RESEARCH

Diversion of the Ganges Water at Farakka and Its Effects on Salinity in Bangladesh

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ABSTRACT / The Ganges River supplies water to the southwest region of Bangladesh mainly through one of its distributaries—the Gorai River. India commissioned a barrage on the Ganges River at Farakka in April 1975 to divert water and make the Bhagirathi-Hooghly River navigable. The diversion has reduced the dry season discharge of the Ganges and Gorai rivers in Bangladesh. Statistical analyses indicate that the changes in the dry season discharge of these rivers are significant. Reduced discharge in the Gorai River has induced accelerated sedimentation and increased salinity in the southwest region of Bangladesh. Empirical analyses demonstrate the relationship between discharge in the Gorai River and salinity. Analyses also determine the requirement of flow for the Ganges and Gorai rivers to keep salinity at threshold limits. Increased salinity has caused negative effects on agriculture, forestry, industry, and drinking water in the southwest region of Bangladesh.

The Ganges is one of the largest river systems in the world. It rises south of the main Himalayan divide near Gangotri (elevation 4500 m) in Uttar Pradesh, India. On its way to the sea, numerous tributaries join the Ganges from India and Nepal. The river divides into two channels below Farakka. The right arm continues to flow south through West Bengal as the Bhagirathi-Hooghly, on which the Port of Calcutta is situated. The left main arm enters Bangladesh 18 km below Farakka and joins the Brahmaputra River at Goalundo.

The Ganges basin is distributed over parts of China, India, Nepal, and Bangladesh (Figure 1). Agriculture is the main economic activity in the basin and about 64% of the land is cultivable (Mirza 1997a). Most of this agriculture is dependent on water from the Ganges River. The population directly or indirectly dependent on the Ganges River is estimated to be about 410 million (Verghese and Iyer 1993).

Bangladesh is located at the tail end of the Ganges basin. During the dry season (November–May) in the Bangladesh part of the basin, adequate water supply from the upstream stretch of the Ganges River is important for agriculture, forestry, industry, fisheries, and drinking water supplies. It is also vital for maintaining river depths for navigation and keeping in check inland penetration of saline water from the Bay of Bengal. Before 1975, dry season flow in the Ganges River was adequate to meet water requirements in the Bangladesh part of the basin. However, the river flow declined significantly when India commissioned a barrage in 1975 on the Ganges River at Farakka, 18 km from the western border of Bangladesh. The Port of Calcutta is dependent on the navigability of the Bhagirathi-Hooghly River. Construction of the barrage was aimed at restoring the navigability of the Bhagirathi-Hooghly River by diverting 1133 m^3/sec (40,000 ft^3/sec) of water from the Ganges River.

The diversion of water by the Farakka Barrage has introduced significant changes in the hydrology of the Ganges River system[1] in Bangladesh. Available discharge data show that the water supply during July–October in the monsoon has increased while the dry season (November–May) flow has decreased considerably. Increased monsoon flow has introduced changes in the annual flooding pattern in Bangladesh (Khan 1993). There are concerns that the reduced dry season flow may have significant socioeconomic impacts in the Bangladesh part of the basin by altering the hydrological pattern, inducing accelerated sedimentation in the Gorai River (an offtake of the Ganges) and helping saline water to penetrate further inland from the sea (MOEF 1995, Swain 1996). So far, these concerns have been based on general observations rather than statistical analyses of relevant data.

The objectives of this article are to study: (a) the effects of the Farakka Barrage on mean monthly discharge of the Ganges River; (b) the consequent effects of diverted water on the mean monthly discharge of the

KEY WORDS: Bangladesh; Ganges River; Gorai River; Farakka diversion; Salinity

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[1] The Ganges River system in Bangladesh includes mainly the Ganges River; Mahanada, an important tributary; and the Gorai, Mathabhanga and Arial Khan rivers, three distributaries. This article considers changes in the Gorai River (the most important distributary) which supplies water to the southwest region of Bangladesh.

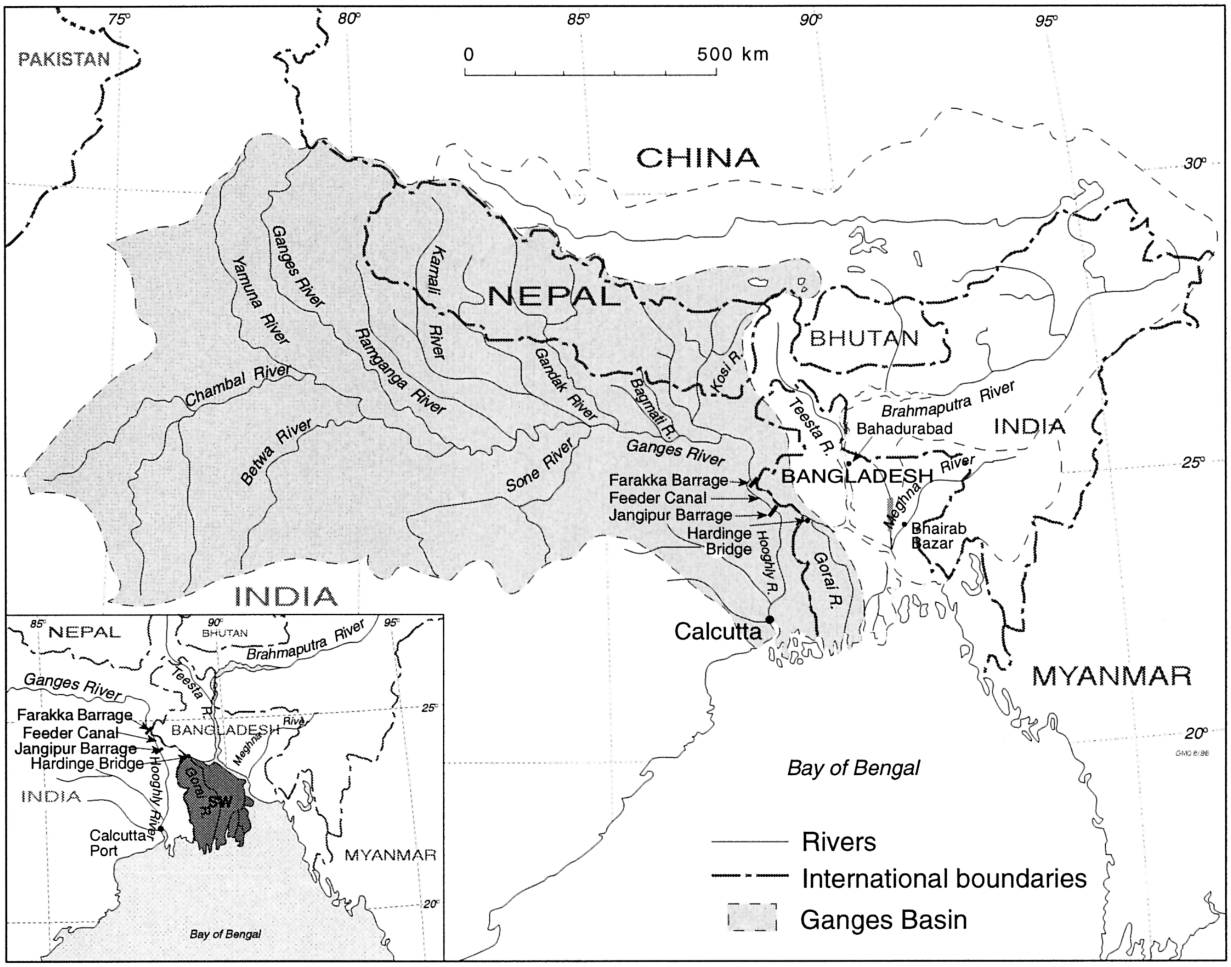

Figure 1. The Ganges River Basin and Farakka Barrage project. Area (shaded) dependent on the flow of the Ganges River is shown in the inset.

Gorai River and on salinity in an area in the south-west region of Bangladesh; and (c) the effects of increased salinity on agriculture, forestry, industry, and drinking water sectors.

Farakka Barrage and Diversion of the Ganges Water

The entire Farakka Barrage scheme comprises a barrage across the Bhagirathi River at a place about 6.5km upstream of the town of Jangipur and a feeder canal taking off from the Ganges River upstream of the Farakka Barrage and rejoining into the Bhagirathi River downstream of the Jangipur Barrage (Figure 1) (Begum 1987, Abbas 1984). The project plunged India and Pakistan into protracted negotiations from 1952 to 1970. After the independence of Bangladesh from Pakistan in 1971, negotiations for an amicable solution to sharing the water of the Ganges continued.

Under a temporary agreement signed in April 1975, Bangladesh consented to a "test operation" of the Farakka Barrage for 41 days (21 April–31 May). India was allowed to divert 312–454 m^3/sec (11,000–16,000 ft^3/sec) of water in various periods as specified in the agreement (Abbas 1984). After expiry of the temporary agreement, India unilaterally withdrew water from June 1975 to November 1977 (Abbas 1984). A five-year agreement on the sharing of the Ganges waters was signed in November 1977. The agreement expired in 1982, but the sharing arrangement was renewed twice with some modifications[2] under the "memoranda of understanding." The first memorandum of understand-

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[2] The first MOU was a modified version of the 1977 Sharing Agreement on the Ganges Waters. Under Clause ii of Article II of the agreement, in case of exceptionally low flow, Bangladesh was guaranteed 80% of the flow to be released to it as agreed upon in the agreement. This clause was deleted from the first MOU signed in October 1982.

ing (MOU) was signed in October 1982 and the second in November 1985.

During 1988–1996, there was no sharing arrangement between Bangladesh and India on the dry season flow of the Ganges River. In 1991 and 1992, the dry season availability of water (measured at Hardinge Bridge in Bangladesh) fell below the level of an earlier nonagreement period (June 1975–November 1977). It was observed that substantial changes in the Ganges River flow generated effects on the Gorai River and the area dependent on it (Figure 1). In the dry season, reduced flow in the Gorai River exacerbated problems of salinity in the southwest region of Bangladesh. Increased salinity adversely affected agricultural, forestry, industrial production, and drinking water (Khan 1993). A 30-year treaty on sharing the Ganges waters was signed on 12 December 1996. For details of the treaty, its possible implications, and implementation see Dixit and Mirza (1997) and Mirza (1997b).

The Data

This study is based on analyses of hydrological and salinity data collected from various agencies. Daily discharge data for the Ganges at Hardinge Bridge in Bangladesh for the period 1965–1992 were collected from the Bangladesh Water Development Board in Dhaka (BWDB 1995a). Monthly mean discharge data for the Ganges at Farakka (1949–1988) were supplied by the Global Runoff Data Centre (GDRC 1995), Koblenz, Germany, and the Indo-Bangladesh Joint Rivers Commission (JRC 1995a), Dhaka, Bangladesh. For the Gorai River, daily discharge and water-level data were supplied by the BWDB (1995b) for the period 1964–1993.

The hydrological data sets contained some missing observations, which were estimated (up to a reasonable limit). In the BWDB discharge set, observations for 1971 were missing. Missing monthly mean discharge records for the Hardinge Bridge site were estimated by correlating with the Farakka Barrage site and applying the method of Salinger (1980). For the Farakka Barrage site, four years of monthly mean records (1961–1964) are missing. These missing records were not estimated because corresponding observations for the Hardinge Bridge site were also unavailable. For purposes of analysis, 1965 was therefore considered as the base year. Missing observations in the salinity data were not estimated because the records of the nearby stations were also missing. Station-wide monthly maximum salinity data (measured at 25°C) for various periods for the stations Khulna, Goalpara Power Station, Chalna, and Mongla (Figure 2) have been supplied by the JRC (1995b).

Analytical Methods

Four specific types of analyses were performed. First, the discharge time-series data for the Ganges River at Hardinge Bridge and Farakka stations and for the Gorai River at Gorai Railway Bridge were divided into pre- and post-Farakka periods. Then, monthly mean discharges for the two periods were calculated. The parametric Student's *t* test, Cramer's test, and the nonparametric Kruskal-Wallis test and Mann-Whitney U test were applied to determine the significance of the changes in the mean of the discharge values. Critical values for two-sided probability were used in all four tests with a 0.05 significance level. The unbiased standard deviation (SD) weas calculated using the following formula:

$$SD = \sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}$$

and the coefficient of variation (CV) was determined by dividing the standard deviation by the corresponding mean monthly discharge value. Second, besides the statistical analysis, the possible effect of the reduced flow in the Ganges River on the Gorai River was examined by reviewing the sedimentation process from the published literature. Third, effects of the reduced flow in the Gorai River on salinity were examined by fitting logarithmic equations to monthly mean discharge and maximum salinity data at Khulna station. Discharge requirements for the Gorai River for the two threshold salinity levels for February, March, and April were determined from the fitted equations. The corresponding discharge for the Ganges at Hardinge Bridge was determined from the monthly linear regression relationships between the monthly mean discharge of the Gorai and Ganges rivers. The adequacy of the regression models was checked by the standard methods. Fourth, implications of the increased salinity on agriculture, forestry, industry, and drinking water were considered based on secondary information.

Changes in Mean Monthly Discharge of Ganges and Gorai Rivers in Bangladesh

This section discusses changes in the monthly mean discharge of the Ganges and the Gorai rivers that occurred during the post-Farakka period (1975–1992). Reduced dry season flow in the Gorai River and its effects on increased salinity is discussed in the next section.

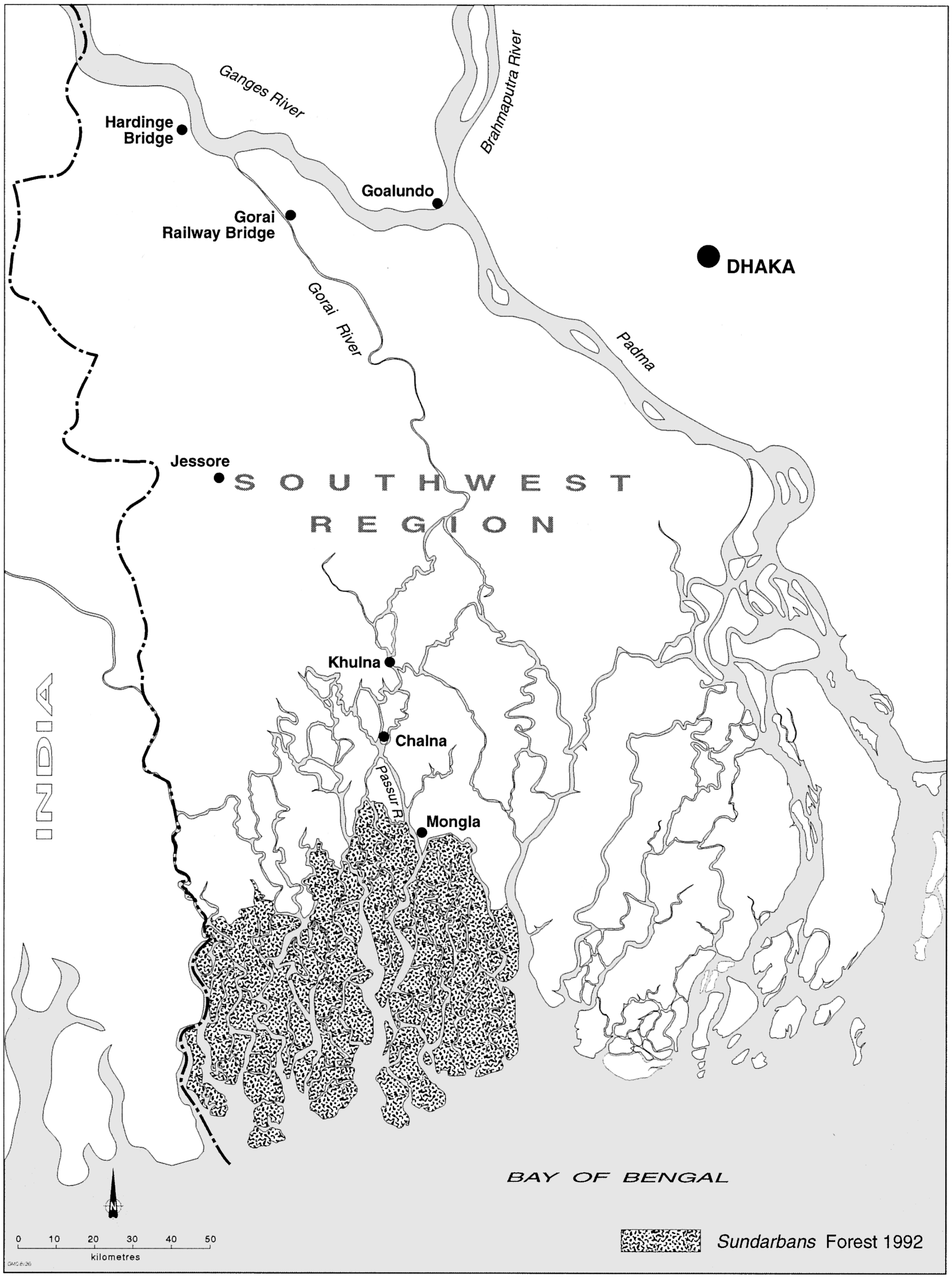

Figure 2. The southwest region of Bangladesh. Locations of the salinity recording stations and the Sundarbans are also shown.

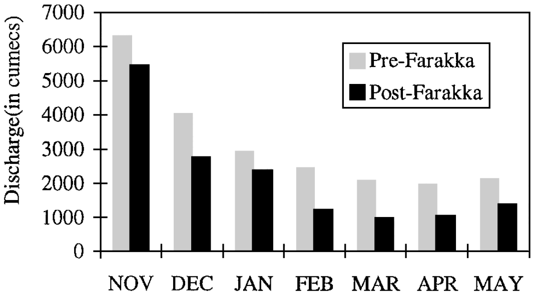

Figure 3. Mean monthly discharge of the Ganges River at Hardinge Bridge in Bangladesh for the seven months of the dry season. Cumecs refers to 1 m^3/sec flow of water.

Ganges River at Hardinge Bridge

Spectacular effects of diversion are noticed in the mean monthly discharges (Figure 3). Inspection of Table 1 shows that the monsoon months (June–October) experienced an increase (except June) in discharge while the dry months (November–May) had a substantial decrease. Increases in the monsoon discharge possibly resulted from the changes in the frequency of various discharge groups. FAP 4 (1993a) reported that increases in the frequency of discharge greater than 50,000 m^3/sec occurred in the post-Farakka period.

In the post-Farakka period, low flows below 2500 m^3/sec are more pronounced in the dry season (FAP 4 1993a). The decrease in the dry season flow is worst in February and March, followed by April and May. Statistical tests found changes in the flows of the dry months to be significant.

Apart from the changes in the mean monthly discharge in the pre- and post-Farakka periods, it is also important to compare changes that occurred in the agreement and the nonagreement periods. The magnitude of reduction for each month is comparable with the pre- and post-Farakka periods (Table 2). It demonstrates that March is also the worst month in the nonagreement period.

Changes in the other statistical parameters are also noticeable. For example, in the dry season, the standard deviation has increased for February, March, and April. All months of the monsoon also show increases in standard deviation. In order to reveal the relationship between regulation of discharge and changes in standard deviation, regression analyses were conducted. Standard deviations of the five months of the dry season of pre- and post-Farakka periods were regressed on the corresponding mean monthly discharge values. Mean monthly dry season discharges of the pre- and post-Farakka period explain 43% and 95% of the variations, respectively. The high R^2 value for the post-Farakka period is likely due to the regulation of discharge. The results demonstrate conformity with the findings from other parts of the world having regulation problems (UNESCO 1976).

The coefficients of variation (CVs) have also changed throughout the dry season and monsoon. The changes in the CVs in the monsoon seem to be considerably less than those for the dry season. High variations in the CVs in the dry season demonstrate various magnitudes of regulation in various periods in a given month. For example, in the agreement period, water was regulated based on the sharing formula adopted for each 10-day cycle from 1 January to 31 May. However, during the nonagreement period, the magnitude of regulation was not known, but assumed to be considerable, as evident from Table 2.

Gorai River at Gorai Railway Bridge

In the post-Farakka period, a notable decline occurred in the discharge of the Gorai River. This decline coincided with particularly low flows in the Ganges due to extraction upstream at Farakka (FAP 4 1993a). Significant aggradation in the river, especially at its mouth, was also noticed. The river receives a very low discharge in the dry months mainly due to reduced flow in the Ganges River. Changes in the mean monthly discharge in the Gorai offtake and associated causes are discussed below.

Mean monthly discharge. Mean monthly discharge for all months except July decreased significantly during the post-Farakka period. With regard to the seven months of the dry season, changes in the Gorai River discharge are relatively greater than those for the Ganges River. Recorded observations for the Gorai River show that the discharge starts to decrease significantly in October and gradually continues until April. The analysis indicates that April is the worst month as the discharge decreased by 73% followed by 68% for March. On an average, the December–February discharge was reduced by 63%. A 58% decrease occurred for the May discharge (Figure 4).

As noted before, India continued diversion of the Ganges water at Farakka after the expiration of the temporary agreement of 1975. The consequence of the diversion became evident in the discharge of the Gorai River in the dry season of 1976. The signing of the 1977 sharing agreement on the Ganges water helped improve the flow situation in the Gorai River. However, the situation changed later when the Ganges agreement expired in 1988. Since then, the dry season flow of the Ganges River at Hardinge Bridge has dropped further (Table 2). The dry season discharge of the Gorai River also dropped sharply and reached zero in the dry

Table 1. Statistical parameters of mean monthly discharges of Ganges River at Hardinge Bridge in pre- and post-Farakka periods[a]

Statistical parameter	Dry months							Monsoon months				
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Mean discharge (m^3/sec)	6,323 5,432	4,039 2,741	2,938 1,663	2,473 1,202	2,093 959	1,987 1,044	2,138 1,382	4,268 3,455	15,955 19,025	34,322 37,766	31,944 37,761	14,921 15,896
Change (%)	−14	−32	−44	−51	−54	−47	−35	−19	+19	+10	+18	+7
Standard deviation (m^3/sec)	1,524 2,088	674 660	444 430	329 383	293 371	318 384	412 408	1,341 1,750	3,908 6,910	8,199 9,311	7,528 9,861	5,670 6,982
Change (%)	+37	−2	−3	+16	+26	+21	−1	+30	+77	+14	+31	+23
Coefficient of variation (CV) (%)	24 38	17 24	15 26	13 32	14 39	16 37	19 30	31 51	25 36	24 25	24 26	38 44

[a] The upper and lower figures in rows 1, 2, 3, 4, and 5 indicate pre- (1965–1974) and post-Farakka (1975–1992) values.

Table 2. Mean monthly discharge of Ganges River at Hardinge Bridge for dry season in agreement (1977–1988) and nonagreement (1989–1992) periods

	Observed discharge (m^3/sec)		
Month	Agreement period	Nonagreement period	Decrease (%)
November	5,718	4,402	23.0
December	2,890	2,215	23.0
January	1,723	1,344	22.0
February	1,318	731	45.0
March	1,071	538	50.0
April	1,144	659	42.0
May	1,493	1,063	28.0

Source: BWDB (1995a).

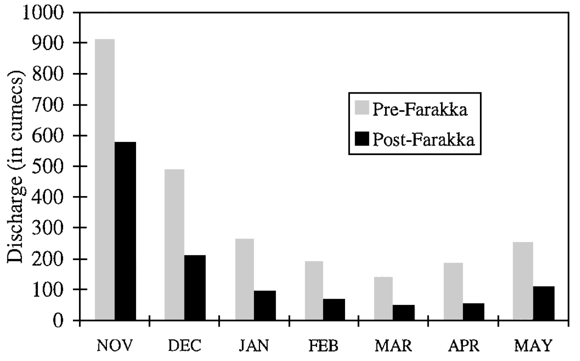

Figure 4. Dry season (November–May) mean monthly discharge of the Gorai River.

season of 1992. It should, however, be noted that a shorter period of decline in discharge occurred in the early 1950s. It is also reported that the low flows in the Gorai River follow a cyclic trend, which is exacerbated at present by the very low flows in the Ganges during the dry season (FAP 4 1993a).

Sedimentation. Another factor that could account for reduced discharge in the Gorai River is the deterioration of the Gorai channel, especially through sedimentation. There are three aspects: (1) point bar in the Ganges along the mouth of the Gorai; (2) sedimentation of the Gorai mouth; and (3) aggradation of the Gorai channel.

Barua and others (1995) identified a right-bank point bar (along the mouth of the Gorai) of the Ganges River as being responsible for the deteriorating dry season discharge of the Gorai River. This point bar has gradually built up since 1973 and reached maturity in 1987 (FAP 4 1993a). The formation of point bars in these river systems is very common. Usually, they form at the end of the monsoon and are washed away in the following monsoon. The relationship between the rapid growth of the point bar in the post-Farakka period and the sudden drop in post-monsoon Ganges discharge has not, however, been investigated. Even without this point bar, the Gorai River would have experienced low discharge as a result of the reduced discharge of the Ganges.

According to FAP 4 (1993b) and FAP 24 (1993), it is the physical intervention in the Ganges flow that has accelerated sedimentation in the Gorai mouth, which has almost isolated it from the Ganges River. Pre-Farakka low flows transported significantly higher percentages of sediment load than those of post-Farakka low flows. In the post-Farakka period there have been large reductions in the sediment moved by low flows (less than 2000 m^3/sec) and high flows (greater than 6500 m^3/sec). The lack of low-flow transport could be responsible for raising the riverbed levels.

Table 3. Pre- and post-Farakka average monthly maximum salinity[a] at four stations in southwest Bangladesh

Station	January Pre-Farakka	January Post-Farakka	February Pre-Farakka	February Post-Farakka	March Pre-Farakka	March Post-Farakka	April Pre-Farakka	April Post-Farakka	May Pre-Farakka	May Post-Farakka
Khulna	293	1,254	371	3,396	467	8,305	1,626	12,149	1,508	11,208
Goalpara Power Station	340	515	397	1,303	750	4,422	1,320	7,422	786	5,456
Chalna	2,600	6,280	2,625	11,510	8,950	17,310	8,675	21,927	12,000	19,009
Mongla	2,300	5,200	3,900	7,880	7,500	11,075	11,800	17,150	13,500	17,100

[a] Salinity expressed in micro-mhos/cm (m-mhos/cm) and measured at 25°C.

These changes in dominant discharge and sedimentary distributions indicate that the Gorai's morphological response to Farakka may be significant (FAP 4 1993b). The overall effect is to reduce the discharge carrying capacity of the Gorai River and thereby increase salinity.

Reduced Dry Season Flow in the Gorai River and Its Effects on Increased Salinity

A vast network of rivers in the southwest region of Bangladesh is dependent on the water supply through the Gorai River (Figure 2). Water from this river is used for irrigation, industry, and urban water supply. Most importantly, the Gorai River flow pushes away the saline water front in the Passur River, near Khulna. Monsoon flow is adequate for repelling the salinity intrusion. The dry season flow of the Gorai River is most critical in controlling salinity in a large part of the southwest region of Bangladesh.

Generally, with the decrease of the Gorai flows, the average salinity at Khulna and adjacent areas starts to increase. During spring tides, a very large increase in salinity is noticed. Stronger spring tides push more saline water into the Rupsa–Pussur river, but during the following neap tide, the salinity is not totally flushed out. Therefore, a successive buildup of salinity occurs with each tidal cycle, which requires a sufficient supply of water from the Gorai River to flush out (MPO 1987).

During the post-Farakka period, salinity in the southwest region of Bangladesh increased significantly (Table 3). For example, at the Khulna station, the average monthly maximum salinity for April in the pre-Farakka period was 1626 μmho/cm. During 1976, when the Gorai discharge dropped to 0.5 m^3/sec from its pre-Farakka average of 190 m^3/sec, maximum salinity in April increased to 13,000 μmho/cm. Recall that the Farakka Barrage was commissioned in April 1975 and India unilaterally withdrew water from June 1975 to November 1977. Note also that natural causes (which influence the interannual variations of salinity) might also have had some effect.

The salinity situation started improving after the signing of the 1977 Ganges Water Sharing Agreement. When the second MOU expired in 1988, the salinity situation again deteriorated. The 500 μmho/cm salinity front moved 241 km from the coast in 1986 (MPO 1986) to 280 km in 1992 (Khan 1993). The highest ever salinity for February, March, and April was recorded in 1992 when the flow in the Gorai River was zero. The April salinity rose to 29,500 μmho/cm. That is 1800% higher than the pre-Farakka average.

How much river flow is required to keep salinity at tolerable levels for agriculture and human consumption? In order to determine the required flows, an empirical analysis was conducted. The monthly maximum salinity at Khulna station and monthly mean discharge at Hardinge Bridge for the Ganges River and at Gorai Railway Bridge for the Gorai River are considered for the empirical analysis, and the analysis was accomplished in two stages.

First, monthly salinity was plotted against monthly mean discharge, which demonstrated a nonlinear relationship. Blühdorn and Arthington (1995) also reported a nonlinear relationship between discharge and salinity while assessing the effects of regulation for Barker Creek in Australia. Regression analyses were conducted for three critical dry months—February, March, and April and are shown in Figure 5.

Second, the correlation between monthly mean discharge for the Ganges River at Hardinge Bridge and the Gorai River at Gorai Railway Bridge was checked and found to be significant at the 95% confidence level. Then, linear regression relationships between monthly mean discharge for the Gorai and the Ganges rivers were developed for the three months of the dry season (February–April). The results of the regression analysis are presented in Table 4. No observations were deleted from the sample. The low R^2 values for March and April are possibly due to some unusual observations for the Gorai River in the post-Farakka period. For all regression equations, high t values for the slopes indicate that they are significantly different from zero. The F test for the significance of regression was also conducted (Draper and Smith 1981). At the 95% confidence level, the F values also indicate that slopes are nonzero. The

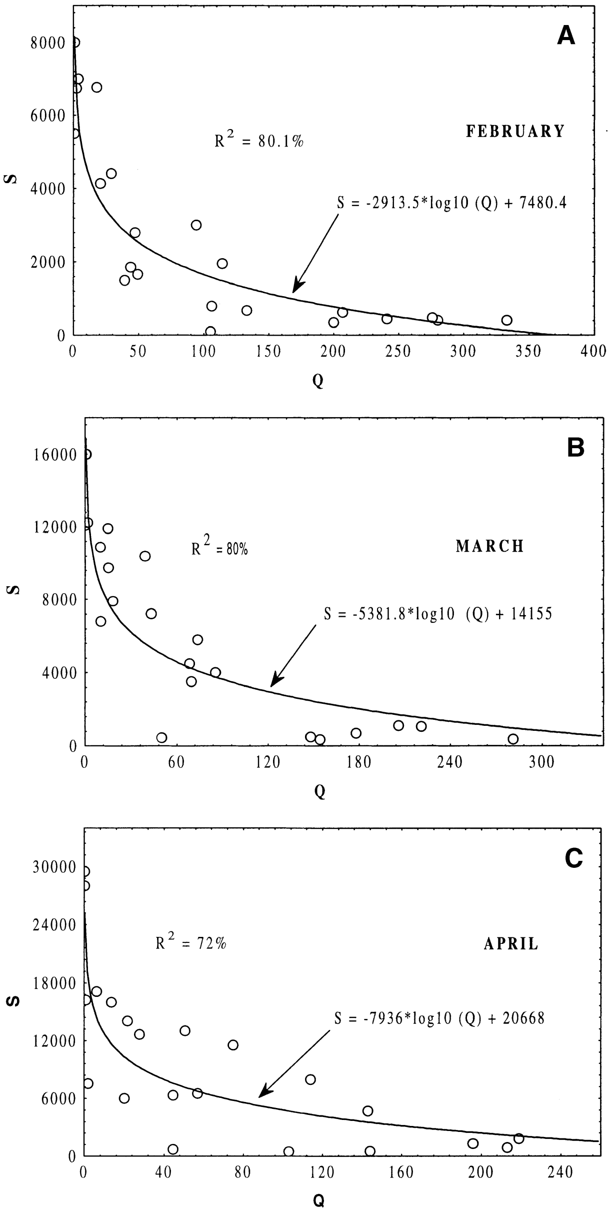

Figure 5. Empirical relationship between discharge at Gorai Railway Bridge for the Gorai and salinity at Khulna station. Here Q and S denote monthly mean discharge (in m^3/sec) and monthly maximum salinity in µmho/cm, respectively.

residuals were checked by standard procedures, and the residual plots demonstrated a homoscedastic pattern. Additional checks were made by normal probability plots (Cook and Wesberg 1982). These checks confirmed the normality of the residuals. Therefore, while there may be limitations to the explanatory power of the regression models, they are considered adequate to estimate the discharge requirements for the Gorai River for given salinity levels.

Table 4. Summary of linear regression relationship between monthly mean discharge of Gorai and Ganges rivers

Month	Intercept	Slope	R^2	$F_{1,25}$
February	−49.1	0.098 (t = 4.89)	0.49	24.00
March	−20.6	0.159 (t = 3.78)	0.36	14.35
April	−51.00	0.101 (t = 3.41)	0.32	11.70

Two salinity thresholds are considered in estimating the discharge requirements in the Gorai and Ganges rivers. FAO (1976) recommended a 750 µmho/cm salinity level for irrigation. However, MPO (1987) accepted a level of 2000 µmho/cm in the worst case scenario. The former threshold is also permissible for human consumption.

The discharge requirements resulting from the analysis indicate that in order to keep salinity below either of the threshold limits at Khulna, April requires the highest discharge of 240 m^3/sec and 158 m^3/sec as opposed to the current 52 m^3/sec (Table 5). The estimated requirements are consistent with the pre-Farakka mean monthly discharge in the Gorai and Ganges rivers. The analysis demonstrates the requirement of increased flow for the Ganges River at the Hardinge Bridge by as much as 1844 m^3/sec over the 1044 m^3/sec. The possible implications of increased salinity are discussed in the next section.

Implications of Increased Salinity

Diversion of the Ganges water at Farakka has caused increased river salinity in the southwest region of Bangladesh to intrude further inland (Figure 2). This has many implications for agriculture, forestry, industry, and drinking water, as shown in Figure 6. Evidence suggests these sectors have suffered enormously as a result of salinity changes in recent years.

Agriculture

Agriculture is the mainstay of the economy of Bangladesh. Currently, at 1984–1985 constant prices, this sector contributes about 35% of the gross-domestic product (GDP) (BBS 1995). It is claimed that an increase in salinity has already caused considerable damage to the agriculture sector in the southwest region of Bangladesh (GOB 1977, Hussainy 1987, MPO 1987, Khan 1993).

Among many other crops, all rice paddy varieties are very sensitive to increases in salinity. The tolerance of rice paddy varieties to salt concentration starts dropping sharply when the electrical conductivity exceeds

Table 5. Mean monthly discharge requirements for Gorai and Ganges rivers to limit maximum salinity at 750 and 2,000 µmho/cm at Khulna

	Required discharge (m^3/sec)				
	Gorai River			Ganges River	
Month	Present discharge (m^3/sec)	750 µmho/cm	2,000 µmho/cm	750 µmho/cm	2,000 µmho/cm
February	64	187	78	2,015	1,466
March	46	201	125	1,951	1,573
April	52	240	158	1,844	1,585

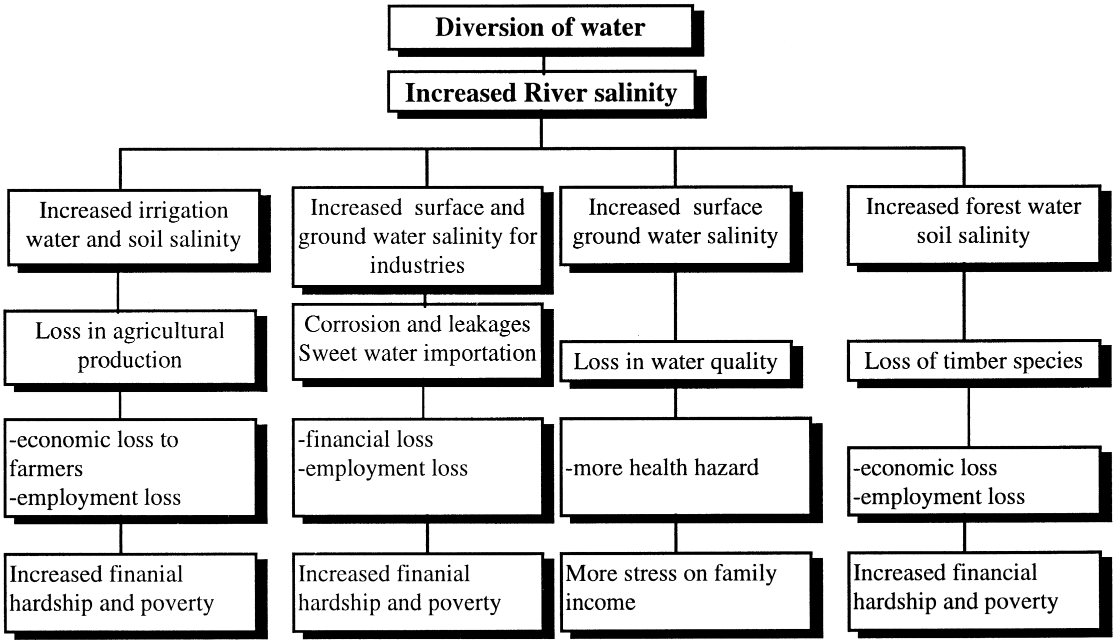

Figure 6. Increased river salinity and its possible effects.

2000 µmho/cm. At 6000 µmho/cm, plant growth, expressed in terms of weight, drops to below 50%. At 16,000 µmho/cm yields approach zero (MPO 1986). The harmful effect of salinity is more pronounced on young plants, which are less resistant to salt. Rice paddy yield is affected at the transplant stage using irrigation water with a salt concentration of only one-tenth of what causes yield reduction after the panicle or the head of the crop emerges (Hussainy 1987). The Bangladesh Agricultural Research Council (BARC 1990) uses a five band classification of soil salinity that explain the possibility of crop damage under the salinity classes (Table 6).

As a consequence of the water diversion, various estimates of agricultural production loss have been made. These losses were mainly due to soil moisture depletion, delayed plantation and increases in salinity. In 1976 (the initial year of unilateral diversion), the total crop loss was estimated to be 650,000 tons (GOB 1976). This claim was verified by an independent estimate. Hannan (1980) estimated that the agricultural production loss was 647,000 tons in 1976, of which the increased salinity related loss was 21%. In 1993, the government of Bangladesh claimed an estimated annual loss of US$675 million in the agriculture sector as a consequence of the Farakka Barrage (Xinhua 1993). Bangladesh University of Engineering and Technology (BUET) estimated an overall US$625 million per year loss compared to the natural pre-Farakka productivity of the Ganges basin in Bangladesh (Swain 1996). These two estimates seem to be very close, although their assessment methodologies are not known. Neither, however, separated out sources, so that losses due to salinity alone cannot be given.

Table 6. Classification of coastal salinity

Salinity class	Electrical conductivity (μmho/cm)	Plant growth condition	Rice yield reduction reported (%)
Nonsaline (S_0)	<2,000	Salinity effects mostly negligible	none
Slightly saline (S_1)	2,000–4,000	Yields of very sensitive crops may be restricted	1–6
Moderately saline (S_2)	4,000–6,000	Yields of many crops are restricted	11–35
Saline (S_3)	8,000–16,000	Only salt tolerant crops yield satisfactorily	31–50
Highly saline (S_4)	>16,000	Only very salt tolerant crops yield satisfactorily	68–72

Source: BARC (1990).

Forestry

In the Sundarbans[3] forest, there is an extensive network of tidal rivers and streams, together with small, local drainage channels (Figure 2). The main mangrove species in the Sundarbans are: Sundari (*Heriteria 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 (FEC 1989, Potkin 1987). Reduction in the flow of freshwater through the Ganges, the consequent depletion of soil moisture, and the increase in salinity have considerably affected the Sundarbans (FAP 4 1993b).

The adverse effects of increased salinity on the ecosystem of the Sundarbans can be seen by the dying tops of Sundari trees, retrogression of forest types, slowing of forest growth, and reduced productivity of forest sites (MPO 1986). However, increases in salinity alone may not be responsible for the top dying of the Sundari trees. This may be a synergic effect of a number of factors including salinity, sedimentation, water logging, cyclone damage, and accumulation of toxic elements from agricultural wastes and port discharge (FAP 4 1993b). Of these factors, increases in salinity and sedimentation in the coastal creeks are more pronounced in the post-Farakka period. Information on other factors is not available.

The economic loss from the Sundari trees is reported to be substantial. In the period 1976–1982, Bangladesh lost some 1.43 million cubic meters of Sundari timber (DOF 1982). Note that in the Sundarbans, Sundari alone contributes 14.75 million cubic meters of timber. This is about 73% of the total available timber in the forest. A very conservative estimate of the timber loss from the Farakka effect was US$320 million (Swain 1996).

Industry

Khulna (population about 800,000) is the second largest industrial city in Bangladesh. Its largest industries include the Khulna Newsprint Mill (the only one of its kind in Bangladesh), a number of jute mills, and the 60-mW thermal power plant (the only one in the southwest region). By and large, most of the industries have suffered significantly due to the increase in salinity. For example, the Khulna Newsprint Mill requires about 300 tons of fresh water daily for its operation. In the post-Farakka period, it has had to import fresh water from a source 40 km upstream. The high cost of water importation compels the use of saline water for cooling purposes, resulting in frequent leakages of condensers and hampering production (Rahman 1984). Similarly, the Goalpara power plant has to bring fresh water by barge from 50 km upstream to keep its turbine running. It also uses saline water for cooling, which leads to corrosion and resulting leakages. In 1981, the plant had to replace relatively new condensers and power generation had to stop for several months. Disruption in power supply to the industrial belt of Khulna and Jessore caused losses in production and labor time (Rahman 1984). The salinity hazard north of Khulna caused the Pakshi Paper Mill to close down in April 1993 (*Dhaka Courier* 1993). From December 1975 to June 1976, it was estimated that increased salinity caused industrial losses of US$8 million (IECO 1977). In the period 1976–1993, the total loss in the industrial sector was estimated to be US$37 million.

Drinking Water

Drinking water, both surface and groundwater, has become unfit for human consumption (Khan 1993) since the salinity has exceeded the recommended level of 960 μmho/cm for potable water (MPO 1987). As the vast majority of the population is not served by munici-

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[3] Sundarbans, the largest mangrove forest in South Asia. One part of the Sundarbans is located in Bangladesh and the other part is in India. The Bangladesh Sundarbans cover 580,000 ha and are confined to the southwest corner of the Bangladesh coast, with a small remnant of the Chakaria Sundarbans in Cox's Bazaar district.

pal water supplies, they are exposed to and affected by various diarrheal diseases (FAP 4 1993b). Colwell (1996) reported the growth of *V. cholerae* in water of low salinity and high temperature in presence of high concentrations of organic nutrients in the inland coastal areas in Bangladesh. However, whether the progression of the salinity front further inland in the post-Farakka period has exposed people to more diarrheal diseases needs to be comprehensively investigated.

Conclusion

The diversion of the Ganges water at Farakka has caused hydrological changes in the mean monthly discharge of the Ganges and Gorai rivers, accelerated aggradation in the Gorai River due to sedimentation, and increased salinity in the southwest region of Bangladesh. Natural causes might also play a part, but this is difficult to ascertain when physical interventions are made on a natural system. The increased salinity has caused considerable adverse effects on the agriculture, forestry, industry, and drinking water sectors. The analyses demonstrate the need to increase the discharge of the Ganges River at Hardinge Bridge during the dry months in order to limit salinity at certain threshold limits. Recently, some progress was made in this regard.

In December 1996, Bangladesh and India signed a 30-year treaty on sharing the dry season flow of the Ganges River at Farakka. The entire dry season (January–May) was divided into a total of 15 ten-day cycles. The treaty considered average discharge available at Farakka in a ten-day cycle for the period 1948–1988. Under the sharing formula, Bangladesh would receive a maximum of 58,180 ft^3/sec and a minimum of 32,623 ft^3/sec water in January and April, respectively. Therefore, the dry season flow in the Ganges River may increase from the nonagreement period when mean monthly discharge was 47,416 ft^3/sec and 23,250 ft^3/sec in January and April, respectively (Table 2). However, the increased discharge in the Ganges River may not substantially increase discharge in the Gorai River because of excessive siltation at its mouth. FAP 4 (1993b) recommended physical intervention by building a control structure at the Gorai mouth and a barrage across the Ganges River in order to increase water supply to the southwest region of Bangladesh. The dry season flow currently available at Farakka is not sufficient to meet requirements of India and Bangladesh. Instead of political bickering over the Farakka issue, it is necessary to initiate research on how to optimize the flow augmentation in the Ganges River during the dry season.

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