

The background state leading to arsenic contamination of Bengal Basin groundwater

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ABSTRACT

The Bengal basin has the world's densest water diversion constructions on the natural courses of rivers. The most damaging water diversion construction is the Farakka Barrage upon the international River Ganges. The diversion of water through this barrage and other constructions upstream of it has reduced the Ganges flow rate by 2.5 times. The resulting downstream effects are the depletion of surface water resources, more withdrawal than recharge of groundwater, sinking groundwater table, spread in depth and extension of the vadose zone, changes in surface features, climatic changes, etc. An investigation was carried out to find the contributions of water diversion to the arsenic contamination of groundwater in the Bengal basin. The reasonable scenario for arsenic contamination is the oxygen deficiency in groundwater and aeration of arsenopyrites buried in the sediment that would remain under water prior to 1975. The mineral forms water-soluble compounds of arsenic when react with atmospheric oxygen. These soluble arsenic compounds infiltrates to the groundwater. This article summarizes the short-time and incomplete study-based quick conclusions reached by investigators that have totally avoided the vital issue of water diversion. It then shows the depleting condition of the water resources under continuing diversions, the generation of favorable condition for arsenic release, the reasons for low sulfur concentration, the reason for first contamination in the Hugly basin, and the hindrance to water's self-purification. The articles advocates that the restoration of the virgin wetland ecosystems in the Bengal basin following the stoppage of the inordinate amount of unilateral upstream water withdrawals can remove the catastrophe.

Key words | aeration, arsenic contamination, hydro-geochemistry, re-aeration, river dams, surface water hydrology, water diversion

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INTRODUCTION

The Bengal Basin is composed of West Bengal (WB) in India and Bangladesh. The Ganges, the world's largest river, bifurcates in West Bengal before entering Bangladesh through the upper west side of the Indo-Bangladesh border. The Bhagirathi, the branch of the Ganges in West Bengal, flows south to fall into the Bay of Bengal. The Ganges flows through Bangladesh and joins with two other rivers – the Brahmaputra and the Meghna – before falling into the Bay of Bengal. There are at least twelve major tributaries which carry water to the Bhagirathi in

WB as shown in Figure 1. In Bangladesh, the only tributary of the Ganges is the Mahananda. About 74 active rivers bisect the basin (Figure 1).

In the 1950s, the Indian Government set up the Damodar Valley Corporation. Under this authority, the government started building dams upon the tributaries of the Bhagirathi for water diversion and withholding. The approximate locations of nine such major dams and reservoirs are shown in Figure 1. With the blockage of the natural flow of water into the Bhagirathi, siltation started in

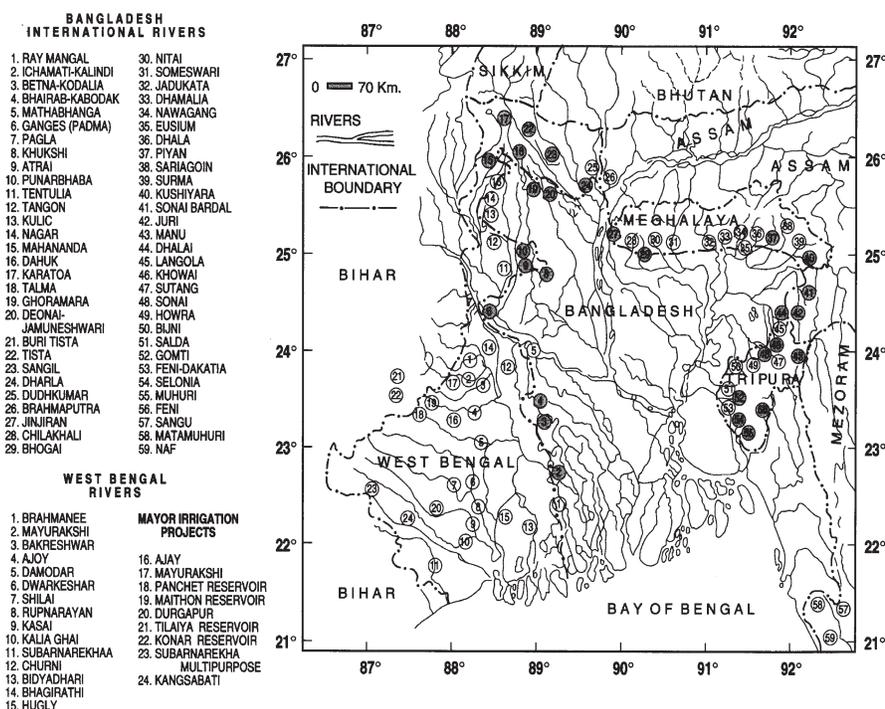


Figure 1 | Illustration of the river systems of the Bengal Basin along with approximate locations of water diversion constructions (Adel 2001).

the tributaries as well as in the Bhagirathi. Prior to the construction of these dams, timely, adequate, and forceful floods in the tributaries of the Bhagirathi/Hugli never resulted in siltation (Prakash, 1998). Around the Indo-Bangladesh border from the southwest side, there are at least forty major water diversion constructions including the ones in and to the west of WB. There are multiple dams upstream on some of the rivers or on their tributaries, making the total number of dams and barrages more than forty. Satter (1996) presents a good account of these multiple water diversion constructions.

Recently, the groundwater in the basin was found contaminated with arsenic (Adel 2000a). About 75,000,000 people in the basin now live with the risk of arsenic poisoning. The concentration of arsenic in the water in the unconfined aquifers is up to 2 mg/litre of arsenic and in some cases is greater, whereas the recommended level of arsenic is 0.05 mg/litre (USEPA 1993). The district-wide (approx. 1,000 km²) concentration of arsenic is shown in Figure 2. The contaminated areas lies to the east of the Bhagirathi in WB and in the Ganges delta in Bangladesh.

Upstream water diversions have created a downstream shortfall of surface water and recharging of groundwater.

The local water balance, obtained from precipitation, inflows via streams in rivers and canals, subsurface groundwater inflows and outflows, evapotranspiration, and water extraction, is disrupted. The loss of the water balance has the potential to cause hydrogeochemical changes affecting underground, ground, and surface environments.

One of the naturally occurring forms of arsenic minerals, arsenopyrites is not soluble in water as long as it is kept under water. However, if arsenopyrites, deposited in sediments, is exposed to air, the minerals produce arsenic compounds soluble in water by reacting with atmospheric oxygen. This water-soluble natural toxic substance can be leached into groundwater during infiltration of surface water. Depending on the deposition of pyrites in different sites, infiltrating water with varying concentrations of arsenic can reach the groundwater table.

Inadequate recharging causes two more problems. The first one is that it places aquifers under reducing conditions favoring increased mobility of arsenic. The second one is that it interferes with natural processes limiting arsenic solubility. This self-purification process was found to occur in Lake Michigan (Syed 1972). Iron in water forms iron

or no weight to the water diversion episode upstream of the delta (Paul & De 2000). A Swedish group, without any prolonged and extensive investigation for sinks of sulfur, concluded in favor of oxyhydroxide reduction theory following their observation of low sulfur concentration (Gunnar Jacks, personal communication, July 17, 2001). Furthermore, a member of the same group commented on the lack of oxygen in floodplain waters even although the floodplains are cultivation grounds for rice plants, whose roots need oxygen for growth, and are natural breeding grounds for Gangetic fishes. This communication does not recognize the problems generated by water diversion as being worth scientific investigation. (Bhattacharya *et al.* 1999; Bhattacharya, personal communication to Husain, 2001).

To date, no one has given any consideration to the annual withdrawals of billions of cubic meters of surface water upstream of Bangladesh – about 37 billion cubic meters/year from the Ganges alone and an additional undisclosed amount from other water diversions. Furthermore, the speculations of Nickson *et al.* (1999) cannot account for the arsenic-free water in open wells during the open-well era, principally prior to the 1970's when the people of Bangladesh and WB used water from open wells for drinking. In about 28,000 village areas in the Ganges basin in Bangladesh, a total of about 280,000 open wells were in operation. Open wells would draw the same water as the tube-wells.

Apart from these speculations, there are reports that attribute a significant risk of hypertension to the presence of inorganic arsenic in drinking water (Rahman *et al.* 1999). The outbreak of this environmental disease is related to the fluctuation of temperature which is well documented in the scientific literature (Rogot 1973; Rogot & Padget 1976; Kalkstein & Valimont 1987; Hussain & Hays 1993, 1997; Hays & Hussain 1995). Temperature fluctuations have been reported in the areas of Bangladesh, hard-hit by the diversion of water, which have the highest natural heat and which absorb and store heat during summertime, releasing it in wintertime to stop environmental temperature drop (Adel 1999, 2000b, 2002).

The objective of this article is to investigate water diversion as a potential cause of arsenic contamination in the groundwater of the Bengal Basin.

MATERIALS AND METHODS

To investigate the loss of water balance and its potential to contaminate groundwater with arsenic, various data were obtained from government offices and field surveys in the Ganges basin. The data pertained to dams and barrages on the common rivers of India and Bangladesh, river flows, floodplains, ponds, and climate. The field survey data for floodplain and pond water depths and their water holding times – both for pre- and post-Farakka periods – were binned in short intervals and areas falling in the same data bin of water depths and water holding times were added cumulatively to get the total area in depth and time interval bins. The regional water balance equation was developed. The direct, indirect, and feedback effects of water diversion, and the published reported effects of water loss were considered in the water balance equation.

Surface water resources data were used to show the current water shortage and a proportionate shortage in recharging groundwater since both the surface and groundwater complement each other. In the absence of changes of any other features (*viz.*, deforestation) in the environment, temperature changes in the environment were attributed to the changes in surface features from water bodies and water-covered land to dry land areas. The guiding fact was the highest specific heat of water. The generation of heating and cooling events (*viz.*, the rise of the summertime maximum and the fall of the wintertime minimum temperatures) which affect atmospheric convection and precipitation were considered. Furthermore, a consideration was given to the increase in potential evapotranspiration following an increase in temperature, and the dependence of groundwater recharging on surface water and rainfall patterns. The arsenic buildup in the groundwater was studied via consideration of the infiltration of water-soluble arsenic compounds and seepage of contaminated water from WB along with the scavenging activity of iron hydroxides for arsenic.

PROJECT SITE

Water diversion by the Farakka Dam on the Ganges is the best known and has the widest effect of all the water diversions in the delta. A part of the Ganges basin which includes one

tributaries, India constructed the Farakka Dam in 1975 (marked #5 in Figure 1) on the Ganges about 18 km upstream from the Indo-Bangladesh border. Other dams and water diversion facilities were built around the Indo-Bangladesh border and on the west side of the Bhagirathi river (Abbas 1993; Joint River Commission 1995; India Drainage 1996; Satter 1996). Seventeen more rivulets which are not shown in the illustrations face the upstream water diversion (Satter 1996). Out of the $3.6 \times 10^{12} \text{ m}^3$ of water withdrawal annually by humans worldwide (Kates *et al.* 1993), the single most withdrawal takes place upstream of Bangladesh – about $3.7 \times 10^{10} \text{ m}^3$ annually from the Ganges alone along with an undisclosed amount from the rest of the twenty nine water diversion constructions bordering Bangladesh and the nine major and other minor dams in WB (Figure 1).

It was found by measurement that the Ganges water carries a sediment load of 4.5 kg/m^3 . The post-Farakka annual mean flow of $769.5 \pm 284.5 \text{ m}^3/\text{s}$ in the Ganges is about 40% of the pre-Farakka annual mean flow which had been $1,932 \pm 22.8 \text{ m}^3/\text{s}$ as illustrated in Figure 4 (Hebblethwaite 1997). The weakened flow and the deposition of sediment have reduced the flushing power of the Ganges in the delta. The resulting condition of the Ganges bed is shown in Figure 5. The cracks in the Ganges bed have let in

air for aeration (oxygenation) of the subsurface and depths beyond. The sediment has raised the riverbeds and increased the size and number of shoals in the Ganges. As of 1983, the Ganges was reduced to $5.44 \times 10^6 \text{ m}^2$ from its value of $6.69 \times 10^6 \text{ m}^2$ in 1973. Along with this 19% shrinkage, the number of shoals increased by more than 7 times and the shoal areas increased by 12 (Elahee & Saleheen 1992). The condition has further worsened in the two decades following 1983 (see later in ‘The condition of distributaries’). New shoals have emerged at the points of origin of the distributaries and distributaries’ distributaries, where the stream velocity is the weakest due to a change in the flow direction, consequently allowing the deposition of sediments.

The Ganges Basin water budget

During the pre-diversion era, the total runoff, the groundwater infiltration, the surface water runoff, evapotranspiration, and total wetting of the area (which is the annual infiltration along with surface retention) in the Ganges basin including the delta were 496 mm, 104 mm, 392 mm, 790 mm, and 686 mm, respectively (L’vovich 1974). With a 60% reduction in the flow of the Ganges, these figures have been proportionately affected. The percentage of the annual infiltration which would go to groundwater runoff and

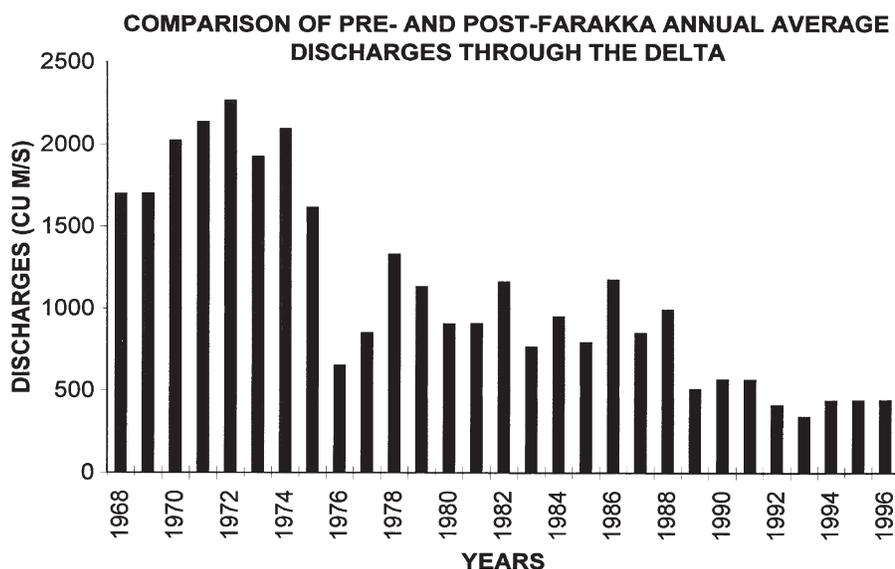


Figure 4 | Illustration of the gradual shortfall in the Ganges water due to withdrawal and diversion by the Farakka Barage outside the Bangladesh border (Hebblethwaite 1997).

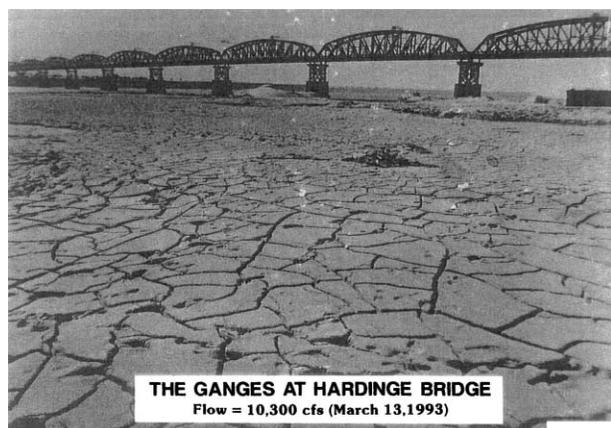


Figure 5 | Illustration of the dry and fissured bed of the Ganges.

evapotranspiration are 15% and 42%, respectively. Also, the basin had a drainage area of $1,073 \times 10^3 \text{ km}^2$, a discharge area of $15,500 \text{ m}^3 \text{ s}^{-1}$, and the ratio of long-term average discharge to long-term average precipitation of 0.42 (Dingman 1994).

The condition of distributaries

The dwindling Ganges flow deposited sediments at the mouth of the distributaries where the stream velocity was further weakened. Figure 6 shows one such shoal measuring about 1/2 km in width and 1 km in length at the mouth of the Baral distributary. The shoal seems to rise above the bank of the river. The Baral distributary used to discharge at a rate of about $2000 \text{ m}^3/\text{s}$ for at least five months (June–November) of the year. Now, it can hardly discharge a quarter of that amount. In the network of distributaries, the Musa Khan flows out of the Baral (Figure 3). The point of origin of the Musa Khan has been obliterated by a shoal about the size of $100 \text{ m} \times 10 \text{ m}$. Its current state is shown in Figure 7. For at least four months (July–October) of the year, the Musa Khan would discharge at about $1 \times 10^3 \text{ m}^3/\text{s}$ and provides a basin area of nearly $1 \times 10^9 \text{ m}^2$. During July–September, in a stretch of about 20 km of the Musa Khan river, about 45 canals each about 3 m wide, 2 m deep and 10 kilometers long would carry the Ganges water to distant floodplains which had been the natural breeding grounds for over 100 species of Gangetic fish as well as providing natural wells for recharging groundwater both from the Ganges water and the monsoon runoffs. The Musa Khan has not received a single drop of Ganges water since 1975.



Figure 6 | Above, a huge shoal at the mouth of the Baral distributary. Below, the dry bed of the Baral used for paddy cultivation.

Similar reduced or no-flow conditions have occurred in the basin areas of other distributaries. The area of distributaries dropped from $1.64 \times 10^7 \text{ m}^2$ in 1973 to $6.8 \times 10^6 \text{ m}^2$ in 1983, followed by further worsening condition.



Figure 7 | The shoal at the mouth of the Musa Khan, the distributary of the Baral.

Currently, the $STRM_{in}$ term is zero in the Musa Khan basin, and the Baral's annual flow has been reduced to about 25% of the pre-dam flow following the Ganges flow drop by 60%. Runoffs and recharging have proportionately been reduced in the basins.

Precipitation, runoffs, and recharging

A study of rainfall records for seventeen years (1973–1990) covering the pre- and post-diversion eras shows a decrease of over 30% (from 1300 mm to 895 mm). The frequencies of 100 mm or more rainfall have been halved after the diversion of the Ganges water (Adel 2002).

The rainfall drop in the Ganges basin caused a proportional drop in runoffs which is 40% of the rainfall. Revelle & Waggoner (1983) reported a 30% decrease in runoff for a 3.6°F rise in temperature. Their findings predict a decrease in runoffs from 520 mm/yr to 107 mm/yr.

Changes in rainfall patterns and runoff have a serious impact upon recharging even if the total amount of rainfall remains the same. The recharge is more likely to occur when (i) soils have high conductivity, (ii) water table lies at a shallow depth, (iii) soil is relatively wet, and (iv) the water input rate is low and lasts for a relatively long interval of time (Freeze & Cherry 1969). Under the current conditions of scorching heat (discussed below) and dry soil in summer, the dropping groundwater table, and no week-long intermittent rainfalls, recharging by rainwater is not as effective as it had been in the pre-diversion days of the Ganges water. Even occasional torrential rains cannot effectively recharge the groundwater.

Subject to direct recharge from infiltration, an earlier estimate of recharge was about 2,000 mm/yr (approximated by the product of the drops of 3,000–6,000 mm/yr in open wells and ponds and the soil porosity of 25–50%). Currently, it is very difficult to have more than 1,000 mm/yr of recharge. To cope with the dropping groundwater table, ordinary hand-tube-wells that were used to extract groundwater from a depth of about 8 meters are being replaced by the Tara pumps that can extract water from depths of 16 meters or more.

The storage term

Floodplains, ponds, ditches, etc. contribute to the surface water portion of the STRG term. Its absolute determination

is not necessary. It will be shown in the following sub-sections that the stored amount is being depleted.

Condition of floodplains

Results of field surveys for the pre- and post-diversion periods of the Ganges water show the floodplains that previously held water for 10–12 months within depths of 0.6–2.7 meters, 7–8 months within depths of 0.5–0.6 meters, and up to 6 months within depths up to 0.5 meters have lost water by about 30%, 50%, and 70%, respectively. Comparison of the monsoon season floodplain water depths is made in Table 1 for the pre- and post-barrage periods. In the 2,700 acres of floodplains of varying depths that were surveyed, the water level effectively dropped by about 50% in post-Farakka years. The water detention time of the floodplains are tabulated in Table 2. In the second column of the table, a zero indicates a period of less than a month. It shows that floodplains that could hold water up to

Table 1 | Rainy season water depths in floodplains

Cumulative area (Sq. km)	Water depth (m)	
	Pre-Farakka	Post-Farakka
0.34	0.20	0.08
2.45	0.31	0.10
4.29	0.45	0.18
6.64	0.53	0.33
41.22	0.69	0.41
19.48	0.81	0.48
10.67	0.91	0.59
21.25	1.09	0.61
1.21	1.22	0.97
0.41	1.27	0.76
1.13	1.40	0.70
0.44	1.52	0.76

Table 2 | Flood plains water holding times

Average depths (m)	Pre-dam (months)	Post-dam (months)
0.25	6	0
0.32	4	0
0.45	6.8	0
0.57	8.3	3.5
0.70	10.9	6.0
0.85	11.6	9
0.95	11.5	9.5
1.10	12	8
1.21	12	12
1.36	12	9
1.46	12	9
1.60	12	12

about seven months in pre-barrage days, can now hold water for less than one month.

Condition of ponds and ditches

Survey results summarized in Table 3 show that in ponds, the flood season water level in the post-diversion era is about the same as the dry season water level in the pre-diversion era. Ponds of average size of 20 meters wide by 30 meters long by 5 meters deep were the reservoirs for collection of monsoon runoffs and flood residues of the Ganges water to recharge groundwater. These were the sources of water for domestic use and fish raising. Ditches (half as large as a pond or smaller) would also work as reservoirs for monsoon runoffs and the Ganges water to recharge groundwater as well as being a facility for jute retting, seasonal fish raising, and washing water. The ratio of the areas occupied by ponds, ditches and canals in the area surveyed was about 20:10:1. The ponds and ditches together would occupy about 760sq.km of land, and the permanent and the seasonal surface water bodies together about 44,900 sq. km.

The water shortage has led to aeration deeper than 6 meters, the approximate maximum aeration depth for

Table 3 | Illustrations of pond water depths in pre- and post-barrage years

Cumulative area (sq km)	Pre-barrage depths (m)		Post-barrage depths (m)	
	Rainy season	Dry season	Rainy season	Dry season
0.02	5.18	2.44	3.66	1.83
0.04	4.57	1.89	1.73	0.85
0.06	3.75	1.37	1.83	0.83
0.09	3.20	1.22	2.07	0.76
0.12	2.68	1.22	1.37	0.67
0.19	2.29	1.13	1.43	0.61
0.20	1.43	0.85	0.91	0.52
0.22	1.00	0.61	0.70	0.27

pre-diversion summer periods, following the increase of vadose zone depth in the wake of the sinking groundwater table (Personal Communication, DPHE, 1995). The water shortage has also introduced longer periods and wider areas of aeration than used to occur during March through May for larger floodplains, and during January through May for shallow ones, canals, small ponds and ditches.

The shortage in the rain water supply in the surface water bodies is, at least, supported by the finding of Stockton & Boggess (1979). They used the relationship developed by Langbein (1949) and found that a 3.6°F temperature rise and a 10% decrease in precipitation (which is consistent with some GCM projections) can reduce water supply by 50%.

Subsurface inflow and outflow

GW_{in} and GW_{out} depend on the elevation of the watershed and hydraulic conductivity which may be taken to be uniform in the region under consideration. Then, following Van Tonder & Kirchner (1990), the approximation of $GW_{in} = GW_{out}$ can be justified by the general form of Darcy's law which is:

$$G = KSA \quad (2)$$

where G is the liquid flowing through the cross-sectional area A per unit time = n (soil porosity) $\times v$ (liquid travel velocity

through the soil) $\times A$ (flow-through cross-sectional area), K is the coefficient of hydraulic conductivity which depends on the soil type as well as fluid properties, and S is the hydraulic gradient which is defined as the change in the elevation of free water surface between two points under consideration divided by the travel distance of water.

Temperature rise and evapotranspiration

Following the depletion of surface water resources, the water surfaces that absorbed solar radiation have been transformed to radiation reflecting and reradiating (after absorption) pieces of land. It has resulted in a rising trend of summertime maximum temperature, which has risen to about 110°F from their pre-diversion values of about 99°F. Similarly, the wintertime minimum temperature of about 47°F has dropped to about 40°F due to lack of water bodies or soil moisture to absorb heat during the summer and retain it for release during the winter. Relative humidity levels beyond 95% occur $1\frac{1}{2}$ times more than in pre-diversion years. An increase in temperature increases the atmospheric demand for moisture which is supplied by evapotranspiration. This factor causes the increase in relative humidity (Adel 2002).

The increase in frequency of the highest relative humidity is, at least, supported by Rind's (1995) findings of a 30% increase in atmospheric moisture following a 7.2°F rise in temperature. Since the Bay of Bengal is far away and the seawater warms up slowly, the additional moisture is supplied by the land putting the flora under stress. However, the critical condition for condensation of vapor for precipitation fails to develop (Adel 2002).

Bouwman (1990) reported about 1,300 mm/yr for evapotranspiration in geographic locations like Bangladesh. If Rind's (1995) result is taken into account for the 30% increase in evapotranspiration, under the current increase in temperature, the new evapotranspiration is estimated to be 1,700 mm/yr.

Withdrawals

In the pre-diversion era, groundwater withdrawal was about 5 mm/yr in residential areas and was only for the purpose of drinking. This figure has risen to about 325 mm/yr for residential areas. Other withdrawals are 30 to 40 mm/yr in

privately irrigated areas, about 100 to 200 mm/yr in the government-owned irrigated areas, and about 40 mm/yr for aquaculture. All these withdrawals are done at the cost of depletion of groundwater. In the absence of upstream water diversion, such large amounts of withdrawal of groundwater would not be necessary. These are forced withdrawals imposed by the upstream diversion of water from the Ganges.

Current water balance

We can apply the water balance equation for about an 11 sq.km area of the Musa Khan basin in the project site. Currently, $STRM_{in} = 0$, and the form of Eq. (1) can be written for the storage term as:

$$STRG = P - E - 0.4W \quad (3)$$

The rise in temperature has increased the rate of potential evapotranspiration, making E about 1,700 mm/yr. The precipitation P has decreased to about 895 mm/y. This shows that water storage is being depleted. The vadose zone is increasing in depth bringing sediments in contact with oxygen, and aquifers are made more and more reducing for lack of oxygen-rich recharging water.

This scenario has been going on since 1975. In 1986, 12% of the unions (local government units in rural areas comprising of 10–15 villages and having 15,000–20,000 population) surveyed had groundwater below the suction limit of 8 metres, where a union is the lowest unit of local government having an average population of about 15,000, and spread over an area of about 18 sq.km. In 1991, 26% of the unions had groundwater below the suction limit. A study by the Department of Public Health Engineering/ UNICEF (DPHE 1995) predicted that by 2000, as much as 50% of the high water table areas would have a water table below the suction limit for at least, part of the year. Annually, the drop in the groundwater table is about 0.5 metre (Miah 1996).

The water balance equation (Eq. 1) may be applied to other affected river basins in the delta. Long time observations will yield the same result of vadose zone oxidation and aquifer reduction.

Shortage of oxygen supply

In the pre-diversion days, due to the abundance of surface water from the monsoon rainfalls and the Ganges water, every square inch of delta would be under water for varying times of days to months during the wet season (mid-June to mid-November). Water from the monsoon rainfalls and the river water flowing to and over the floodplains through canals would be aerated and re-aerated continuously during the wet season. This abundance of surface water would carry oxygen in the infiltration process to recharge groundwater. The aeration and re-aeration (RAR) of water are related to both the velocity of water flow and the depth of current (O'Connor & Dobbins 1958):

$$\text{RAR} = k_r(\text{O}_{\text{Sat}} - \text{O}_{\text{act}}) \quad (4)$$

where the re-aeration constant $k_r = 3.9u^{1/2}/H^{3/2}$, u is the average velocity in m/s, H is the average depth in metres, O_{Sat} is the saturated value of dissolved oxygen, and O_{Act} is the actual dissolved oxygen concentration. In pre-diversion days, large streams of swift to normal velocities would have k_r values in the range of 0.46–1.15/day during August – October, and large streams of low velocity would have k_r in the range of 0.35–0.46/day during June/July and November. Large floodplains would have k_r values in the range of 0.23–0.35/day during December-March. Ponds would have k_r values in the range of 0.10–0.23/day approximately year-round. Ditches would have k_r values in the range of 0.10–0.23/day during November-April. With the advent of the dry season, the sizes of large water bodies would begin to shrink. In post-diversion days, not a single drop of water accumulates in places where knee-deep to chest-deep water would flow during wet season in the 1960's. The Musa Khan river, the perennial water resource, is dry all the year round. Currently, the river basin is survived by ponds and floodplains of reduced sizes and water-holding durations. The k_r values for different sizes of surface water bodies were obtained from Tchobangolous & Schroeder (1985). The difference ($\text{O}_{\text{Sat}} - \text{O}_{\text{act}}$) has been taken as unchanged in the post-diversion days, which should be true because of no change in air. Without considering the actual coverage of these surface water bodies, the ratio of the weighted averages of k_r for post- to pre-barrage days for the surface water bodies becomes about 0.50. This ratio can be taken as

the highest limit, because the surface water coverage-weighted values of k_r will far exceed pre-diversion days. Actually, the current oxygenation rate will be much less than 50% of what it had been in pre-diversion days. A British group reported observations of shortages of oxygen in groundwater (Nickson *et al.* 1999). However, they interpret that subsurface organic carbon absorbed the oxygen. The interpretation is not tenable on the ground that the same organic carbon was present in the deposits in pre-diversion days, and that no reducing condition would exist to manifest the contamination effect.

ARSENIC ACCUMULATION

A number of reasons, described below, have favored arsenic accumulation in water. All these are rooted to water diversion.

Increased aeration of the vadose zone

Water diversion and shortage of surface water have caused increased sub-surface aeration in three different ways. Firstly, the surface area of aeration has increased in proportion to the drying of the total land area that used to remain under water for a part of the year during the pre-barrage period. Secondly, the water shortage has been causing an early drying of water-covered land resulted from water-holding over a shorter duration. The aeration depth has almost been doubled because the current water extraction depth (by Tara pumps) is at least 16 metres and the pre-barrage depth was 8 metres (Personal Communication, DPHE 1995).

Change of redox potential in aquifers

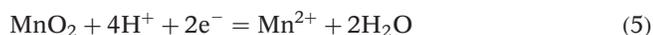
Water diversion has made the vadose zone oxidize, and the consequent lack of recharging water has made aquifers reducing. Conditions that can reduce Fe^{3+} to Fe^{2+} and As^{5+} to As^{3+} favor the mobility of arsenic in the environment. This is because ferrous hydroxide is soluble in water and the trivalent arsenic species is less strongly absorbed than the pentavalent one (Matisoff *et al.* 1982).

If the recharging water is not sufficient (i.e. oxidizing groundwater is not high) and the aquifer contains pyrites, the reducing property of the sulfide can make low dissolved

oxygen and low redox potential. Consequently, more and more $\text{Fe}(\text{OH})_3$ (s) dissolves and reaches an equilibrium with higher concentration of ferrous iron as Eh decreases at a given pH (Deutsch 1997).

Strong reducing conditions favor co-precipitation of arsenic sulfide with pyrite if iron and hydrogen sulfide are present. In the absence of hydrogen sulfide under mildly reducing conditions, arsenic becomes most mobile because iron remains in the form of ferrous iron and arsenic as arsenite (Hounslow 1980).

An aquifers' oxidizing capacity depends on the primary reactions that consume electrons. In many aquifers, the oxidation capacity (OXC) is due to (i) dissolved oxygen, (ii) solid Fe (III), (iii) solid Mn (IV), and (iv) total organic carbon (TOC). In the Ganges Basin, the hydrology in which recurrent annual recharging would occur over a period of six months making fresh contributions of dissolved oxygen, water diversion has deleted the single most important factor (i). If TOC is like quinone, the reactions behind the oxidizing capacity are (Cherry *et al.* 1979; Deutsch 1997):



and

$$\text{OXC} = \text{moles/g of Fe(III)} + 2(\text{moles/g of Mn(V)}) \\ + (1/36)(\text{mg C/g of solid of TOC}) \quad (8)$$

The reducing capacity (RDC) is due to ferrous iron solids and TOC. If TOC is treated like phthalic acid, reactions behind the reducing capacity can be written as:



and

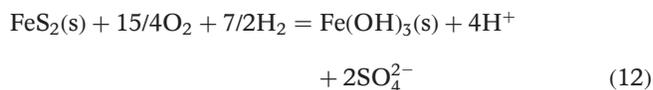
$$\text{RDC} = \text{moles/g of Fe(II)} + (1/3.2) \\ \times (\text{mg C/g of solid of TOC}) \quad (11)$$

Equations (8) and (11) can be applied to aquifers to calculate the post-barrage and estimate the pre-barrage

OXC and RDC. However, in light of the preceding discussions leading to Equation (3), the post-barrage OXC will be lower than pre-barrage OXC, and the post-barrage RDC will be larger than the pre-barrage RDC.

Pyrites decomposition

There are reports that arsenic in the form of arsenopyrite minerals (FeAsS) exists in the ground (Das *et al.* 1996) and also on the surface (Karim *et al.* 1997). This arsenic content varies widely. When pyrites come in contact with oxygen in the air due to the depleting groundwater, water dissolvable compounds of arsenic (acids of arsenic) are produced. The process may be illustrated by the following reactions:



Earth materials in the subsurface have varieties in size distribution, consolidation, and in mineral and chemical composition of particles. In some forms, pyrite minerals may be more prone to oxidation than in others. Following increased subsurface aeration, more pyrite minerals are likely to come in contact with oxygen and form water-soluble compounds.

In Equation (12) above, molecular oxygen oxidizes Fe (II) and S_2 (-II) to the stable ferrihydrite ($\text{Fe}(\text{OH})_3$), and dissolves sulfate (S(VI)) and hydrogen ions. In an acidic solution, the release of hydrogen and sulfate anion results, unless reactions occur to neutralize hydrogen cations, and forms compounds of sulfate.

In a solution of 10^{-4} M Fe^{2+} and 10^{-2} M S, equilibrium conditions of ferrihydrite, jarosite ($\text{KFe}(\text{SO}_4)_2[\text{OH}]_6$), pyrite, siderite (FeCO_3), and in a solution of 10^{-6} M/L iron, equilibrium conditions of Fe^{3+} and Fe^{2+} are shown in Table 4. Ferrihydrite is stable under a wide range of Eh-pH. Jarosite becomes a stable iron mineral in presence of sufficient sulfate over a small zone of low pH (acidic) and high Eh (oxidizing). Pyrite is also stable under a wide range of Eh-pH and siderite is stable over small Eh-pH field.

Table 4 | Equilibrium conditions of ferrihydrite, jarosite, pyrite, and siderite in Eh-pH field having activity of Fe^{2+} 10^{-4} M and activity of S 10^{-2} M, and of ferric and ferrous iron having an activity of 10^{-6} mol/L (Deutsch 1997)

Species	Eh range (V)	pH range
Ferrihydrite	$-0.141\text{pH} + 0.931 < \text{Eh} < -0.0592\text{pH} + 1.229$	$2.33 < \text{pH} < 7.50$
	$-0.0714\text{pH} + 0.3494 < \text{Eh} < -0.0592\text{pH} + 1.229$	$7.50 < \text{pH} < 14.0$
Jarosite	$-0.1356\text{pH} + 0.916 < \text{Eh} < -0.0592\text{pH} + 1.229$	$1.80 < \text{pH} < 2.33$
Pyrite	$-0.1333\text{pH} + 0.1 < \text{Eh} < -0.682\text{pH} + 0.325$	$0 < \text{pH} < 1.5$
	$-0.0592\text{pH} + 0.00 < \text{Eh} < -0.0682\text{pH} + 0.325$	$1.5 < \text{pH} < 7.5$
	$-0.0592\text{pH} + 0.00 < \text{Eh} < -0.0714 \text{pH} + 0.3494$	$7.5 < \text{pH} < 14$
Siderite	$-0.0682\text{pH} + 0.325 < \text{Eh} < -0.141\text{pH} + 0.931$	$6.6 < \text{pH} < 7.5$
Ferric ion	$0.756 < \text{Eh} < -0.0592\text{pH} + 1.229$	$0 < \text{pH} < 1.8$
Ferrous ion	$-0.0682\text{pH} + 0.325 < \text{Eh} < 0.756$	$0 < \text{pH} < 1.$
	$-0.0682\text{pH} + 0.325 < \text{Eh} < -0.1356\text{pH} + 0.915$	$1.8 < \text{pH} < 2.33$
	$-0.0682\text{pH} + 0.325 < \text{Eh} < -0.141\text{pH} + 0.931$	$2.33 < \text{pH} < 7.5$
	$-0.0593\text{pH} < \text{Eh} < -0.1333\text{pH} + 0.1$	$0 < \text{pH} < 1.5$

Ferrous ions have a wider field than ferric ions (Deutsch 1997).

More fieldwork is required to find the presence of other arsenic minerals as well as the size distribution of arsenic minerals in the delta's sediment, and to measure Eh-pH of groundwater.

Fate of sulfate

Without in-depth investigation, the Swedish group (Bhattacharya *et al.* 1999; Bhattacharya, personal communication to Husain 2001) links the observed low concentration of sulfur to oxhydroxide reduction theory for the arsenic contamination.

There are many possible sinks for sulfate. In the delta, the dry season is the aeration time, and the wet season is the time for flushing away. Sulfur is likely to be flushed away during the wet season. Different seasonal observations on spatial scales are necessary to conclude on the lower concentration of sulfur. Del Fanning supports these views (personal communication, July 18 2001).

Among the sulfates, jarosite and barite (BaSO_4) are insoluble in water. Barite limits the barium concentrations and not the sulfate concentration. If sulfate concentration increases, an equilibrium reaches with gypsum ($\text{CaSO}_4 \cdot \text{H}_2\text{O}$) which is relatively soluble. Strontium sulfate is sparingly soluble in water. Sulfate can act as a sink for strontium and barium which are not found in much abundance in natural waters.

CaSO_4 can be reduced to CaS by sulfate reducing bacteria such as *Desulfovibro spp.*, *Desulfotomaculum spp.* and others. CaS readily hydrolyzes to H_2S . Ca^{2+} then reacts with CO_3^{2-} which is made available by the oxidation of organic matter by sulfate-reducing bacteria (Ehrlich 1996)

The conditions for CaCO_3 precipitation are loss of CO_2 from the environment, the presence of a suitable buffer system, or formation of alkaline conditions.

Roemer & Schwartz (1965) reported on calcite formation from gypsum and anhydrite by sulfate reducers.

Sulfate can serve as terminal electron acceptors in the respiration of some bacteria under anaerobic conditions,

and is reduced to sulfite, and then to sulfide via a number of intermediate steps involving trithionate and thiosulfate (Kobiyashi *et al.* 1969; Akagi *et al.* 1974; Drake & Akagi 1978). The reactions between elemental sulfur and sulfite is pH-dependent. Elemental sulfur also reacts with sulfide (Roy & Trudinger 1970).

There are pathways for assimilation of organic sulfur. Cysteine (HSCH₂CH(NH₂)COOH) may be desulfurized by bacteria anaerobically to produce hydrogen sulfide (Freney 1967; Roy & Trudinger 1970).

All pathways of sulfur have to be investigated to check the reality of low sulfur concentration.

Dissolved arsenic forms in water

The important states of dissolved arsenic are the pentavalent (+5) arsenate state H_nAsO₄³⁻ⁿ, and the trivalent arsenite state H_nAsO₃²⁻ⁿ. The equilibrium condition is shown in Table 5 following Welch *et al.* (1988). In the pH range of

natural waters, the pentavalent species are primarily H₂AsO₄⁻ and HAsO₄²⁻ anions. The trivalent species in water are primarily H₃AsO₃⁰ and H₂AsO₃⁻. Metal oxyhydroxides like ferric hydroxide have a strong affinity for As(V) as well as a very high adsorption capacity for As(V). Fuller *et al.* (1990) reported as high as 0.25 mole of As per mole of freshly precipitated ferrihydrite. Its affinity for As(V) increases with decreasing pH (Pierce & Moore 1982).

Complementary nature of surface water and groundwater

In the delta, the surface water and groundwater complement each other. During the pre-barrage days, at the end of the dry season when the wet season would start in June, accumulation of runoff from rainwater and the Ganges water would fill floodplains, canals, ponds and ditches. These surface water bodies would recharge the groundwater table during the dry season (November–

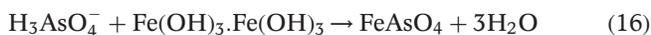
Table 5 | Equilibrium conditions of arsenic species (Welch *et al.* 1988)

Species	Eh range (V)	pH range
H ₃ AsO ₄ ⁰	-0.0585 pH + 0.575 < Eh < -5.85x10 ⁻² pH + 1.22	0.0 < pH < 2.2
H ₂ AsO ₄ ⁻	-0.0833 pH + 0.633 < Eh < -0.0585 pH + 1.22	2.2 < pH < 7.0
HAsO ₄ ⁻²	-0.123 pH + 0.910 < Eh < -0.0585 pH + 1.22	7.0 < pH < 9.2
	-0.091 pH + 0.620 < Eh < -0.0585 pH + 1.220	9.2 < pH < 11.5
AsO ₄ ⁻³	-0.0833 pH + 0.528 < Eh < -0.0585 pH + 1.22	11.5 < pH < 12.1
	-0.0763 pH + 0.443 < Eh < -0.0585 pH + 1.22	12.1 < pH < 14.
H ₃ AsO ₃ ⁰	-0.057 pH + 0.00 < Eh < -0.0585 pH + 0.575	0.0 < pH < 2.2
	-0.057 pH + 0.00 < Eh < -0.0833 pH + 0.633	2.2 < pH < 7.0
	-0.057 pH + 0.00 < Eh < -0.123 pH + 0.91	7.0 < pH < 9.2
H ₂ AsO ₃ ⁻	-0.057 pH + 0.00 < Eh < -0.091 pH + 0.62	9.2 < pH < 11.5
	-0.057 pH + 0.00 < Eh < -0.0833 pH + 0.528	11.5 < pH < 12.1
HAsO ₃ ⁻²	-0.057 pH + 0.00 < Eh < -0.0763 pH + 0.443	12.1 < pH < 13.4
AsO ₃ ⁻³	0.057 pH + 0.00 < Eh < -0.0763 pH + 0.443	13.4 < pH < 14

May). During the dry season, rapid evapotranspiration would occur from surface water bodies that would be replenished by groundwater causing a draw-out of groundwater.

Hindrance to self-purification process of groundwater

The natural self-purification property of water can be hampered if oxygen supply is hampered. Recharging water provides groundwater with oxygen. A shortage of surface water means a shortage of recharging water and a shortage of oxygen in groundwater. Water has a self-cleansing property using iron as the detergent (Hindmarsh & McCurdy 1986). Following Champ *et al.* (1979) and Braman (1983), the reactions under aerobic conditions of groundwater are:



The K_{SP} for the oxidized As species and Fe^{3+} to form FeAsO_4 is 5.7×10^{-21} . Ferric hydroxide also has a very high adsorption capacity for arsenic (Gulledge & O'Conner 1973; Irgolic 1994; Cheng *et al.* 1997). This natural self-purification of water occurs in Lake Michigan (Syedel 1972). Also, this age-old process has been used as remediation for arsenic-contaminated aquifers (Matthess 1981; Pierce & Moore 1982). Furthermore, Meng & Korfiatis (1999) patented a technique based on these reactions, and are using it in Bangladesh for the purification of water. In this exchange, 2 mg iron powder with other chemicals can result in 20 litres of contaminated water arsenic free in about 20 minutes (NFB 2001). The iron powder dissolves and adsorbs arsenic within 2 minutes. The water is then filtered through highly absorptive sand filling. The use of this simple system poses the potential risk of arsenic entrance into the food chain from indiscriminate disposal of the sludge.

The amount of recharging water required to purify the contaminated groundwater via the scavenging activity of iron hydroxide can be estimated. Stoichiometric calculations predict about 8 kg of dissolved oxygen per million

litres of recharging water if oxygen is present at its maximum concentration of 16 ppm. However, depending on the actual oxygen content and the participating oxidizing reactions, billions to trillions of litres of recharging water may be required for the cleansing of arsenic. As measured in specific sites, the pH of groundwater in the Ganges basin lies in the range of 6.7–8.3, and the iron content in the range of 0.3–2.26 mg/litre. These conditions are quite promising for the formation of iron hydroxides and the precipitation of insoluble arsenic compounds if enough recharging water is obtained.

Hugli Basin

The groundwater in the Hugli Basin in West Bengal, India, was contaminated first in the early eighties of the last century. This basin fell short of recharging water first because of implementing schemes for construction of dams and reservoirs upstream of the tributaries on the west side of the Hugli river. The list of these schemes appears in Figure 1. Later, groundwater extraction increased to such an extent that the observation wells were marked to have received a shorter recharge and over extraction (Subramaniam & Kosnett 1998).

Seepage of the contaminated water to Bangladesh

Groundwater moves from one location to another in times of days, months, years, and even centuries depending on the physical setting. The higher elevation of WB favors seepage of contaminated water to Bangladesh. No measured value of hydraulic gradient is available. Further, depending on the hydraulic head, contaminated water from one part of the country can travel to another part, thus spreading the contamination over wider areas. In the absence of any measured value of seepage rate, a range of values can be used. Leeden *et al.* (1990) mention the ground water flow velocity in the range of $0.05-1 \times 10^{-8}-5 \times 10^{-2}$ m/s. For a porosity of 25–50%, and an area of $5.60 \times 10^5 \text{ m}^2$ (1 metre vertical height of the seepage plane and a north-south border length of 5.60×10^5 m between West Bengal and Bangladesh, the annual seepage rate is $1.4 \times 10^{-3}-1.40 \times 10^4 \text{ m}^3/\text{s}$. Observation wells may be set up by the border areas in Bangladesh to find the exact values of annual seepage rates.

CONCLUSION

The entire Bengal Basin is controlled by water diversion constructions. The removal of the water from the Bengal Basin has produced many effects including arsenic contamination. The diversion of water from their natural courses has caused a shortage of groundwater recharge that has increased the depth and duration of the aeration zone that has favored oxidation of buried arsenopyrites. The resulting compounds of arsenic are soluble in water and have made their way into the groundwater through infiltration. The shortage of adequate recharging groundwater has put the aquifers under reducing conditions, too. Furthermore, the lack of adequate oxygen in the groundwater prohibits the natural purification process of water through the scavenging activity of ferric iron. The investigation of arsenic contamination is not complete unless the issue of upstream water diversion is included. The most plausible process of arsenic contamination of the delta's groundwater is the reduction process in aquifers following oxidation in the vadose zone. Siltation in the Hugli River caused by the dam and reservoir schemes on its tributaries to the west side contaminated the groundwater in the Hugli Basin first. Considering that West Bengal and its upper reaches are at a higher elevation and are the sites of major water diversion schemes, water seepage is likely to take place from this part to the Bangladesh Delta. Bangladesh ground water has been contaminated due to the water diversion from the Ganges and other rivers in addition to the seepage of contaminated water from West Bengal. Observation wells should be set up around the Bangladesh border to check the seepage rate. All sinks of sulfur need to be explored over an adequate time period. The permanent solution to the problem lies in the removal of all the upstream water diversion constructions in WB and other adjoining Indian states with Bangladesh. This will restore the original flow of the Ganges, the tributaries and distributaries of the Hugli and other international rivers, and reestablish the lost wetland ecosystems. The revitalized wetland ecosystems will allow wider areas and a longer time for the recharge of the groundwater, and will reestablish the natural purification process of water work. The purification of water will be a slow process. Over time, arsenic minerals in the sediment will remain covered

with water and not be exposed to atmospheric oxygen. Silted rivers and canals need to be properly dredged before such a step.

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