat & Faisal, 2000; Rahaman, 2009; Pandey, 2014; Kawser & Samad, 2016). But these studies did not cover any quantitative analyses of the dry season flows to assess the tangible outcome of the Treaty. Only a few studies have taken various statistical approaches to quantify the impacts of the Farrakka Barrage and the performance of the Treaty on dry season flow availability (Tanzeema & Faisal, 2001; Mirza, 2002; Islam *et al.*, 2013; Gain & Giupponi, 2014; Thomas, 2017). These studies quantifiably recognized that Bangladesh has been frequently deprived of its minimum share during the most critical periods of the dry season. However, these works were more or less limited to piecemeal analyses due to the lack of sufficient hydrological data. Furthermore, most of the studies did not systematically investigate the critical features of the Treaty which led to severe water scarcity in a number of dry years; thus leaving a knowledge gap on the major barriers against the successful implementation of the Treaty.

Thus, a quantitative evaluation of the current Treaty is essential to negotiate further revision and extension of the Treaty. An understanding of future risks related to the new emerging conflicts will also be major concerns for the revision of the Treaty. Therefore, the present study focuses on the current status of the Treaty and explores the outcome of the Treaty provisions using a long-term data set on water availability recorded at Farakka in India and Hardinge Bridge in Bangladesh. The main objective of this paper is to perform a quantitative analysis of the implications of the Treaty by (1) examining its performance on water sharing arrangement during the leanest seasons to evaluate its success (or failure), (2) identifying the critical features of the Treaty that facilitate perpetuation of the ongoing conflicts, (3) evaluating the weaknesses in some of the provisions negotiated in the Treaty that lead to contentious issues on water scarcity, and (4) providing a summary of the major barriers against successful implementation of the Treaty and possible considerations to cope with them during revision of the Treaty.

Farakka Barrage dispute in the Ganges basin

Ganges basin

The Ganges River originates in the Central Himalayas at an altitude of 7,010 m, and extends into the alluvial Gangetic Plains and drains into the Indian Ocean at the Bay of Bengal. The Ganges is a transboundary river, which has a total length of approximately 2,600 km and a total catchment area of about 1,087,000 km^2 (Ahmad & Ahmed, 2003). The river basin spreads across India, Nepal, China and Bangladesh (Figure 1) where India shares the major portion (79%) of the total basin area. In contrast, Bangladesh is the furthest downstream country of the basin and shares only about 4% of the basin area, which nevertheless represents 37% of the total area of Bangladesh (Gain & Giupponi, 2014). The hydrological cycle and water resources of the Ganges basin are governed by the southwest monsoon, characterized by high temperatures, heavy rainfall and strong seasonal variations (Caesar *et al.*, 2015). The region is characterized by flooding in the wet season (June–October) and water scarcity in the dry season (November–May). During the monsoon season there is an abundance of water, but during non-monsoon season lower precipitation causes reduced flow in the basin. The insufficient supply of water in the downstream during the dry season causes significant socio-economic impacts through disruption to the agriculture, fisheries, forestry and navigation of this region.

Farakka Barrage and dispute over water extraction

Unregulated dry season flows in the Ganges were sufficient to meet water requirements in Bangladesh until 1975. The conflict between India and Bangladesh over sharing the Ganges water started when

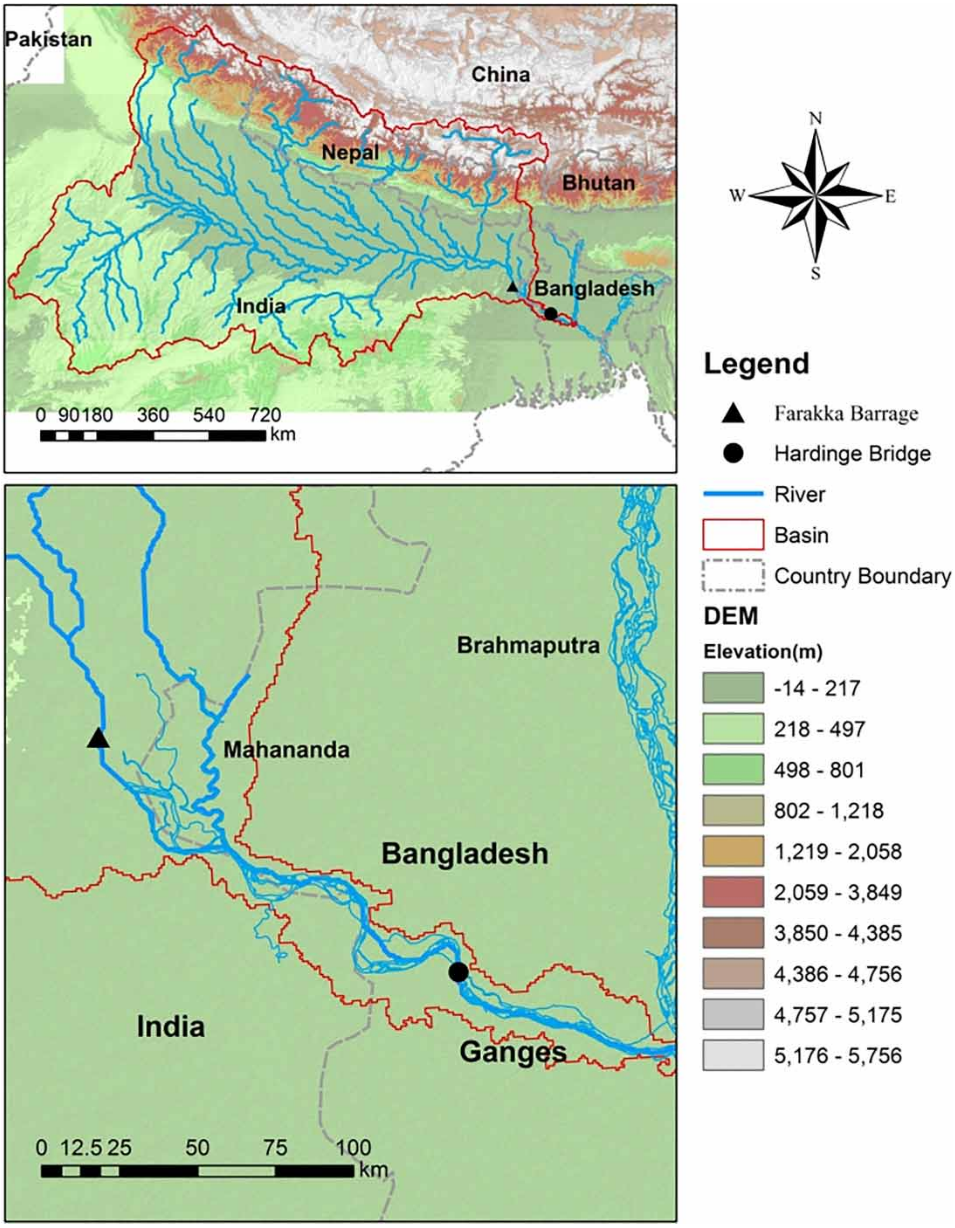

Fig. 1. The Ganges basin and detailed map with location of the Farakka Barrage and the Hardinge Bridge.

India commissioned the Farakka Barrage in 1975 at a location approximately 18 km upstream from the Indo-Bangladesh border (Figure 1) (Mirza, 2002). The barrage is about 2,240 m long and started its operation on April 21, 1975 (Salman & Uprety, 1999). The purpose of the construction of the barrage was to divert 40,000 cusec (equivalent to 1,133 m^3/s) water from the Ganges River to the moribund Hooghly River (a distributary of the Ganges) for maintaining the navigability of the Kolkata Port (Tanzeema & Faisal, 2001). This diversion of flow from the main stem of the Ganges in the dry season changed the hydrology of the river downstream, which significantly affected the riverine ecosystem and biodiversity in Bangladesh.

The Ganges Agreement of 1977

A 5-year agreement was the first major sharing arrangement of the Ganges waters, which was signed in November 1977 soon after India unilaterally carried out water withdrawal from June 1975 to November 1977 (Hossain, 1998). According to the 1977 Agreement, the water would be shared during the dry season from January to May, divided into 10-day periods. A schedule of dry season flows (see *Appendix A* for details, available with the online version of this paper) was established based on 75% availability of flow at Farakka from the recorded historical data between 1948 and 1973. An important feature of the 1977 Agreement was a guarantee clause which ensured Bangladesh received a minimum of 80% of the scheduled flow if actual flow at Farakka dropped to less than 80% of the flow specified in the schedule (Salman & Uprety, 1999).

Memoranda of Understanding in 1983 and 1988

After the expiry of the 1977 Agreement in 1982, India and Bangladesh signed two 'Memoranda of Understanding' (MoU) between 1983 and 1988 with minor adjustments to the 1977 Agreement. The total amount of share between India and Bangladesh remained the same, but the guarantee clause included in the 1977 Agreement was removed from these MoUs (Rahaman, 2009). Between 1989 and 1996, there was no operational mechanism for sharing Ganges waters between the two countries.

The Ganges Water Sharing Treaty 1996

The Ganges Water Sharing Treaty between Bangladesh and India, signed on 12 December 1996 for a period of 30 years (GWT, 1996), was marked as a major footstep towards the conclusion of a longstanding conflict over sharing of the Ganges water. According to the Treaty, the flow at Farakka would be shared based on a unique sharing formula (see *Appendix B* for details, available online) between India and Bangladesh during the dry season (January–May), further divided into fifteen 10-day cycles. The Treaty also sets out the basis through an indicative schedule, calculated by the total average historic flow at Farakka between 1949 and 1988, on which each country's share of water is to be determined (see *Appendix C* for details, available online). The most notable feature of the Treaty is the condition that each country is guaranteed to receive 35,000 cusec (equivalent to 991 m^3/s) of flow in alternate 10-day cycles during the most critical periods between March 11 and May 10.

Comparative analysis between 1977 Agreement and 1996 Treaty

In both the 1977 Agreement and the 1996 Treaty, it was agreed that the quantum of Ganges flow to be released at Farakka and the sharing arrangement would be effective for the fifteen 10-day periods of dry season (January 1 to May 31). However, there were notable differences between some of the critical features of these two agreements such as estimation of flow availability at Farakka, share distribution, sharing arrangement in critical months and guarantee clause for Bangladesh. Table 1 summarizes the significant differences between these two sharing arrangements.

Table 1. Comparison of the features between the 1977 Agreement (1977–1982) and the 1996 Ganges Water Sharing Treaty (1996–2026).

Component	1977 Ganges Agreement	1996 Ganges Water Treaty
Calculation of Indicative flow at Farakka	Considered pre-Farakka (1948–1973) dry season (Jan–May) flows at Farakka. Indicative flows are estimated based on the 75% availability of the historical 10-day average flows.	Considered combination of pre-Farakzka (1949–1974) and post-Farakka (1975–1988) dry season (Jan–May) flows at Farakka. Indicative flows are estimated based on the total historical 10-day average flows.
Sharing arrangement mechanism	Ganges waters would be shared according to an indicative schedule. Any deviated amount from the schedule during a 10-day period would be shared proportionately.	Ganges waters would be shared during a 10-day period based on a sharing formula stipulated in the Annexure – I of the Treaty, irrespective of the indicative schedule.
Sharing in critical months	No such provision	India and Bangladesh each would receive guaranteed 991 m^3/s of water in alternate three 10-day periods during the period March 11 to May 10.
Guarantee clause for Bangladesh	Bangladesh would receive a minimum of 80% of the scheduled flow during extremely low water availability at Farakka.	No such provision. However, during review process if no mutual agreement on necessary adjustment of flows, Bangladesh could obtain at least 90% of scheduled flow.
Protection of upstream flow	No such provision	Upstream countries would protect the indicative 40-year average water availability at Farakka by every effort.
Flow augmentation	Recognized the need of mutual cooperation to develop solutions, and specified clear arrangements for carrying out investigation and studying schemes for augmenting dry season flow.	Recognized the necessity of mutual cooperation only, but did not specify any terms of reference for joint studies to develop long-term solutions to augment dry season flow.

Quantitative analysis of the 1996 Ganges Water Sharing Treaty

Data

All the flow data for this study, in the form of 10-day average flows, were collected from different government organizations of Bangladesh. The historic (1949–1996) 10-day average dry season flow (January–May) data at Farakka (India) and at Hardinge Bridge (Bangladesh) were obtained from the Water Resources Planning Organization (WARPO) and Bangladesh Water Development Board. Furthermore, water sharing data between India and Bangladesh during the 1997–2007 period was also collected from various reports of WARPO. The Joint Rivers Commission (JRC) in Bangladesh has been publishing complete water sharing data between India and Bangladesh on their official website since 2008 (Joint Rivers Commission Bangladesh, 2017). Thus, the data sharing information between 2008 and 2016 were collected from JRC's website. The area-weighted monthly and annual rainfall data for 14 meteorological sub-divisions (which are located within the Ganges basin) of India, available from 1951 to 2014, was downloaded from Open Government Data Platform of India (Government of India, 2017).

Analysis of historical flows at Farakka

The 40-year average indicative schedule of the Treaty was compared with the historical average availability of flows during three periods: pre-Farakka (defined as 1951–1974), post-Farakka (defined as 1975–1996), and post-Treaty (defined as 1997–2016). The average dry season flow for the post-Farakka period (1975–1996) was consistently lower than that of the pre-Farakka period (1949–1974), except for May (Figure 2). It indicates that the indicative flow in the Treaty did not consider the decreasing trend of flows at Farakka during the post-Farakka period.

However, after the Treaty was signed in 1996, the average flow availability during the post-Treaty period (1997–2016) matched the indicative flow availability stipulated in the Treaty. But there were frequent occurrences of flows at Farakka considerably lower than the indicative flows stipulated in the Treaty (Figure 2). Analysis of the flow availability during individual years indicated repeated occurrences of low flow at Farakka during the drier years in the post-Treaty period. Extreme low 10-day average flows at Farakka occurred frequently after 1996, for example, 1372 m^3/s in 1997 (March 21–31), 1487 m^3/s in 2008 (April 11–20), 1465 m^3/s in 2010 (March 21–31) and 1429 m^3/s in 2016 (March 11–20). Such low-flow events during different individual years indicate that obtaining the indicative flows at Farakka is always uncertain, and depends on the climate variability in the basin.

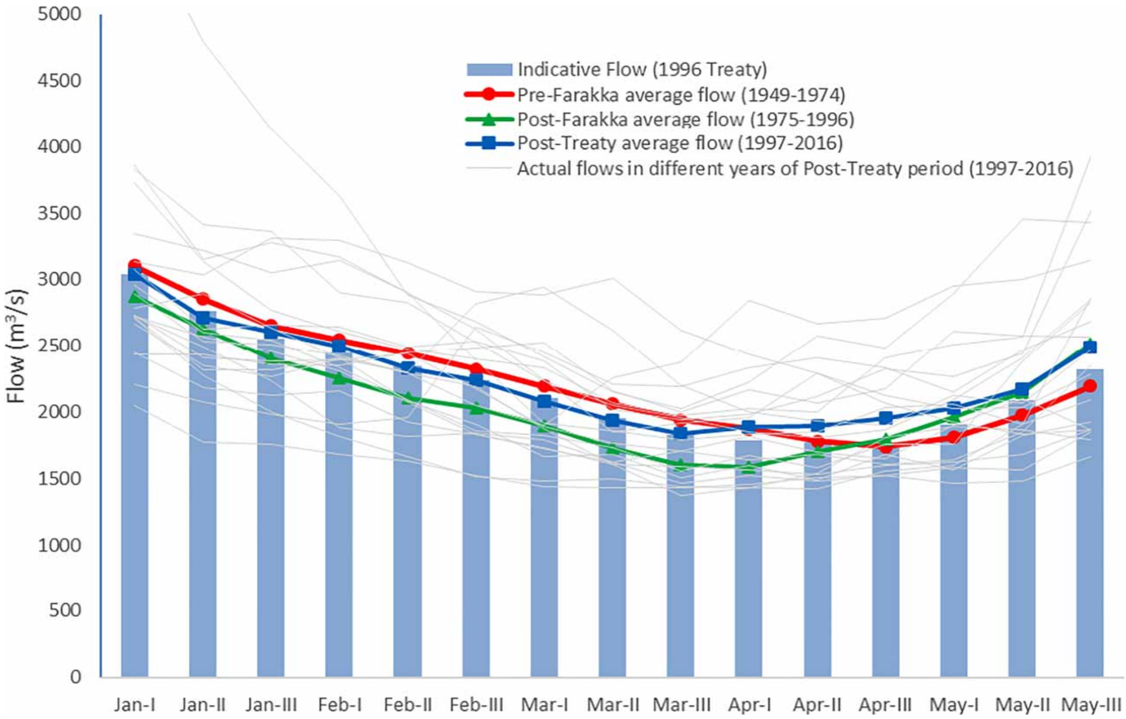

Fig. 2. Comparison of the average dry season (Jan–May) flows of the Ganges at Farakka during pre-Farakka (1949–1974), post-Farakka (1975–1996), post-Treaty (1997–2016) periods and the actual yearly flows during post-Treaty (1997–2016) period. Shaded bars show the indicative flows of the Treaty.

Analysis of basin rainfall and streamflow trends

Since the availability of Ganges flow at Farakka depends on the climatic conditions of the basin, it is necessary to analyse basin rainfall and their trends for different time-scales. The area-weighted monthly rainfall data for 14 meteorological sub-divisions of India was used to perform the non-parametric trends analysis (Mann–Kendal). Figure 3 shows Boxplots of dry season (January–May) & annual (January–December) precipitation over the Ganges basin, and dry season flow of the Ganges at Farakka and Hardinge Bridge for different time slices.

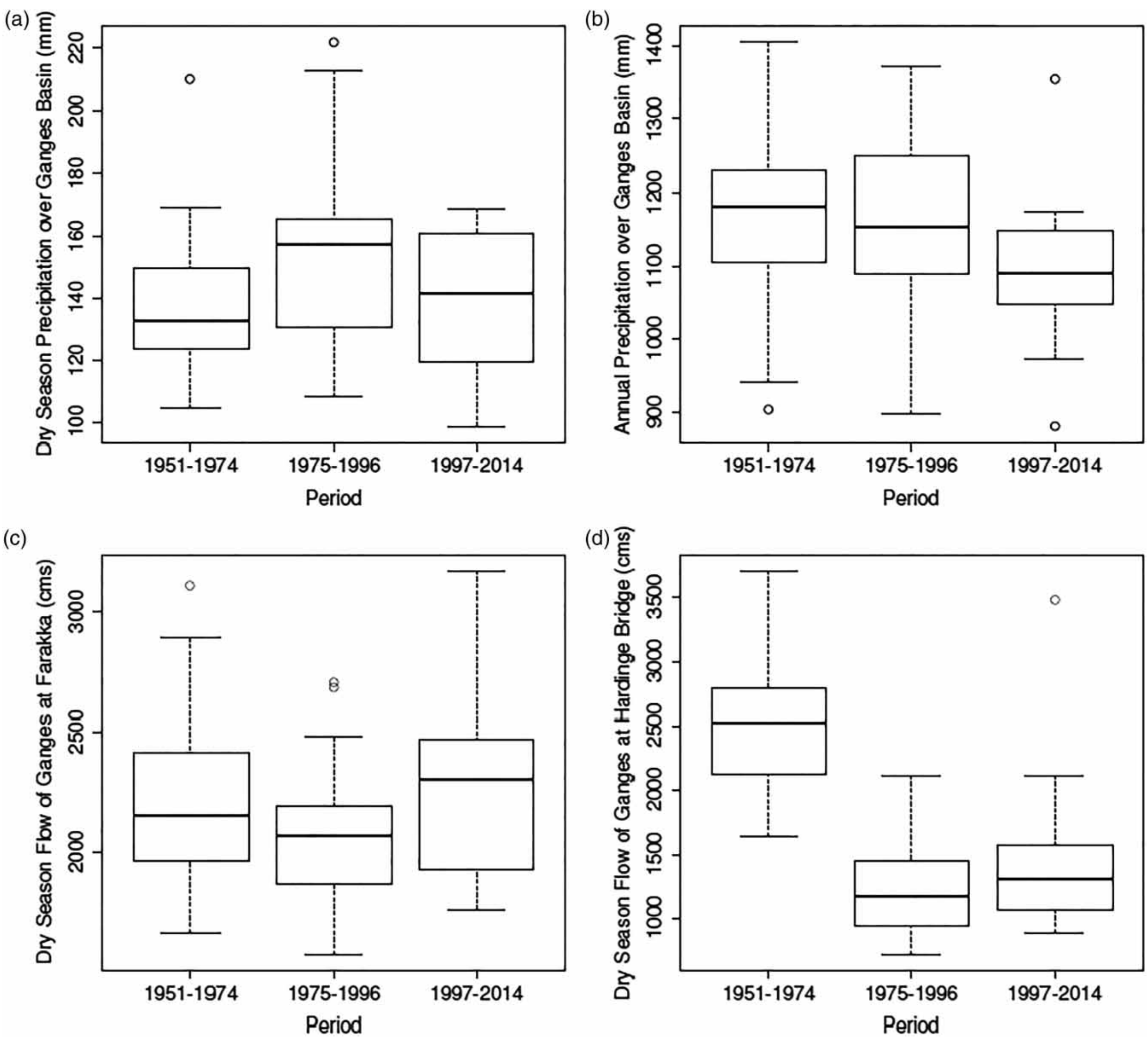

Fig. 3. Boxplots showing (a) dry season (Jan–May) and (b) annual (Jan–Dec) precipitation over Ganges basin, (c) dry season flow of Ganges at Farakka (in India) and (d) Hardinge Bridge (in Bangladesh) for pre-Farakka (1951–1974), post-Farakka (1975–1996), and post-Treaty (1997–2014).

Neither the precipitation over the Ganges basin nor the dry season streamflow of the Ganges at Farakka has significantly changed during the post-Farakka and post-Treaty period (as shown by Figure 3(a)–3(c)). However, the dry season streamflow of the Ganges at Hardinge Bridge has decreased significantly in the post-Farakka period (Figure 3(d) and *Appendix D*, available online), although the basin dry season rainfall increased for the same period. It clearly demonstrates how the flow regulation at Farakka Barrage has impacted Bangladesh during the post-Farakka period. Surprisingly, after the signing of the Treaty in 1996, the situation has not improved much for Bangladesh; the dry season flow at Hardinge Bridge was only marginally increased in the post-Treaty period compared to the post-Farakka period. The cumulative rainfall versus cumulative flow of the Ganges at Farakka and Hardinge Bridge and associated non-parametric trends and their confidence intervals were also analysed (see *Appendix E* for details, available online). The Theil slope between cumulative dry season precipitation and cumulative dry season flow at Hardinge Bridge was 19.134 m^3/s/mm for the pre-Farakka period, then dropped to 7.619 m^3/s/mm in the post-Farakka period, and marginally improved to 9.92 m^3/s/mm for the post-Treaty period, which demonstrate that the Treaty does not significantly improve the dry season streamflow situation in Bangladesh.

Analysis of actual flow released to Bangladesh

The share of the Ganges flow that Bangladesh was receiving from Farakka during the post-Treaty period (1997–2016) usually fluctuates in different years due to the variable amount of flow at Farakka (Figure 4). The flow availability at Farakka, and hence corresponding release to Bangladesh as per the Treaty depends on the climate variability of the basin, e.g. favourable during wetter seasons, but lower during

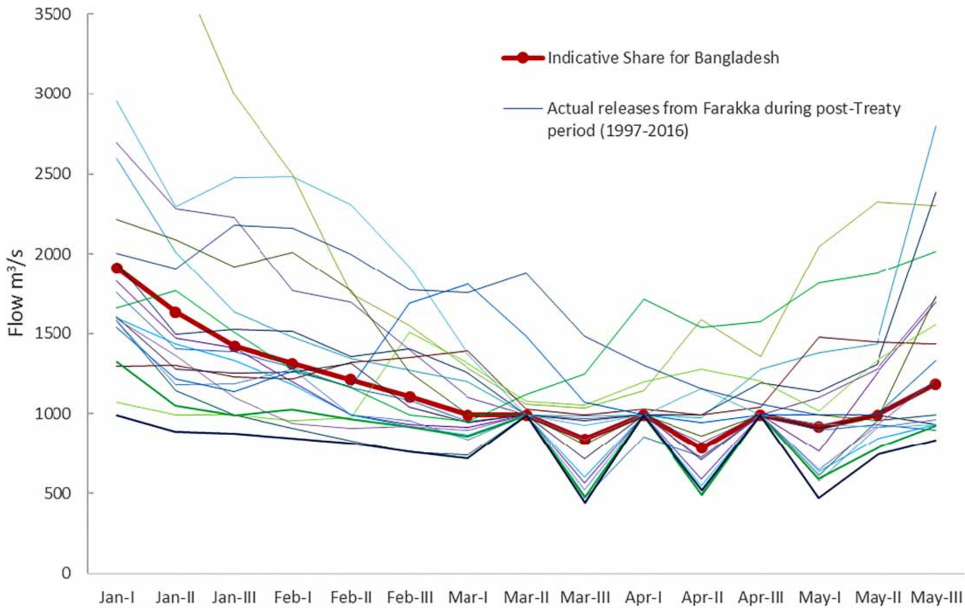

Fig. 4. Comparison of the actual yearly flows released to Bangladesh during the post-Treaty period (1997–2016) with the indicative release to Bangladesh from Farakka according to the Treaty.

drier seasons. Therefore, the focus of this analysis was to investigate the fluctuation of the actual flows released to Bangladesh during comparatively drier years for examining the effectiveness of the Treaty.

Results of the analysis showed that a substantially lower amount of water than the indicative share as per the Treaty was released to Bangladesh during the six critical periods from March 11 to May 10 (Figure 4). During the March 21–31 cycle in the year 2010, the actual release to Bangladesh was only 474 m^3/s, which was 44% lower than the indicative release of 841 m^3/s flows. There were further 38% and 36% decreases of 10-day average flows during the other alternate critical periods of April 11–20 and May 1–10 in 2010, which confirmed a consistent lower share for Bangladesh. In 2016 the situation became even worse than that of 2010; the actual release during March 21–31 was only 442 m^3/s, which was 47% lower than the indicative share, followed by a further 34% and 49% decrease of flows during the other alternate critical periods.

The actual flow distribution for different years with varying availability of flows during the six critical periods in the dry season was further analysed. It indicates that the Treaty performed poorly for both countries during low to moderate flow events, depicting a wide variation of flows released or withdrawn from Farakka (Figure 5(a) and 5(b)). Such sharp 'rise and fall' fluctuation of flow distribution is the result of the obligation of providing a guaranteed 991 m^3/s flow alternately to each country in the six 10-day cycles between March 11 and May 10. However, during favourable wetter years, it showed that the flow distribution was more than satisfactory (Figure 5(c) and 5(d)), and most of the time India was able to release more water than was specified in the Treaty.

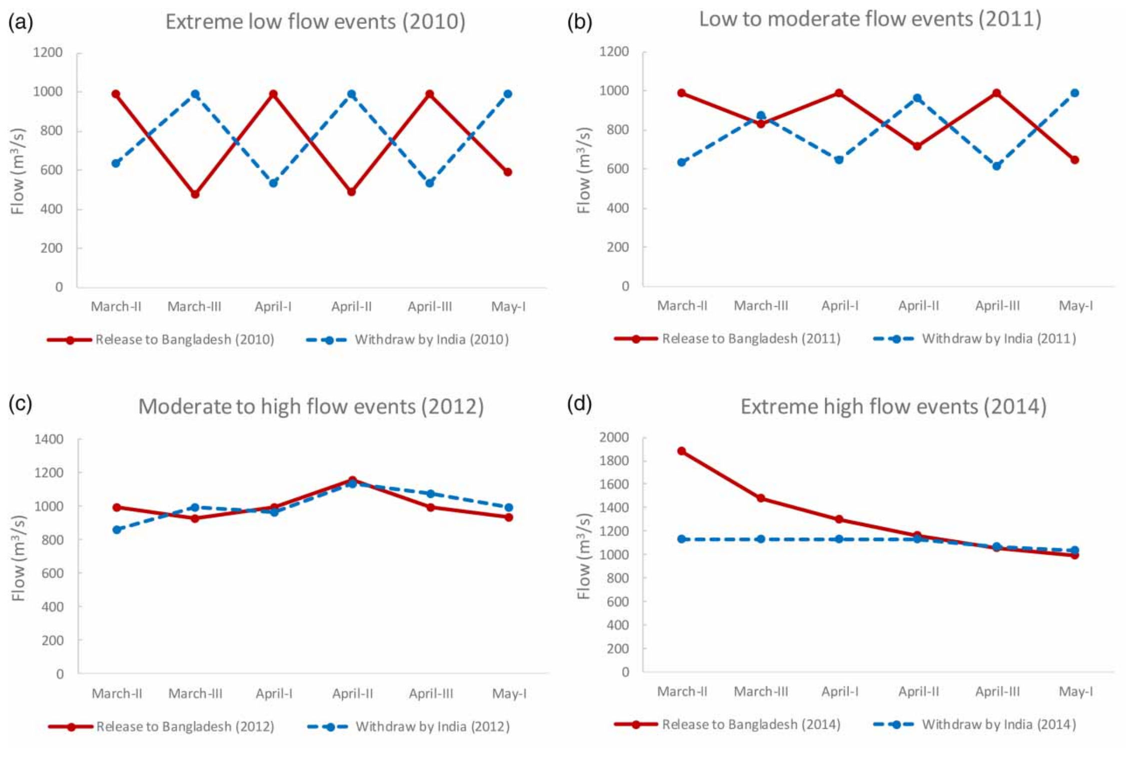

Fig. 5. Comparison of water sharing between India and Bangladesh during the six critical 10-day periods (from March 11 to May 10) during different flow events in the years (a) 2010, (b) 2011, (c) 2012 and (d) 2014.

Analysis of historical flows at Hardinge Bridge

The pre-Farakka (1949–1974) dry season average flows of the Ganges at Hardinge Bridge (presumably at natural state) in Bangladesh were approximately 16% higher than the historical dry season average flow at Farakka (Figure 6(a)). The higher flow is attributed by the tributary inflows from the Mahananda River located between Farakka and Hardinge Bridge (Figure 1), a larger basin area of the Ganges at Hardinge Bridge compared to Farakka, local rainfall and base flow contribution by groundwater. However, during the post-Farakka (1975–1996) period, the difference between dry season average flows at Hardinge Bridge and the release at Farakka was reduced to approximately 9%. Even after the signing of the Treaty, the overall difference between these two flows was further reduced to 8% during the post-Treaty period (1997–2016) (Figure 6(a)). Results even indicated that the average flows at Hardinge Bridge during April 1–10 and April 21–30 cycles were unusually 5% and 2% lower than the flow released from Farakka, respectively.

The actual yearly release from Farakka and corresponding flow at Hardinge Bridge were also compared during the post-Treaty period (1997–2016). It showed that overall 31% of the time (94 out of 300 events) Bangladesh received less water at Hardinge Bridge compared to what presumably was released from Farakka (Table 2). Furthermore, the failure rate was relatively much higher during the critical periods when Bangladesh was guaranteed to receive 991 m^3/s flows for each 10-day cycle. Results indicate that Bangladesh did not receive its guaranteed flow 65% of the time (39 out of 60 events) during alternate 10-day cycles from March 11 to May 10. Such failure of ensuring minimum guaranteed flows to Bangladesh occurred frequently during the most critical periods in several recent drier years between 2008 and 2011. It showed that Bangladesh did not receive its guaranteed 991 m^3/s flows for 10 out of 12 alternate events between 2008 and 2011. Most of the times the flows at Hardinge Bridge were recorded as unusually lower than the actual release from Farakka (Figure 6(b)). In 2010, for instance, the flows at Hardinge Bridge during three alternate 10-day cycles were 9% (March 11–20), 38% (April 1–10) and 21% (April 21–30) lower than the stipulated release of 991 m^3/s flow from Farakka.

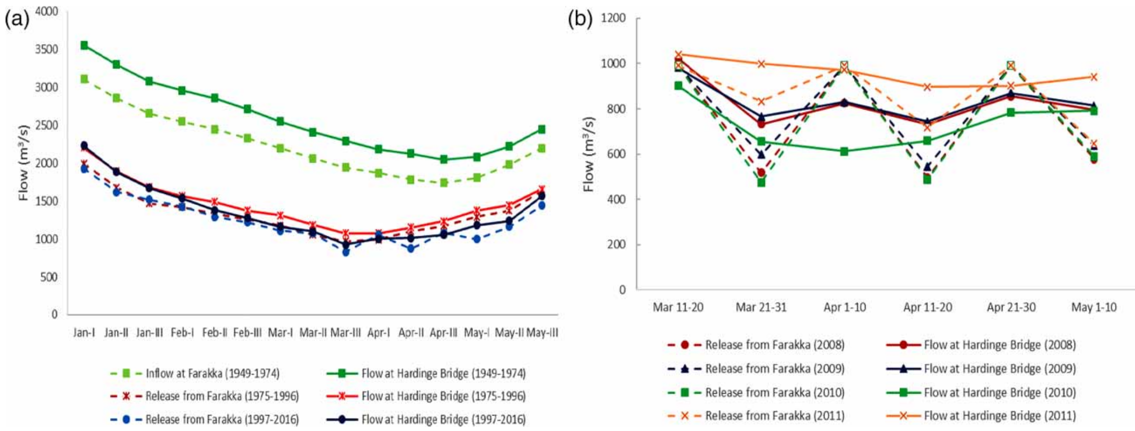

Fig. 6. Comparison of (a) the dry season average flows of the Ganges at Farakka and at Hardinge Bridge during pre-Farakka (1949–1974), post-Farakka (1975–1996) and post-Treaty (1997–2016) periods and (b) the actual release to Bangladesh from Farakka and the actual flows at Hardinge Bridge during the most critical periods (from March 11 to May 10) between 2008 and 2011.

Table 2. Percentage (%) of Bangladesh receiving lower water at Hardinge Bridge than was presumably released from Farakka into Bangladesh during the post-Treaty period (1997–2016).

10-day period	Rate of failure (%)			
	(1997–2001)	(2002–2006)	(2007–2011)	(2012–2016)
January				
1–10	0%	0%	0%	20%
11–20	0%	0%	0%	0%
21–31	20%	20%	0%	20%
February				
1–10	40%	20%	0%	40%
11–20	40%	40%	0%	20%
21–28/29	40%	20%	20%	40%
March				
1–10	40%	40%	20%	20%
11–20	**80%**	**20%**	**40%**	**20%**
21–31	80%	60%	0%	0%
April				
1–10	**80%**	**100%**	**100%**	**40%**
11–20	20%	20%	0%	0%
21–30	**80%**	**100%**	**80%**	**40%**
May				
1–10	40%	20%	0%	0%
11–20	40%	60%	60%	20%
21–31	60%	20%	40%	20%
5-yearly average rate of failure:	45%	36%	24%	20%
Rate of failure in the post-Treaty period (1997–2016):			31% (94 times out of 300 events)	
Rate of failure in the six critical periods (1997–2016):			43% (52 times out of 120 events)	
Rate of failure in the three guaranteed periods (1997–2016):			65% (39 times out of 60 events)	

The rate of failure is calculated by observing how many times in a given period Bangladesh did not receive the Treaty-negotiated flows. The dashed box covers the six critical 10-day periods from March 11 to May 10. The bold 10-day cycles represent the periods when Bangladesh is guaranteed to receive 991 m^3/s flow.

Discussion

The signing of the Ganges Water Sharing Treaty in 1996 was considered as a new prospect to offer the opportunity for regional cooperation between India and Bangladesh. India, in spite of being the hydro-hegemon controlling most of the Ganges waters, showed positive intention towards a peaceful resolution of the conflict by incorporating the principles of equity and ‘do no harm’ to either riparian in the Treaty (GWT, 1996). But despite having a unique water sharing formula, the efficacy of the Treaty was questioned several times due to the low availability of flow at Farakka during the post-Treaty periods. Therefore, we systematically reviewed the outcome of the Treaty with quantitative analysis of dry season availability of the Ganges flows at Farakka and Hardinge Bridge. The review indicates that the major barriers for successful implementation of the Treaty are (i) inaccurate projection of future available flows at Farakka, (ii) inappropriate provision of guaranteed flow during critical dry periods, (iii) inadequate protection of flows at Hardinge Bridge, (iv) lack of guarantee clause for Bangladesh and (v) no consideration of environmental and economic drivers. Each of these factors is discussed in detail below.

Inaccurate projection of future available flow at Farakka

The water sharing of the Treaty was based on the average flows at Farakka between the years 1949 and 1988. The Treaty, however, did not take into account climate variability in the basin as well as the decreasing trend of flows at Farakka during the post-Farakka period (Figure 2). This reduction in Ganges flow at Farakka was also well demonstrated in Figure 3(c). When we compared the indicative flows with the post-Farakka (1975–1996) flows at Farakka, it became clear that the Treaty-negotiated indicative values were probably overestimated. When we analysed the flows during individual years during the post-Treaty period (1997–2016), it showed that there were repeated occurrences of extremely low flows at Farakka in some drier years (Figure 2). Therefore, such estimation of future flows at Farakka with only flat average availability during a certain time frame (1949–1988) underestimated the impact of increased climate variability and the frequency of low-flow events; thus, this raised the Treaty indicative flows unusually higher than the actual dry season flows.

Furthermore, there are concerns that potential climate change could exacerbate the water scarcity problem in the future in the Ganges basin (Moors *et al.*, 2011; Jeuland *et al.*, 2013). It is predicted that impacts of climate change will affect the intensity, frequency and magnitude of precipitation in the Ganges basin, and there are projections for reduced dry season flow across the basin (Biemans *et al.*, 2013; Pervez & Henebry, 2015). As the Ganges River is also highly regulated with dams, barrages and irrigation canals, the combined impact of climate change and increased withdrawal upstream of Farakka would result in more years in which the actual flow is lower than the indicative flows of the Treaty. Therefore, a proper investigation of the impacts of climate change and anthropogenic activities should be carried out to project the reliable future flows at Farakka.

Inappropriate provision of guaranteed flow during critical dry periods

The establishment of a new sharing formula in the Treaty allowed the flexibility to divide the 10-day average flows to each country, irrespective of how much water was available at Farakka, by putting either percentage (%) or numeric amounts with respect to three different scenarios of water availability at Farakka. However, our analyses indicated that the efficacy of the Treaty mostly relied on the flow variability at Farakka, and often failed to release the indicative share of Bangladesh due to insufficient availability of flow at Farakka (Figure 5).

The provision of allocating a guaranteed 991 m^3/s flow to each country in every alternate 10-day cycle during the most critical periods resulted in severe water scarcity in a number of years. The low availability of flows at Farakka during critical periods in most of the post-Treaty years (1997–2016) largely affected the usefulness of such provision (Figure 6). The obligation to meet the condition created sharp fluctuation of flows and consequently reduced flows for both countries during the driest years (Figure 5(a)). Our quantitative analysis clearly indicates that such an arrangement pattern is one of the weakest features of the Treaty. Furthermore, the gradual reduction of flows at Farakka would certainly create a worse situation for both riparian countries in future, and put the effectiveness of the Treaty at risk. In our opinion, there would be no requirement for allocating a guaranteed flow to each country in alternate 10-day cycles. Instead, a simple straight-forward percentage (%) distribution, similar to non-critical periods, could be sufficient to ensure that no countries experience extreme low-flow events during the most critical dry periods.

Inadequate protection of flows at Hardinge Bridge

The proper implementation of the 1996 Treaty had been widely criticized due to the fact that the share received by Bangladesh, verified at the Hardinge Bridge inside Bangladesh, was often lower than the flow presumably released at Farakka. The flows at Hardinge Bridge should be higher than the flows released to Bangladesh at Farakka, mainly because of the inflow from the tributary Mahananda located between Farakka and Haridinge Bridge. The historical comparison of these two flows also supported such comparatively higher flows at Hardinge Bridge (Figure 6(a)). Only large-scale local withdrawal could have changed such a pattern. According to Article II of the Treaty, however, India was permitted to locally withdraw a maximum 5.66 m^3/s of the water released to Bangladesh from the river part downstream of Farakka (GWT, 1996).

Despite this restriction of local water withdrawal set in the Treaty, Bangladesh was frequently deprived of its guaranteed minimum flow during the most critical period of the dry season. Most of the cases when Bangladesh was guaranteed to receive a minimum 991 m^3/s, we noticed that the 10-day average flow at Hardinge Bridge was much lower compared to what presumably was released from Farakka. A recent study identified that India failed to release the minimum guaranteed share to Bangladesh 55.5% of the time during the 2008–2016 period (Thomas, 2017). Another study found that Bangladesh received less water 25% of the time during the 2008–2011 period (Islam *et al.*, 2013). Our analysis during the post-Treaty period (1997–2016) also showed that 65% of the time (39 out of 60 events) Bangladesh did not receive its guaranteed flow (Table 2). It also revealed that Bangladesh was most vulnerable to not getting enough water in April. Therefore, to protect the flows that enter Bangladesh and are verified at Hardinge Bridge, it is necessary to examine the dynamic factors that could potentially contribute to the addition or reduction of flows in the reach between Farakka and Hardinge Bridge.

Lack of guarantee clause for Bangladesh

The 1996 Treaty did not have a direct guarantee clause similar to the 1977 Agreement which ensured Bangladesh received a minimum of 80% of the scheduled flow during extremely low-flow events at Farakka (Salman & Uprety, 1999). However, the Treaty indirectly, through Article X and XI, ensured that Bangladesh could obtain at least 90% of the share stipulated in the Treaty in case there were no mutual agreements on sharing arrangement during the review process (GWT, 1996). Thus, it is inferred that the Treaty recognized the necessity of guaranteed flows for Bangladesh to safeguard its fair share in the event of substantial reduction of flows at Farakka.

Article II of the Treaty further admitted the requirement for the two countries to urgently meet if the available 10-day average flow at Farakka dropped below 1,416 m^3/s. Thus the flow at Farakka below 1,416 m^3/s could be acknowledged as an extreme low-flow condition. During such low-flow events, a guaranteed share for Bangladesh would ensure a minimum flow in the downstream. The guarantee clause would, however, certainly affect India's share during such critical low-flow events. But the Treaty had already instructed India, through Article II, to make every effort to protect the available flows at Farakka. As long as India could prohibit the flow from falling below 1,416 m^3/s at Farakka, there would be no obligation to allocate guaranteed flow for Bangladesh, since the guarantee clause would come into action only if the flow dropped below 1,416 m^3/s. Therefore, the provision of such a guarantee clause would certainly safeguard the downstream ecological balance in Bangladesh, and also accommodate India to limit the excessive water withdrawal upstream of Farakka for the sake of protecting the indicative flows at Farakka.

No consideration of environmental or economic drivers

Apart from the weaknesses identified above, the water sharing formula of the Treaty also includes a fixed allocation mechanism (e.g., only volumetric allocation of the river flow). Many transboundary water sharing treaties adopted such an allocation mechanism by limiting withdrawal rates or maintaining a minimum flow among treaty-signing countries. The Mahakali Treaty, signed in 1996 between India and Nepal, allowed Nepal to withdraw 28.35 m^3/s of water from the Sarada Barrage in the wet season, and 4.25 m^3/s of water in the dry season, while India should maintain a minimum flow of 9.91 m^3/s downstream of the barrage to maintain and preserve the river ecosystem (Salman & Uprety, 1999). The 1987 bilateral agreement between Turkey and Syria over the allocation of waters of the Euphrates River obliged Turkey to release a minimum flow of 500 m^3/s of Euphrates water to Syria (Kibaroglu & Scheumann, 2013). The 1959 Agreement signed between Egypt and Sudan established the annual water allocation for the two downstream riparian states in the Nile basin and guaranteed 55.5 billion m^3 of water for Egypt and 18.5 billion m^3 for Sudan (Cascao, 2008). Unlike treaties that allocate waters by flow or quantity, the Indus Treaty, signed in 1960, divides the Indus river system into eastern and western parts, and gives control of the three eastern rivers (Ravi, Sutlej and Beas) to India and three western rivers (Indus, Jhelum and Chenab) to Pakistan (Zawahri, 2009). However, the distribution of waters on the basis of historical rights or volumetric allocation typically limits the flexibility of water allocation regimes and presents multifaceted challenges (Tir & Stinnett, 2011). Therefore, the above agreements still do not reflect meaningful cooperation between the co-riparian states which suggests the necessity of reforming the agreements.

It is worth noting that all these treaties, including the Ganges Treaty, do not consider environmental (e.g., water quality, flood mitigation, navigation) or economic drivers (e.g., water charges, payment for ecosystem services, efficiency subsidies). The Convention on the Protection of the Rhine indicated that efforts must be made to further improve the water quality of the Rhine River (Convention on the Protection of the Rhine, 1999). The Framework Agreement on the Sava River Basin (2002) included integrated management of surface and groundwater resources in a manner that should provide water in sufficient quantity and of appropriate quality for the international navigation regime and preservation, protection and improvement of aquatic ecosystems (Komatina & Groselj, 2015). The Mackenzie River Basin Bilateral Water Management Agreement signed between Alberta and Northwest Territories of Canada (Government of Alberta and Government of Northwest Territories, 2015) includes provisions to create ecosystem objectives, such as water quality and quantity and biological objectives, to maintain the ecological integrity of transboundary water ecosystems.

Therefore, we suggest that the revision of the Ganges Treaty beyond 2026 should adopt a holistic approach by addressing other water issues apart from the provision of water quantity. The reform of water allocation regimes may also address the use of economic instruments to achieve sustainable water governance. Considering water as a distinctive economic good, there are many alternative economic instruments which comprise well-designed regulations like water pricing, pollution charges, water abstraction fees, incentives and subsidies (Gomez *et al.*, 2017). Economic instruments are gaining momentum in European countries with different allocation systems and regulations to ensure a meaningful contribution to water policy objectives (Rey *et al.*, 2018). However, it is critical to carefully recognize the strengths of each economic instrument and its potential as a tool for reforming water allocation mechanisms between the riparian states.

Conclusion

We critically reviewed the performance of the 1996 Ganges Water Sharing Treaty during the post-Treaty period (1997–2016) and identified the major weaknesses in the apparently noteworthy features of the Treaty. One of the major limitations of the Treaty was the unjustified assumption of future water availability at Farakka based on 40-year average flows. It underestimated the impact of climate variability, the frequency of low-flow events and increased water extractions upstream, thus raising the future expected flows in the Treaty unusually higher – particularly during the most critical periods. Furthermore, future climate change and higher upstream water demand are likely to result in more frequent years with very low-flow at Farakka. Therefore, we recommend projecting the future water availability at Farakka through hydrological models; such modelled flows would establish the reliable capacity of Farakka flows to meet the future water requirements, and would be the basis of a future water allocation formula between the riparian countries.

Besides, we question the provision of the guaranteed minimum 991 m^3/s flow alternately during the most critical periods and proclaim that such provision has already created complications for both countries. On several occasions, neither Bangladesh nor India was able to receive their respective shares as stipulated in the Treaty. It implied that the condition of allocating guaranteed flow in alternate 10-day cycles would be unnecessary, and thus should be eradicated from the present Treaty. Furthermore, our statistical analyses of recent flow data at Farakka and Hardinge Bridge showed that Bangladesh frequently did not receive its (fair) share during the most critical periods of the dry season when water demand is relatively high in both countries. Therefore, we suggest providing a guarantee clause to safeguard the fair share of Bangladesh during the occurrence of extreme low-flow events.

The present tenure of the Treaty will expire in 2026 after completing its 30 years of operation of the water sharing arrangement between India and Bangladesh. Our results indicate that the implementation of the Treaty has failed to generate a substantial contribution to improving the dry season water availability in Bangladesh. However, without the Treaty, the situation could become worse, disrupting the ecological balance in the downstream. Nevertheless, the Treaty could still overcome the water scarcity issues and enhance the cooperation between the riparian countries if modified with our recommended adjustments to its terms and conditions. Further extension and implementation of the revised Treaty beyond 2026 could promote the peaceful resolution of many unresolved issues and could improve the current transboundary water governance in this region.

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