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ORIGINAL ARTICLE

Impacts of Farakka barrage on hydrological flow of Ganges river and environment in Bangladesh

Md. Mahbubur Rahman[1] **· Muhammad Mizanur Rahaman**[1]

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Abstract The Ganges river is the major source of water for dry season irrigation, navigation, fisheries and reducing salinity intrusion as well as maintaining ecosystem of south-western region in Bangladesh including Sundarbans, the largest mangrove forest in the world. Farakka barrage was constructed on the main stem of Ganges river by India at 18 km upstream of India–Bangladesh border. The barrage was commissioned in 1975 to divert water for improving navigability of Kolkata port and providing saline-free water for Kolkata city. Hydrological analyses have been carried out on historical discharges and water levels data (1935–2015) at Hardinge Bridge station in Bangladesh to find out whether significant changes have occurred in the hydrological flow of Ganges river during pre-Farakka (1935–1975) and post-Farakka (1976–2015) periods. The impacts of Farakka barrage on discharges and water levels have been triggered an abrupt change in Bangladesh since 1975. During post-Farakka period, monthly maximum, average and minimum discharges have been reduced significantly in February–May, December–May and February–April, respectively. Ganges water sharing treaty has been signed between Bangladesh and India in 1996. In comparison with pre-Farakka period (1935–1975), it has been observed that during post-Ganges water sharing treaty period (1997–2015), the maximum, average and minimum discharges have remain reduced around 23, 43 and 65%, respectively, in dry season (January–May). Due to long-term significant reduction of the Ganges flow at Farakka for about 40 years, south-western region of Bangladesh has been suffering from environmental degradation.

Keywords Ganges river · Farakka barrage · Discharges · Water levels · Bangladesh

Introduction

Bangladesh is the lower riparian on a large number of rivers that flow from the neighboring countries of India and Myanmar. Bangladesh has around 57 international rivers; among those 54 are coming from India and 3 from Myanmar. The climate of the country is monsoonal in character, with rainfall concentrated in a few months, and in the dry season, international rivers are the major source of water for irrigation and other consumptive demands, as well as non-consumptive uses such as fishing, navigation and salinity control. For Bangladesh, the Ganges river represents the major source of dry season irrigation water supply for the greater districts of Kushtia, Jessore, Barisal, Pabna, Faridpur, Khulna and Rajshahi. It acts as a major waterway for river transport, not only in the main river but also in the many distributaries. Bangladesh is also highly dependent on the Ganges to regulate salinity levels in the south-western regions and the Sundarbans (BWDB 1986).

The Ganges basin is located 70°–88°30′ east longitude and 21°–31° north latitude (Rahaman 2009). The Ganges river has total length of about 2600 km. The river Ganges rises in the Gangotri glacier in the Uttar Kashi district of Uttarkhand (former Uttar Pradesh) province in India, at an elevation of about 3139 m above sea level (Rahaman 2009). The Ganges enters Bihar after leaving Uttar Pradesh. Flowing through Bihar it enters in West Bengal province. Then, it has been divided into two arms nearly

✉ Muhammad Mizanur Rahaman
rahamanmm@gmail.com

[1] Department of Civil Engineering, University of Asia Pacific, Dhaka, Bangladesh

40 km below the Farakka (Rahaman 2009). The right arm flows south through Bhagirathi–Hooghly river system on which Kolkata Port is situated. The left main arm flows east and enters in Bangladesh. The right arm, called Bhagirathi, continues to flow south through West Bengal. The Bhagirathi flowing west and south west of Kolkata (formerly Calcutta) is known as Hooghly. After reaching Diamond Harbour, it attains a southward direction and is divided into two streams before joining the Bay of Bengal. The right arm known as Haldi River also joins the Bay of Bengal. Inside Bangladesh, Mahananda is the only tributary that joins the Ganges. The major and medium rivers of Nepal that feed the Ganges are Mahakali, Karnali, Gandak, Kosi, Bagmati, Kamala, Babai and West Rapti. The rivers of Nepal contribute more than 45% of the total flow of the Ganges and nearly 70% of its dry season (January–May) flow reaching Farakka (Rahaman 2009).

After entering Bangladesh, the river flows for another 113 km before joining the Brahmaputra near Goalanda. The combined course of the Ganges and the Brahmaputra takes the name of Padma, which joins the Meghna river at Chandpur. From this confluence, the combined course of the three rivers continues as the lower Meghna and empties into the Bay of Bengal (Tanzeema and Faisal 2001; Rahaman 2012).

Bangladesh is the most downstream country of the Ganges basin (Fig. 1). With regard to the distribution of the 1,080,000 km^2 basin area, India, Nepal, Bangladesh and China contribute 79, 14, 4% (this is equivalent to 37% of Bangladesh) and 3%, respectively (Rahaman 2009; Chowdhury and Ward 2004). The river has great importance for the socio-economy of the co-basin countries (Mirza 1997; Rahaman 2009; Gain et al. 2008; Gain and Hoque 2013). The water supply of the Ganges depends partly on the monsoon-dominated rainfall (during July–October) and Himalayan snow melting during the summer season (April–June) (Rouillard et al. 2014). The region is characterized by flooding in the monsoon season that is during June to October (Gain and Hoque 2013; Rahaman 2009, 2012; Mirza 1997, 1998), and water scarcity in the non-monsoon season that is during November to May (Gain and Wada 2014).

The Farakka barrage

The basic plan of the barrage was made in 1951. The construction of the barrage begins on 30th January 1961 and was completed in 1974. The barrage has been built in the village Jongipur in the Murshidabad district of west Bengal, 18 km upstream from the Indo–Bangladesh border (Fig. 1) (BWDB 2012). The Ganges is a perennial river; however, withdrawal of water at Farakka barrage blocks the perennial flow of the river in Bangladesh (Abbas 1983).

Under a temporary agreement signed on 18th April 1975, Bangladesh consented to a "test operation" of the Farakka barrage for 41 days (21st April–31st May) (Rahaman 2009). India was allowed to divert 312–454 m^3 s^{-1} of water in various periods as specified in the agreement. After expiry of the temporary agreement, India unilaterally withdrew water from June 1975 to November 1977 (Abbas

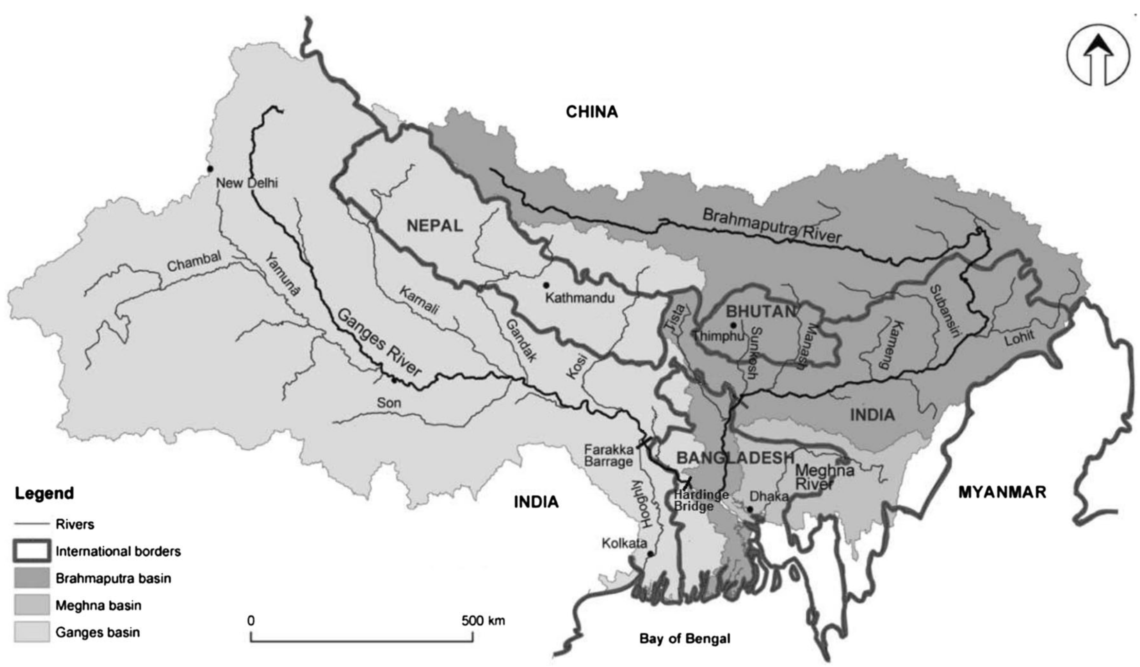

Fig. 1 The Ganges, the Brahmaputra, the Meghna river Basin. Source: Rahaman 2009

1984). After test operation of the Farakka barrage, the first maximum diversion started in 1976 and the diversions in subsequent years exceeded the initial maximum (Sattar 1996; Mirza 1997, 1998; Rahaman 2009; Gain and Giupponi 2014).

A 5-year agreement between Bangladesh and India on the sharing of the Ganges waters was signed on 5th November 1977 (Rahaman 2009). The Agreement expired in 1982, but the sharing arrangement was renewed twice under the title "Memorandum of Understanding" (MOU) with some modifications. The second MOU expired in 1988. During 1988–1996, there was no sharing agreement between Bangladesh and India. On 12th December 1996, a 30-year treaty on sharing the dry season (January–May) flow of the Ganges river at Farakka was signed by Bangladesh and India. The treaty is widely known as the 1996 Ganges Water Sharing Treaty (hereinafter GWT). Table 1 presents the chronology of water conflict and cooperation between Bangladesh and India.

The rationality of Farakka barrage

Kolkata port was established in 1890 without consideration of proper technical and hydraulic factors but even prior to that the Bhagirathi–Hooghly being cutoff from the Ganga for 9 months was gradually drying up and each year around 9 crore cubic feet silt accumulated in the Hooghly river. The permissible drafts for ships entering or leaving the port have been seriously declining from 1938 to 1959 (Banerjee 1999). Farakka barrage projects have been designed for improve navigability of the Bhagirathi–Hooghly river system and flush out the deposited sediment in the port of Kolkata and also provide salt-free water supply for the Kolkata city and the surrounding area (cited in Crow et al. 1995; FBP 2015).

During the British colonial rule (1870–1946), Kolkata port had a golden day for exporting goods from entire Bengal. During that period, the entire former Bengal was the hinterland of the Kolkata port. All raw materials from India were exported to the UK through the Kolkata Port. From the statistics of the traffic in Kolkata port, it has been found that after the partition of Indian sub-continent, India has spent less for the Kolkata port compared to any other ports (Adel 2013). Prior and around the time of India's independence in 1947, Kolkata port carried 40–50% of total Indian imports and exports. In 1960s, the total import and export through Kolkata port have dropped at 23%. During 1970s and 1980s, the total import and export have dropped to around 11 and 10%, respectively (Crow et al. 1995).

Many argue that the decline of the Kolkata port not was caused by the physical limitations of the river system, but the industrial growth rate in the hinterland of the port becomes slower (Sau 1990; Crow et al. 1995; Rahaman 2009). There is another argument that in 1870s, after the opening of the Suez Canal, Bombay port has become much closer compared to the Kolkata port, an expanded rail system, coupled with the decline of the Kolkata port trade (Novak 1993; Rahaman 2009).

In the post-Farakka days, Patel (1996) wrote that the dredging was probably the only effective solution for improving navigability of the Kolkata port because the volume of traffic did not increase but reduced significantly. He also wrote that the importance of the Farakka barrage was not demonstrated in a convincing manner. Rahaman (2009) mentioned that the diversion of Ganges flow at Farakka barrage to improve the navigability of Kolkata port is questionable. The problem of saline water in Kolkata city is not solved yet (GAIA 1997). So, Crow et al. (1995) mentioned: "The sad reality of the Farakka barrage is that it was a heroic piece of engineering designed to solve the wrong problem".

Objectives of the study

This research has two following objectives:

(a) Analyzing the changes in discharges and water levels of Ganges river during 1935–2015 at Hardinge bridge station in Bangladesh to find out the hydrological impacts of Farakka barrage in Bangladesh.
(b) Identifying social, economic and environmental impacts in south-western region of Bangladesh due to unsustainable water diversion through Farakka barrage.

Literature Review

Mirza (1997) studied on hydrological changes in the Ganges system in Bangladesh in the post-Farakka period. Annual peak and annual mean discharge observation data set during the period 1934–1992 of Hardinge bridge point have been obtained for his study. Peak discharge data series have been examined, to find out the possible changes in the peak discharge. Peak discharges have been increased around 13% during post-Farakka period compared to pre-Farakka period. Another discharge data series (1965–1992) also has been analyzed to derive monthly mean discharges and found significant changes during post-Farakka period. Time series (1965–1992) of monthly mean flows for February, March, April and May showed that sharp changes of discharge have been occurred during the two non-water sharing agreement periods due to unilateral withdrawal of water by India and these periods were 1976–1977 and 1988–1992.

Table 1 Chronology of water conflict and cooperation between Bangladesh and India. Source: updated from Rahaman 2009

Time line	Outcome
1951	Pakistan (Bangladesh after 1971) officially objected to India's plan to construct Farakka barrage on 29 October 1951
1961	India officially admitted the unilateral construction of the barrage on 30 January 1961
1972	On 24 November 1972, India and Bangladesh signed statutes of the Indo–Bangladesh Joint River Commission (JRC)
1974	Farakka barrage construction is completed
1975	On 18 April 1975, Bangladesh allowed India to divert 310–450 m^3/s of Ganges water from 21 April to 31 May 1975 to test the feeder canal of the Farakka barrage through a ministerial level declaration. Farakka barrage started operation on 21 of April 1975
1976	India continued unilateral diversion of the Ganges flow beyond the stipulated period in the 1975 ministerial declaration throughout the 1976 dry season and withdrew 1133 m^3/s of water (full capacity of the feeder canal) at Farakka. Bangladesh raised the issue at the United Nations. On 26 November 1976, the UN General Assembly adopted a consensus statement, which directed both countries to urgently negotiate a fair and expeditious settlement of the Farakka problem to promote the well-being of the region (UN, 1976)
1977	Upon the direction of the United Nations, India and Bangladesh signed the 1977 Ganges Water Agreement for the duration of 5 years
1978	According to the instructions of the 1977 Agreement (Articles VIII–XI), Bangladesh and India exchanged their official proposals for augmenting the dry season flow of the Ganges. The Bangladesh side proposed augmentation of dry season flow through building storage reservoirs in Nepal. India proposed augmentation through diversion of water from the Brahmaputra river to the Ganges river. Neither side agreed to the other's proposal
1982	An MoU was signed between the two countries for sharing dry season flow of Ganges at Farakka in 1983 and 1984
1985	There was no agreement for the 1985 dry season (January–May). In November, an MoU was signed for 3 years (1986–1988), which expired on 31 May 1988
1986	On 29–31 October 1986, a team of experts from Bangladesh and India officially approached Nepal regarding the potential water storage projects at upstream of the Ganges basin in Nepal. The meeting ended without any outcome
1988	1985 MoUs expired. No agreement for the period 1988–1996
1993	Bangladesh raised the issue at the Commonwealth Summit held in Cyprus in October 1993
1995	On 23 October 1995, Bangladesh again raised concern in the 50th UN General Assembly about the negative consequences on Bangladesh due to the unilateral water diversion at Farakka barrage
1996	An agreement on sharing the Ganges water at Farakka was signed for the duration of 30 years
2005	In the 36th Indo–Bangladesh JRC meeting, held on September 2005, Bangladesh again proposed to have tripartite talks involving Nepal for building water reservoirs in Nepal in order to augment the dry season flow of the Ganges
2015	Second Water Resources Management Joint Working Group (JWG) on Sub-Regional Cooperation between Bangladesh, Bhutan, India and Nepal (BBIN) was held in New Delhi during January 30–31, 2015. The power trade and inter-grid connectivity between four countries were the main focus of the meeting. The JWG agreed to explore and share information regarding future hydropower development projects and inter-grid energy connectivity. It also agreed to improve the existing flood forecasting data sharing mechanism and exchange best practices on Basin wide water resources management
2016	Third Water Resources Management JWG on Sub-Regional Cooperation Between BIBN was held in Dhaka during 19–20 January 2016. The JWG decided to constitute an expert group on the specifics of hydropower development project, power trade, inter-grid connectivity and flood forecasting

Rahaman (2009) studied on integrated Ganges basin management. Data series of Ganges discharge (1934–1995) at Hardinge bridge station has been analyzed and found that during the dry season (January–May), the average pre-Farakka (1934–1975) discharge was 2340 $m^3\ s^{-1}$ whereas the average post-Farakka (1975–1995) discharge was only 1236 $m^3\ s^{-1}$.

Afroz and Rahman (2013) studied on hydrological changes in the Ganges river in Bangladesh during post-Farakka period. Discharge data set of Ganges river (1970–2011) at Hardinge bridge station has been analyzed and found that around 80% mean annual peak discharge increment has been occurred after the operation of Farakka barrage and around 73% mean annual peak discharge increment has been occurred after the Ganges water sharing treaty (1996) compared to before the operation of Farakka barrage and around 82% annual minimum discharge has been decreased after the operation of Farakka barrage and mean annual minimum discharge has been slightly increased after the Ganges water sharing treaty (1996) compared to pre-Farakka but average discharges of these three phases have been observed almost constant.

Gain and Giupponi (2014) studied on impact of the Farakka barrage in Bangladesh. Discharge data of Ganges river at Hardinge bridge station have been analyzed for the period of 1934–2005. The impact of Farakka barrage has been calculated by comparing threshold parameters for the pre-Farakka and the post-Farakka period. The flow threshold has been calculated using RVA method. This method derives from hydrologic characteristics of magnitude, frequency, duration, timing and the rate of the change of flow and reveals that every year after the construction of Farakka barrage, annual minimum and annual maximum flows failed to meet the threshold limit during post-Farakka period. During dry season (December–May), the mean monthly flow of the post-Farakka period also failed to meet the RVA criteria. That is why the ecological consequences of such hydrologic alterations cause the destruction of the breeding and raising grounds for a large number of Gangetic species, the increase of salinity in the south-western region of Bangladesh and a reduction of fish and agricultural diversity.

Baten and Titumir (2016) studied on environmental challenges of trans-boundary water resources management: the case of Bangladesh. Core issues related to environmental security by analyzing various environmental impacts due to water diversion and its significance have been analyzed and concluded that due to upstream water diversion through the Farakka barrage, fresh water supply has been decreased considerably at the downstream. As a result, reduced river flow restricts navigation, creates disturbance in fish habitat, reduces soil moisture, lowers ground water table and ultimately threatens economic livelihood, salinity intrudes towards landward, increased river salinity hampers irrigated agriculture, reduces efficiency of industries, pollutes drinking water, retards regeneration and growth of forest trees and all these effects cumulatively result in expanded poverty.

Thomas (2017) studied on the Ganges water treaty: 20 years of cooperation, on India's terms. Qualitative interviews and previously unpublished hydrological data have been analyzed to evaluate assertions that hydrological hazards in south-western region of Bangladesh result from India's activities and that India is failing to uphold of Ganges Water Sharing Treaty, 1996. Analysis result indicates that India is broadly adhering to the Ganges water Sharing Treaty, but unilaterally withdraws water during a critical period of the dry season when regional livelihoods are most vulnerable.

This research contributes to the existing literatures on Ganges basin by focusing on hydrological and environmental impacts on Bangladesh due to upstream water withdrawal at Farakka barrage. Discharge and water level data (1934–2015) of Hardinge bridge station, located in Bangladesh, have been analyzed to evaluate hydrological impacts of Farakka barrage on hydrological flow in Ganges river and environment in Bangladesh.

Sources of data

Discharges and water levels of the Ganges in Bangladesh are measured at Hardinge Bridge hydrological station (Fig. 1). Discharges data for the period 1934–1996 have been collected from Joint River Commission (JRC), Bangladesh. Discharges data for the period 1997–2015 and water levels data for the period of 1934–2015 have been collected from the database of Surface Water Processing Branch, Bangladesh Water Development Board. JRC's data set (1934–1996) contains some missing discharges data such as the months of January–March, 1934 and April, 1971 to March, 1972. The data for the period April, 1971 to March, 1972 are missing due to liberation war in Bangladesh. The data for the years 1934, 1971 and 1972 have been discarded from the analysis due to partial data missing.

Data analyses and results

After the operation of Farakka barrage in 1975, India has been withdrawing Ganges water unilaterally till to date. In this section, the discharges and water levels data at Hardinge Bridge station for the period of 1935–2015 are analyzed to find out the hydrological impacts in Bangladesh due to the Farakka barrage. Data have been analyzed as pre-Farakka and post-Farakka periods. Pre-Farakka refers to the period 1935–1975 and post-Farakka refers to the period 1976–2015.

Changes in yearly water levels with discharges

Data have been analyzed according to the yearly maximum, average and minimum discharges and water levels at Hardinge Bridge station in Bangladesh (Figs. 2, 3, 4).

Figure 2 shows that during pre-Farakka period (1935–1975), the highest and lowest yearly maximum discharges have been observed as 73,200 $m^3\ s^{-1}$ (1961) and 35,900 $m^3\ s^{-1}$ (1939), respectively. But during post-Farakka period (1976–2015), the highest and lowest yearly maximum discharges have been observed as 75,800 $m^3\ s^{-1}$ (1987) and 31,500 $m^3\ s^{-1}$ (1989), respectively. Similarly during pre-Farakka period, the highest and lowest yearly maximum water levels have been observed as 14.91 m (1936 and 1954) and 13.60 m (1943 and 1944), respectively. But during post-Farakka period, the highest and lowest yearly maximum water levels were 15.19 m (1998) and 13.26 m (1989), respectively.

Figure 3 shows that during pre-Farakka period (1935–1975), the highest and lowest yearly average discharges have been observed as 16,751 $m^3\ s^{-1}$ (1956) and 7807 m^3s^{-1} (1965), respectively. But during post-Farakka

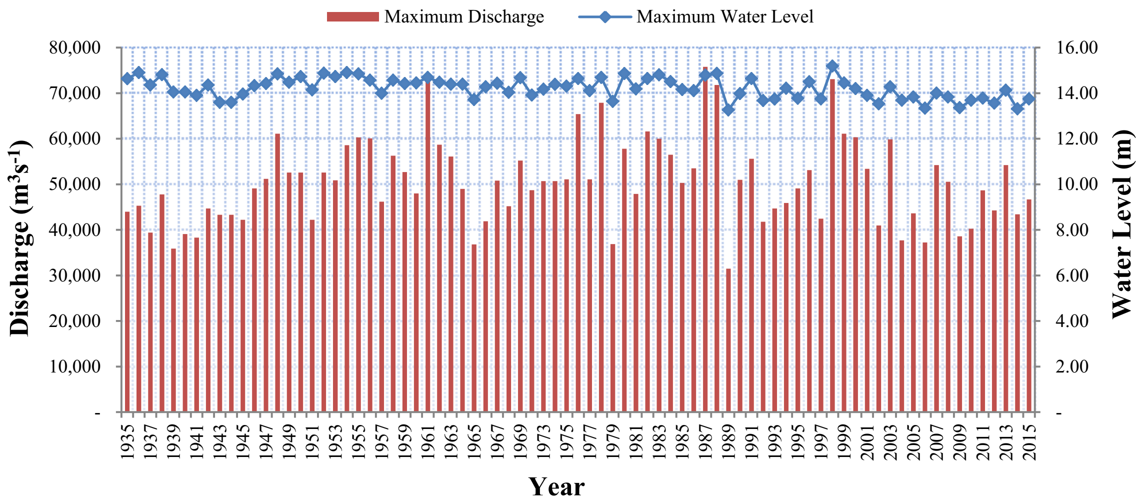

Fig. 2 Yearly maximum water levels and discharges in the Ganges river at Hardinge Bridge station during the year 1935–2015

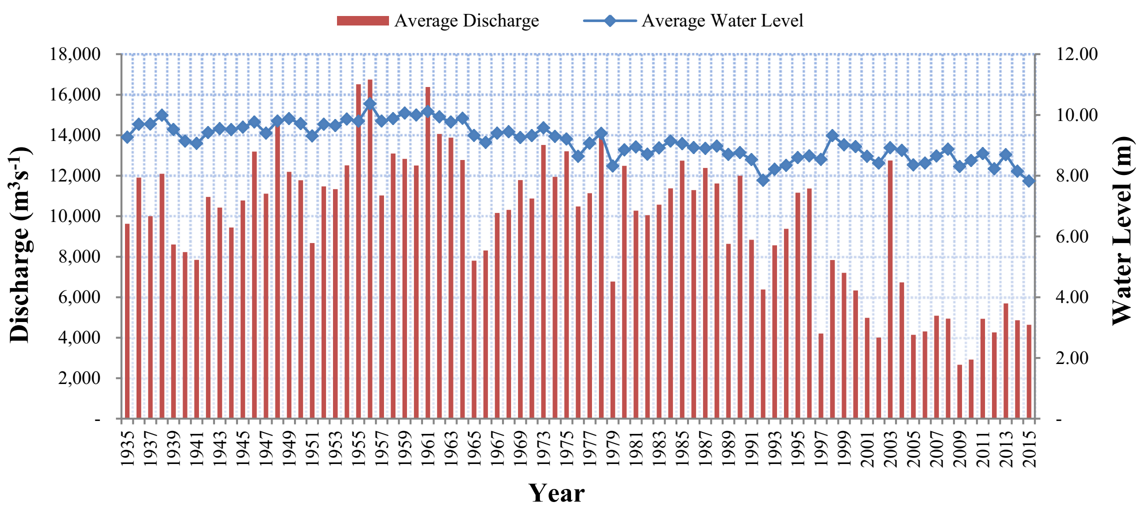

Fig. 3 Yearly average water levels and discharges in the Ganges river at Hardinge Bridge station during the year 1935–2015

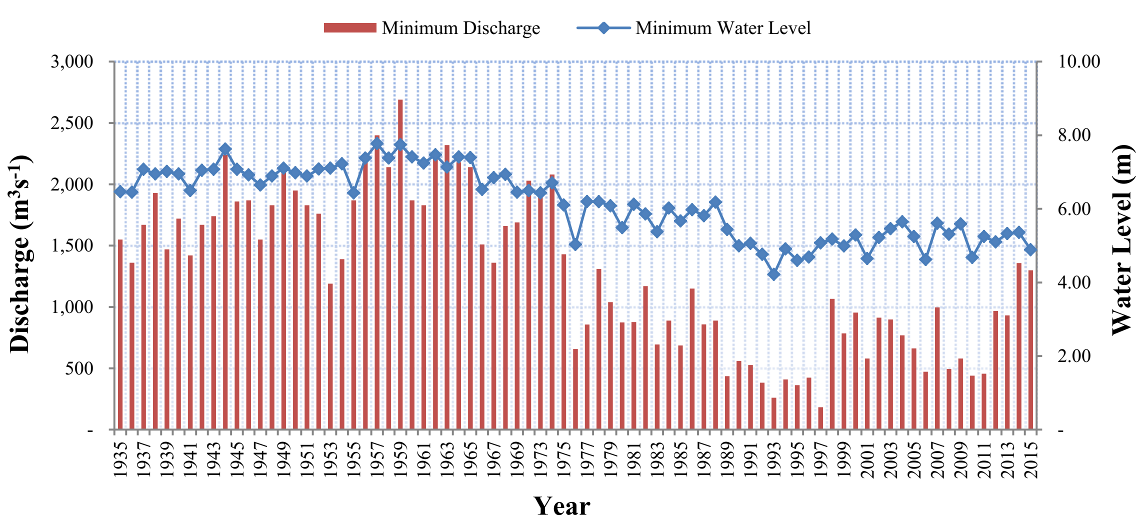

Fig. 4 Yearly minimum water levels and discharges in the Ganges river at Hardinge Bridge station during the year 1935–2015

period (1976–2015), the highest and lowest yearly average discharges were 14,183 m^3 s^{-1} (1978) and 2669 m^3 s^{-1} (2009), respectively. Similarly during pre-Farakka period, the highest and lowest yearly average water levels have been observed as 10.37 m (1956) and 9.06 m (1941), respectively. But during post-Farakka period, the highest and lowest yearly average water levels were 9.39 m (1978) and 7.82 m (2015), respectively. After 1975, the yearly average discharge declination trend is more significant than water levels.

Figure 4 shows that during pre-Farakka period (1935–1975), the highest and lowest minimum discharges (yearly) have been observed as 2690 m^3 s^{-1} (1959) and 1190 m^3s^{-1} (1953), respectively. But during post-Farakka period (1976–2015), the highest and lowest minimum discharges (yearly) were 1358 m^3 s^{-1} (2014) and 183 m^3 s^{-1} (1997), respectively. Similarly during pre-Farakka period, the highest and lowest minimum water levels (yearly) have been observed as 7.78 m (1957) and 6.11 m (1975), respectively. But during post-Farakka period, the highest and lowest minimum water levels (yearly) were 6.20 m (1977 and 1978) and 4.22 m (1993), respectively. Yearly minimum discharges and water levels both are showing more declining trend after 1975.

The results of the above analysis indicate that the impacts of Farakka barrage on discharges and water levels have been triggered an abrupt change in Bangladesh since 1975. The changes of yearly average discharges and water levels (Fig. 3) are significant, but changes in yearly minimum discharges and water levels (Fig. 4) have become more significant.

Changes in dry season discharges

The impacts of Farakka barrage on discharges and water levels in Ganges river occur during dry season. In this section, the changes in dry season (January–May) discharges of Ganges river in Bangladesh during pre-Farakka and post-Farakka periods have been analyzed (Figs. 5, 6, 7).

Figure 5 shows that the trend line of yearly maximum discharges (January–May) during pre-Farakka period (1935–1975) was upward. But in post-Farakka period (1976–2015), it has been suddenly fallen down and is almost constant. During pre-Farakka period (1935–1975), the highest and lowest yearly maximum discharges (January–May) have been observed as 5910 m^3s^{-1} (1957) and 2410 m^3s^{-1} (1953), respectively. But during post-Farakka period (1976–2015), the highest and lowest yearly maximum discharges (January–May) were 5685 m^3 s^{-1} (1998) and 1570 m^3s^{-1} (1994), respectively.

Figure 6 shows that the trend line of yearly average discharges (January–May) during pre-Farakka period has been upward, but in the post-Farakka period, it has been suddenly fallen down and found constant. During pre-Farakka period (1935–1975), the highest and lowest yearly average discharges (January–May) have been observed as 3715 m^3 s^{-1} (1957) and 1643 m^3s^{-1} (1953), respectively. But during post-Farakka period (1976–2015), the highest and lowest yearly average discharges (January–May) were 2343 m^3 s^{-1} (1998) and 713 m^3 s^{-1} (1993), respectively.

Figure 7 shows that the trend line of yearly minimum discharges (January–May) during pre-Farakka period has been upward, but in the post-Farakka period, it has suddenly and significantly fallen down and continues downward trend. During pre-Farakka period (1935–1975), the highest and lowest yearly minimum discharges (January–May) have been observed as 2690 m^3s^{-1} (1959) and 1190 m^3s^{-1} (1953), respectively. But during post-Farakka period (1976–2015), the highest and lowest yearly minimum discharges (January–May) were 1358 2343 m^3s^{-1} (20141998) and 183 m^3 s^{-1} (1997), respectively.

The results of the above analysis reveal that during pre-Farakka period, the trend lines of maximum, average and

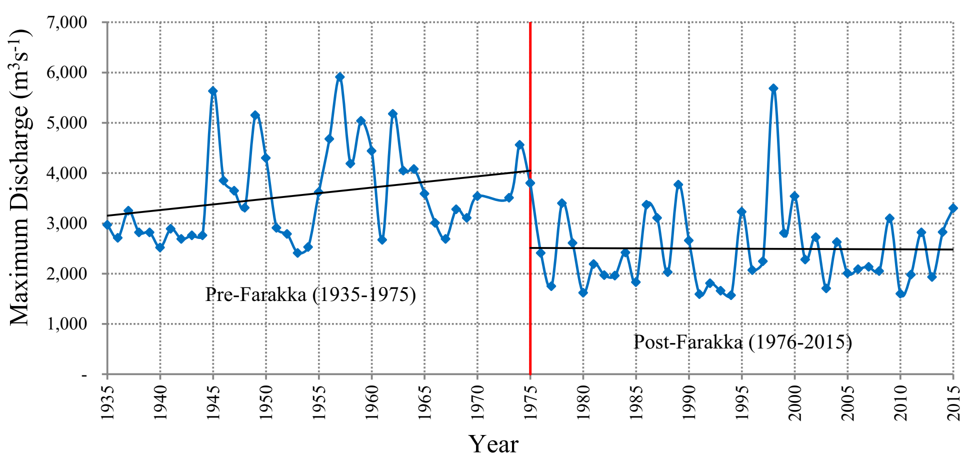

Fig. 5 Changes in dry season (January–May) yearly maximum discharges in Ganges river during pre-Farakka and post-Farakka periods at Hardinge Bridge station, Bangladesh

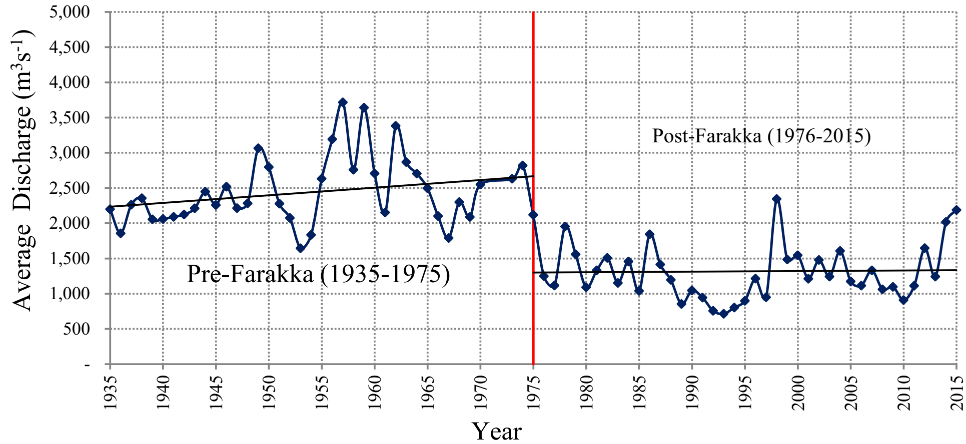

Fig. 6 Changes in dry season (January–May) yearly average discharges in Ganges river during pre-Farakka and post-Farakka periods at Hardinge Bridge station, Bangladesh

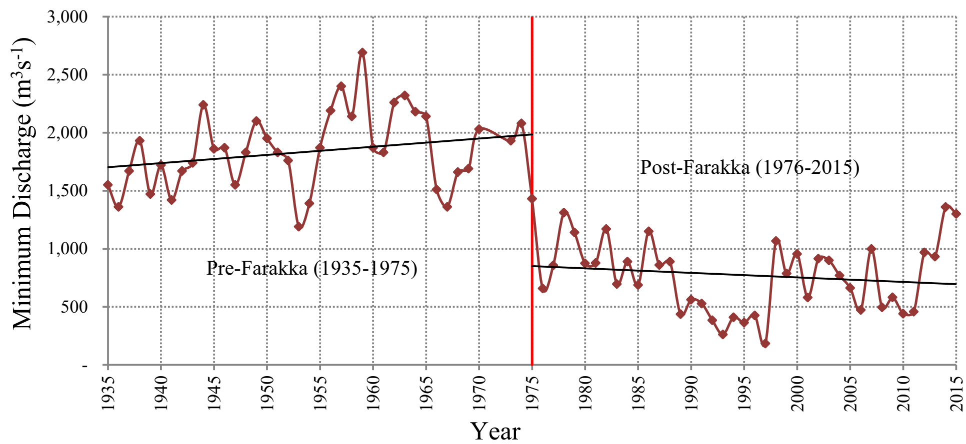

Fig. 7 Changes in dry season (January–May) yearly minimum discharges in Ganges river during pre-Farakka and post-Farakka periods at Hardinge Bridge station, Bangladesh

minimum discharges have been upward, but in the post-Farakka period, trend lines have been suddenly fallen down. During post-Farakka period, the trend lines of maximum and average discharges seem to be constant but trend line of minimum discharges indicates downward.

Changes in monthly discharges

In this section, the changes in monthly maximum, average and minimum discharges of Ganges river in Bangladesh during pre-Farakka (1935–1975) and post-Farakka (1976–2015) periods have been analyzed (Fig. 8).

Figure 8a shows that monthly maximum discharges during February–May are significantly reduced in post-Farakka period. In pre-Farakka period, monthly maximum discharges during January, February, March, April and May have been observed as 5910, 5040, 4080, 3260 and 4330 $m^3\ s^{-1}$, respectively. But in the post-Farakka period, it has been observed that during January, February, March, April and May monthly maximum discharges become 5685, 2827, 2602, 2665 and 3770 m^3s^{-1}, respectively. The maximum discharges reduction rate for the month of January, February, March, April and May is around 4, 44, 36, 18 and 13%, respectively. In each month of post-Farakka period, the monthly average discharges have been reduced except for July and September. Thus, the dry season water availability in Bangladesh has been reduced significantly after the construction of Farakka barrage.

Figure 8b indicates that the monthly average discharges have begun to reduce from November and continue up to May. During December–May, the reduction of average flow is significant. During pre-Farakka period, monthly average discharges for the months of November, December, January, February, March, April and May have been observed as 7119, 4185, 3092, 2677, 2299, 2020, and 2133 m^3s^{-1}, respectively But in the post-Farakka period, discharges during November, December, January, February, March, April and May have been observed as 5512, 2947, 1769, 1306, 1013, 971 and 1328 m^3s^{-1}, respectively. The average discharges reduction rate for the month of November, December, January, February, March, April and May is around 23, 30, 43, 51, 56, 52 and 38%, respectively.

Figure 8c states that the monthly minimum discharges in post-Farakka period have been reduced whole the year.

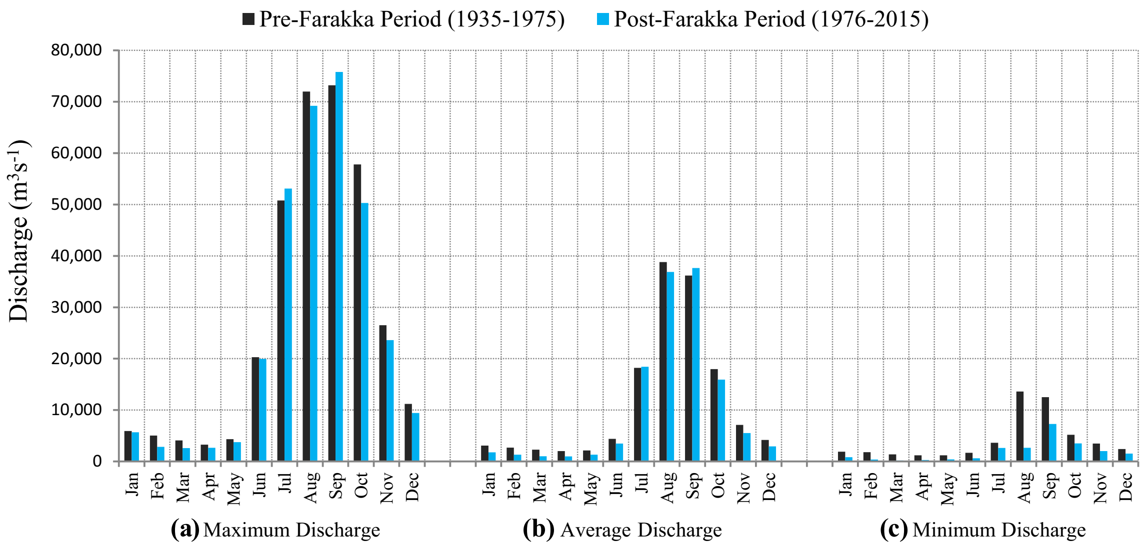

Fig. 8 Changes of monthly discharges in Ganges river during pre-Farakka and post-Farakka periods at Hardinge Bridge station, Bangladesh

During January–May, the reduction of flows is significant, but in February–April it is most significant. Pre-Farakka period monthly minimum discharges during January, February, March, April and May have been observed as 1900, 1800, 1390, 1190 and 1190 m^3 s^{-1}, respectively, but in post-Farakka period monthly minimum discharges during January, February, March, April and May have been observed as 842, 374, 183, 267 and 393 m^3 s^{-1}, respectively. The minimum discharges reduction rate for the month of January, February, March, April and May is around 56, 79, 87, 78 and 67%, respectively.

The above analyses reveal that in post-Farakka period, the monthly maximum discharges reduction is extreme during February–May. In post-Farakka period, the monthly average discharges are reduced from November to May, but reduction is significant during December–May. The monthly minimum discharges reduction has been observed round the year in post-Farakka period, but reduction is significant during January–May and it is more significant during February–April. The above analyses also reveal that in comparison with pre-Farakka (1935–1975) period, it has been observed that in post-Farakka (1976–2015) period, the maximum, average and minimum discharges have been reduced around 22, 48 and 72%, respectively, during January–May. The monthly maximum, average and minimum discharges of Ganges river at Hardinge Bridge station have been summarized for the period of pre-Farakka and post-Farakka in Tables 2 and 3, respectively.

Changes in pre- and post-discharges of Ganges Water Sharing Treaty, 1996

A 30-year treaty has signed as Ganges Water Sharing Treaty (GWT) in between Bangladesh and India on 12th December, 1996. As per provision of treaty, the Ganges flow measures jointly at Hardinge Bridge station for the period of 1st January to 31st May each year since 1997 (JRC 2015).

Changes of monthly maximum, average and minimum discharges among pre-Farakka, pre-GWT and post-GWT have been analyzed and the possible outcomes are as follows. Pre-GWT refers to the period 1976–1996 and post-GWT refers to the period 1997–2015.

Figure 9a shows that in post-GWT period, the monthly maximum discharges have been increased for the months of January, February, March and April around 69, 27, 16 and 41%, respectively, but for the month of May monthly maximum discharges has been decreased around 6% compared to that of pre-GWT period. This figure also shows that compared to pre-Farakka period, the monthly maximum discharges have remain reduced for the months of January, February, March, April and May around 4, 44, 36, 18 and 18%, respectively, in post-GWT period.

Figure 9b shows that, in comparison to pre-GWT period, the monthly average discharges in post-GWT period have been increased during January, February, March, April and May around 19, 22, 23, 24 and 4%, respectively, but compared to pre-Farakka period, the monthly maximum discharges have remain reduced for the months of January, February, March, April and May around 37, 45, 50, 46 and 36%, respectively, in post-GWT period.

Figure 9c shows that in post-GWT period the monthly minimum discharges have been increased for the months of January, February, April and May around 23, 69, 23 and 16%, respectively, but for the month of March discharges have been decreased around 30% compared to that of pre-GWT period. This figure also shows that compared to pre-Farakka period (1935–1975), monthly maximum

Table 2 Monthly maximum, average and minimum discharges of Ganges at Hardinge Bridge station in Bangladesh during pre-Farakka period

Discharge ($m^3 s^{-1}$)	Pre-Farakka period (1935–1975)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	5910	5040	4080	3260	4330	20,300	50,800	72,000	73,200	57,800	26,500	11,200
Average	3092	2677	2299	2020	2133	4387	18,214	38,812	36,179	17,978	7119	4185
Minimum	1900	1800	1390	1190	1190	1680	3620	13,600	12,500	5190	3480	2410

Table 3 Monthly maximum, average and minimum discharges of Ganges at Hardinge Bridge station in Bangladesh during post-Farakka period

Discharge ($m^3 s^{-1}$)	Post-Farakka period (1976–2015)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	5685	2827	2602	2665	3770	19,952	53,107	69,200	75,800	50,300	23,600	9441
Average	1769	1306	1013	971	1328	3494	18,418	36,869	37,635	15,917	5512	2947
Minimum	842	374	183	267	393	622	2620	2651	7300	3524	2010	1520

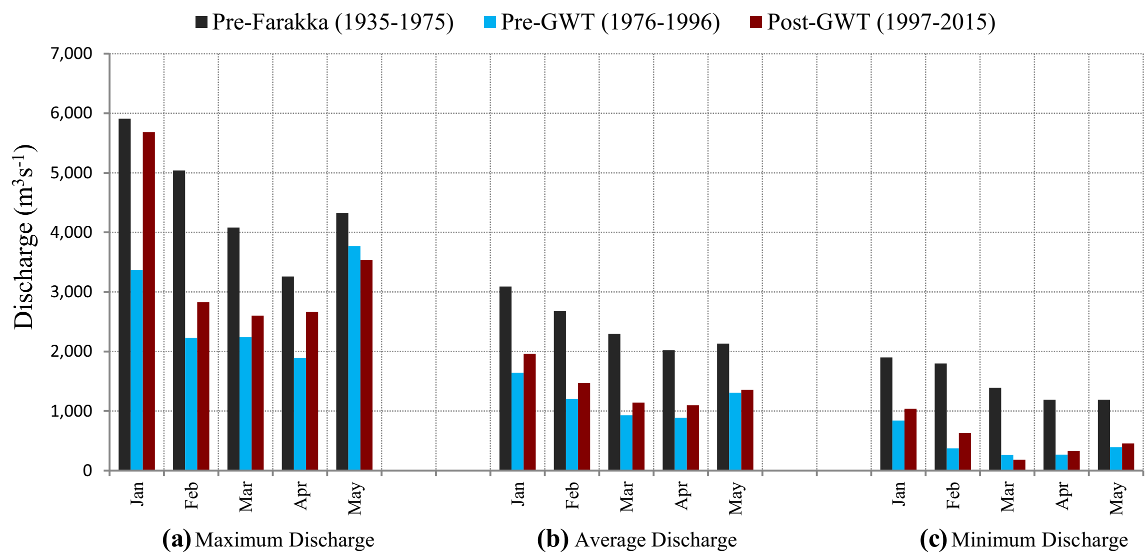

Fig. 9 Variations of monthly maximum, average and minimum discharges for pre-Farakka (1935–1975), pre-GWT (1976–1996) and post-GWT (1997–2015) periods in the Ganges river at Hardinge Bridge station

discharges have remain reduced for the months of January, February, March, April and May around 45, 65, 87, 72 and 62%, respectively, in post-GWT period.

The above analyses reveal that during post-GWT period, the monthly maximum, average and minimum discharges have been slightly increased in dry season (January–May) compared to that of pre-GWT period, except May for maximum discharges and March for minimum discharges. But in comparison with pre-Farakka period, it has been observed that during post-GWT period, the maximum, average and minimum discharges have remain reduced around 23, 43 and 65%, respectively, in dry season (January–May). The monthly maximum, average and minimum discharges have been summarized in Table 4.

Vulnerable impacts in south-western region due to reduced Ganges flow

Fresh water flow of the Ganges maintains the ecological balance in south-western region of Bangladesh through controlling salinity intrusion and abnormal sediment deposition (BWDB 2012). The dry season flow of the Ganges has decreased drastically since 1976 after the

Table 4 Monthly maximum, average and minimum discharges of Ganges at Hardinge Bridge station in Bangladesh during the pre-Farakka, pre-GWT and post-GWT period

Discharge ($m^3 s^{-1}$)	Pre-Farakka (1935–1975)					Pre-GWT (1976–1996)					Post-GWT (1997–2015)				
	Jan	Feb	Mar	Apr	May	Jan	Feb	Mar	Apr	May	Jan	Feb	Mar	Apr	May
Maximum	5910	5040	4080	3260	4330	3370	2230	2240	1890	3770	5685	2827	2602	2665	3539
Average	3092	2677	2299	2020	2133	1644	1202	929	887	1309	1962	1468	1143	1097	1357
Minimum	1900	1800	1390	1190	1190	842	374	261	267	393	1040	631	183	328	457

commissioning of the Farakka barrage in India (see "Data analyses and results"). This flow alteration has had a significant effect on the social–ecological system of Bangladesh through disruption to fisheries, forestry, agriculture, navigation and increasing salinity intrusion from the coast (Gain and Giupponi 2014). Some vulnerable impacts in south-western region of Bangladesh have been discussed below.

Salinity intrusion

The south-western regional rivers of Bangladesh are subject to tides from the Bay of Bengal twice a day. The tides bring saline water through the rivers and overflow into the adjacent lands damaging these with salt deposits. The intrusion of salinity inland is regulated by the upstream fresh water flow through the rivers (Shahjahan 1998). Due to the long-term reduction of the Ganges flow, salinity is continuously creeping up inland and causing a drastic effect on environment. Rahman and Asaduzzaman (2010) stated that the salinity of this region has been increased from 380 μΩ/cm during the pre-diversion period in 1974 to about 29,500 μΩ/cm in 1992.

Salinity in the rivers systems of the south-western region of Bangladesh increases steadily from December to February, reaching maximum in the late March and early April (BWDB 2001). It means that the salinity concentrations of the south-western rivers are higher in the dry season than in the monsoon because of fresh water flow reduction from upstream. "Changes in yearly water levels with discharges" and "Changes in dry season discharges" also reveal that Ganges flow starts to decrease from December to February and reaches more critical in March, April and May.

The Gorai river is important for Bangladesh as it is the largest perennial distributary of the Ganges river. It provides the major fresh water supply to the south-western region of Bangladesh. Therefore, it is also crucial in controlling salinity intrusion and to the maintenance of Sundarbans, the largest mangrove forest in the world (Bharati and Jayakody 2011). Mirza (1998) stated that according to FAP 4 (1993) and FAP 24 (1993), it is the physical intervention in the Ganges flow that has accelerated sedimentation in the Gorai mouth during post-Farakka period (1975–1996), which has almost isolated it from the Ganges river. In 1996, the Government of Bangladesh has initiated the Gorai River Restoration Project. The main target of this project is to augment the flows in the Gorai river and ensure flow in the dry season (Clijncke 2001). The Project was commenced in 1998 and targeted for completion in 2017 (MoP 2014).

Agriculture

It is anticipated that withdrawal of fresh river water from upstream is one of the main causes of increased soil salinity in the topsoil of the coastal region. The highest salt accumulation is observed in Ganges tidal floodplain (SRDI 2012). A comparative study of soil salinity during the last four decades (1973–2009) in coastal areas in Bangladesh has been presented in Table 5. A rise of soil salinity has been noticed since 1975.

Salinity causes unfavorable environment and hydrological situation that restricts the normal crop production throughout the year. The severity of salinity problem in Bangladesh increases with the desiccation of the soil which affects the crop production depending on the degree of

Table 5 Extent of soil salinity in Bangladesh during the last four decades (1973–2009). Source: SRDI 2012

Saline affected area ('000'ha)			Saline affected area increasing during last 9 years ('000'ha) (2000–2009)	Saline affected area increasing during last 36 years ('000'ha) (1973–2009)
Y-1973	Y-2000	Y-2009		
833.45	1020.75	1056.26	35.51 (3.5%)	222.81 (26.7%)

salinity at the critical stages of growth, which reduces yield and in severe cases the total yield is lost (Ahmed et al. 2013).

The Ganges–Kobadak (GK) Irrigation Project, the largest surface water irrigation project in the country, was conceived of in 1954 to improve the quality of life and economic solvency of the people living in south-western region by achieving self-sufficiency in food through increasing agricultural productivity (Gain and Giupponi 2014), but the project is in trouble due to available surface water. The GK project had totally failed to supply water during 1992–1996 due to low flow in Ganges. The project became operational again after signing of the water sharing treaty with India in 1996 (The Kushtia Times 2015).

Fisheries

Bangladesh is well known for its fish wealth and it has a vital importance to the diet of the people of Bangladesh. South-western region is highly dependent on the Ganges river for supply of fresh water. The water diversion at Farakka has caused the destruction of the breeding and raising grounds for 109 species of Gangetic fishes and other aquatic species and amphibians in Bangladesh (Gain and Giupponi 2014). A study conducted by Opstal (2006) on fresh water fisheries in the south-western region of Bangladesh observed that compared to the situation before 1975, the fish catch has been reduced by $^{1}/_{10}$ to $^{1}/_{3}$ and millions of fishermen have lost their fishing job.

Due to the long-term reduction of the Ganges flow, fresh water fish diversity has been negatively affected by increased salinity in the south-western region of Bangladesh. Another study undertaken by Gain et al. (2008) on salinity prone areas in south-western region of Bangladesh such as high saline (20,000–45,000 μΩ/cm) zone and moderate saline (10,000–30,000 μΩ/cm) zone, namely Paikgacha and Rampal, found that due to increased salinity, the fish species in Paikgacha and Rampal have been reduced from 29 to 12 and 24 to 19 species, respectively, during the period 1975–2005.

Forestry

Sundarbans is the largest mangrove forest in the world and also a UNESCO World Heritage Site. Sunderbans is formed about 7000 years ago by the deposition of sediments from the foothills of the Himalayas through the Ganges river system. However, over the last 40 years or more, the discharge of sediment-laden freshwater into the Bay of Bengal from the Ganges river through the Bangladesh part of the Sundarbans has been reduced due to withdrawal of water at Farakka during the dry season (Aziz and Paul 2015).

In the Sundarbans forest, there is an extensive network of tidal rivers and streams, together with small, local drainage channels. The main mangrove species in the Sundarbans are: Sundari (*Heritiera fomes*), Gewa (*Excoecaria agallocha*), Keora (*Sonneratia apetala*), and Goran (*Ceriops decandra*). These species need fresh water as well as saline water for their regeneration and growth. Lack of adequate fresh water because of upstream diversion already poses a threat to the Sundarbans ecosystem by causing the degeneration of freshwater plants (Mirza 1998).

Soil salinity intrusion has been increased gradually in the south-western region after post-diversion period by the upstream Farakka barrage (see Table 5). Upstream water flow control the soil salinity that helps maintaining the biodiversity of Sunderbans in Bangladesh. Rahman and Asaduzzaman (2010) stated that 68% forest resources have been reduced during 1985–2000. By analyzing from the forest department's top dying marking and felling registers, the study also reveals that out of 85,525 trees, 17% of top dying trees were totally dead.

Navigation

The greater districts of Kushtia, Jessore, Barisal, Faridpur and Khulna located in the Ganges basin receive fresh water supplies through the distributaries of the Ganges like the Ichamati, Nabaganga, Bhairab, Kumar, Gorai, Madhumati, etc. (BWDB 2012). Inland navigability of this region has been adversely affected in dry season due to significant reduction of Ganges water (see "Changes in yearly water levels with discharges", "Changes in dry season discharges" and "Changes in monthly discharges") at Farakka barrage in India.

Inland water transport is the less expensive form of transport in Bangladesh and in the south-western region of the country the most cost effective. There are presently about 6000 km of navigable waterways in the wet season and 3800 km in the dry season. This is significantly lower than in 1970 when the navigable waterways during the wet season were about 13,500 km and the dry season waterways were 8500 km in length. An estimated 3 million people rely on inland water transport for their livelihoods (The World Bank 2005). Navigability of rivers in Bangladesh has been deteriorating over a long period. Both natural and morphological processes and the withdrawal of water from the river beyond the border and within Bangladesh for irrigation and other purposes have resulted in a decreased dry season navigability of the rivers as well as decline in channel depths (MoEF 2009).

Environmental flows

An environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. Environmental flows provide critical contributions to river health, economic development and poverty alleviation. They ensure the continued availability of the many benefits that healthy river and groundwater systems bring to society (IUCN 2003).

Article 8 of ILA Berlin Rules on Water Resources (2004) mentioned that States shall take all appropriate measures to prevent or minimize environmental harm. Article 15 of 2004 ILA Berlin Rules on Water Resources (ILA 2004) emphasizes on the need to assure ecological flows or otherwise to maintain ecological integrity or to minimize environmental harm. Article 24 also stated that States shall take all appropriate measures to ensure flows adequate to protect the ecological integrity of the waters of a drainage basin, including estuarine waters.

Due to the long-term unilateral withdrawal of Ganges water at Farakka, the downstream part of Ganges basin located in Bangladesh has been facing environmental harm.

Concluding remarks

This research has following findings:

The impacts of Farakka barrage on discharges and water levels have been triggered an abrupt change in Bangladesh since 1975. The changes are significant in yearly average discharges and water levels but changes are more significant in yearly minimum discharges and water levels (see "Changes in yearly water levels with discharges").

The trend line of yearly maximum, average and minimum discharges in dry season (January–May) during pre-Farakka period (1935–1975) indicates upward, but in the post-Farakka (1976–2015) period, they have been suddenly fallen down and trend line of minimum discharges shows downward (see "Changes in dry season discharges").

During post-Farakka period (1976–2015), monthly maximum discharges extremely reduced in February–May and monthly average discharges reduction is significant in December–May. Monthly minimum discharges in post-Farakka period have been reduced round the year, during January–May this reduction is significant but February–April it is more significant. In comparison with pre-Farakka period (1935–1975), it has been observed that during post-Farakka period (1976–2015), the maximum, average and minimum discharges have been reduced around 22, 48 and 72%, respectively, in dry season (January–May) (see "Changes in monthly discharges").

In post-GWT (1997–2015) period, it has been observed that the overall monthly discharges during dry season (January–May) have been slightly increased compared to that of pre-GWT (1935–1996) period, except May for maximum discharges and March for minimum discharges. But, in comparison with pre-Farakka (1935–1975) period, it has been observed that during post-GWT (1997–2015) period, the maximum, average and minimum discharges have remain reduced around 23, 43 and 65%, respectively, in dry season (January–May) (see "Changes in pre and post discharges of Ganges Water Sharing Treaty, 1996").

Salinity in the river system has been increased from 380 μΩ/cm during the pre-diversion period in 1974 to about 29,500 μΩ/cm in 1992 (Rahman and Asaduzzaman 2010). Breeding and raising grounds for 109 species of Gangetic fishes, other aquatic species and amphibians in Bangladesh have been destructed due to diversion of fresh water at Farakka (Gain and Giupponi 2014). Soil salinity poses an unfavorable situation for agriculture throughout the year; it has been observed that salinity has been increased in the topsoil of the coastal region about 26.7% during post-diversion period (1973–2009) (SRDI 2012). It has also observed that 68% of forest resources have been reduced during period of 1985–2000 (Rahman and Asaduzzaman, 2010). Navigable waterways are around 6000 km during summer and 3800 km during winter, but before 1970 they were around 13,500 km during summer and around 8500 km during winter (The World Bank 2005). Findings indicate that south-western region of Bangladesh has been suffering from environmental harm through disruption to fisheries, forestry, agriculture, navigation and salinity intrusion towards inland due to long-term significant alteration of the Ganges flow at Farakka barrage for about 40 years or more.

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