Over Pumping of Groundwater and its Impacts on the Irrigated Environment in Bangladesh

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Abstract

In Bangladesh, systematic irrigation started in the early 1960s with the introduction of deep tube wells and low-lift pumps. Before that period, farmers used to grow crops under rainfed conditions. Shallow Tube wells Came into operation after 1980. The main purpose of this research was to assess the impact of groundwater over extraction on the rice irrigated environment in Bangladesh. Over extraction from an aquifer at a rate greater than the aquifer recharge rate (SAR) can cause many environmental problems ; including the risk of arsenic release into the groundwater system and movement of arsenic contaminated layers into the deeper layers of the aquifer . The probabilities of arsenic concentration exceeding 10 ppb, 50 ppb, 100 ppb and 250 ppb in the upper 150 m of the aquifer were computed, by analyzing about 4000 deep Tube well's data collected from the secondary source. These values were superimposed on the hydrologic-zone maps of Bangladesh (Figure 1) in order to reveal the distribution patterns of arsenic contamination and its relationship with the hydrologic zone and lowering of water table.

Results analysis indicated that over extraction from the aquifer at a rate greater than the aquifer recharge rate can result in lower the water table level , decreased amount of dissolved oxygen in water which eventually can create reduced or anaerobic environment in the aquifer and release arsenic into the groundwater systems. A 3-D mathematical model analysis indicated that when the extraction rate was greater than the aquifer recharge (SAR) rate, it increased the flow through deeper layers when the aquifer was connected to the river system. But When the aquifer recharge rate (SAR) was greater than the pumping rate (Q) , it reduces the flow through the deeper layers aquifer. Doubling (1230 mm/Yr) or halving (635 mm/Yr) the shallow aquifer recharge rate (SAR) had no or very little impact on the groundwater flow patterns. However, increasing the conductivity of aquifer materials, drew more water to the deeper layers. It implies that over pumping groundwater from an aquifer with more permeable layers may increase the risk of arsenic contamination movement into the deeper layers.

Introduction

In a country like Bangladesh where the population density is 1200/sq km, it will be difficult to ensure their food security. Since its birth, Bangladesh has been confronting the issue of food security. In 1971 population was 75 million, now in 2023, population is about 200 million. Bangladesh still needs assured and reliable food supply for about 200 million population. Bangladesh has targeted for 59 million tons of food grain production in 2023(GOB 2022). Irrigation and introduction of modern HYV- Rice have revolutionized the food production in Bangladesh (39.7 Million tons of foodgrain/year). The systematic irrigation started in Bangladesh during the early 1960s, with the introduction of deep tube wells(DTW) and low-lift pumps(LLP). Before that period, farmers used to grow crops under rainfed conditions. Shallow Tube wells (STW) Came into operation after 1980.

Bangladesh has a land area of about 14.4 million ha of which 9.03 million ha (64%) are under cultivation. Both **small and minor scale irrigation systems including deep and shallow tubewells** play the dominant role in Boro rice cultivation. Large scale -Supplemental irrigation projects, such as ((Ganges -Kobadak Irrigation Project, Thakurgaon DTW Project, Barind Multipurpose Development Authority BMDA, and BADC Bangladesh Agriculture Development Corporation)) also contribute much to ensure dry season rice irrigation by using huge amount of groundwater .

2. .Literature Review

Number of Deep Tubewells (DTW), Shallow Tubewells (STW) and LowLift Pumps (LLP) in Bangladesh

In Bangladesh, about 94% of the irrigated land is under small and minor irrigation. According to a recent survey, water is being lifted in this country through 56,704 Deep Tube wells (DTW), 4,69,226 Shallow Tube wells (STW) , 56,829 low lift pumps(LLP), 1,42,132 manual pumps, and more than 5,65,000 indigenous water lifting devices .
However, limited irrigation is used for non-rice crops. The rice crop alone occupies 90-95% of the irrigated area and only 5-10% is left for other crops. Cultivation of modern varieties (MV) of rice during the Boro season is almost entirely dependent on irrigation water.

In Bangladesh , about 95% of the rainfall occurs during April to October, leaving the winter months, (i.e. November to March), very dry. The early part of Aus and the later part of T. Aman crops sometimes suffer from severe water stress. Therefore, irrigation is a prerequisite for obtaining stable high yields during the dry season.

Use of shallow and deep tube wells for drinking and irrigation purpose and growth irrigation wells in Bangladesh:

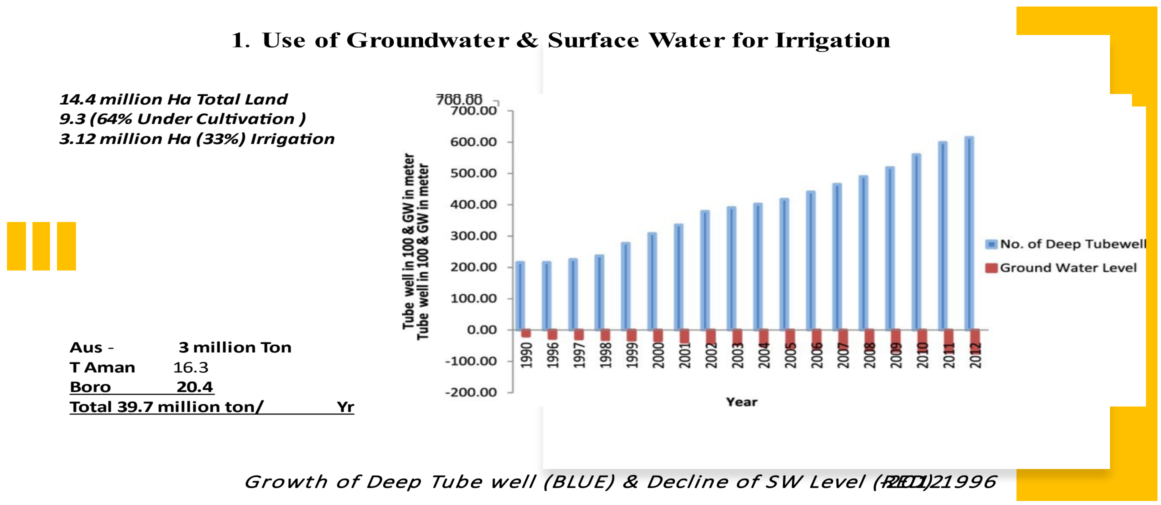
After 1970, the number of irrigation devices has been increasing. The provision of about 4 million Hand Tube wells (HTW) for 97% of the rural population has been credited with bringing down the high incidence of diarrhea diseases and contributing to a halving of the infant mortality rate **(WB 1998).** Paradoxically, the same wells that saved so many lives now pose a threat due to the unforeseen hazard of arsenic contamination. However, Bangladesh mostly depends on groundwater resources as a reliable source of irrigation water despite having large amount of surface water.

Over pumping from aquifers presents multidimensional problems including lowering water table:

The contribution of groundwater to the total irrigated area increased from 41% in 1982/1983 to 71% in 1996/1997 with a tendency of increase in each year. While the contribution of surface water steadily declines from 59% to 29% over the same period (**NMIDP, 1998**). In 2000, the number of shallow tube wells (STW) in the country sharply rose to about 757044 from about 635 units in 1973-74(**NMIDP, 1999; GOB 1999**).
Between 1964 and 1984, groundwater withdrawal in Bangladesh increased from about 30 million M3 /Yr to over 140 million M3/Yr (MPO 1997) . During the same period , the steady state piezometric head declined from around 0.7 m/Yr in 1970 to - 7.6 m below the sea level in 1994 in Dhaka city. Increased withdrawal has caused an average decline of one meter of pressure head for every 15 million M3 in ground water withdrawal (MPO 1987).

Environmental Consequences of Over Extraction of Groundwater:

Literature reviews suggested that because of large scale irrigation water withdrawal and up stream diversion of river water, the depth to groundwater was increased in Bangladesh. The redox potential values (P^e) decreased and were no longer controlled by the dissolved oxygen content in the recharging water, because the dissolved oxygen is consumed by the supply of electron donors (organic Carbon) in the groundwater system. Due to the low oxygen concentration in the aquifer, which favors the process of dissolution of iron oxides and eventually enhance the release of arsenic into the ground water. **Islam (2003**) studied the influence of over extraction of groundwater at a rate greater than that of aquifer recharge and found that it has many consequences on groundwater environment, such as lowering of the water level, decreasing amount of dissolved oxygen content in groundwater ,changing the pattern of groundwater movement, iron content, and likely hood of arsenic release into the groundwater system.



. (**Source**: BMDA)

Figure 1. Growth of Deep Tubewells (Blue Lines) and decline of groundwater water level (Red Lines) between 1990 and 2012 in Barind area.

Interactions between lowering of water level, dissolved oxygen content of recharging groundwater, Iron concentration and arsenic release into the groundwater system of Bangladesh:
Stumm and Morgan (1997) found that precipitation and dissolution reactions of ferric hydroxide are reversible reactions in the environment. It implies that when the oxygen concentration in the groundwater systems reduces , the dissolution of iron oxide will occur and eventually associated arsenic particles will be released into the water from the body of Ferric - oxides. This is how iron and arsenic release into the groundwater systems are related to the dissolved oxygen content in the groundwater.

Importance of dissolved oxygen content in the recharging groundwater and water quality:
Dissolved oxygen concentration in groundwater is an important factor in terms of water quality, especially for the issue of arsenic concentration. In oxygenated water , arsenic acid species ($H_3 As O_4$, $H_2 As O_4$, $HAsO_4^{2-}$, AsO_4^{3-}) are stable. In oxygenated water, adsorption reactions are thermodynamically favored by both enthalpy and entropy change (**Stom & Morgan 1997**). In oxygenated water, dissolved Fe^{2+} is converted to solid $Fe(OH)_3$ and anions of arsenic acids can be adsorbed on to the surface of amorphos solid iron hydroxides. The literature review has revealed that chemical contaminants in natural and ground water can be transported in particulate or colloidal form and in ionic form.

Objectives of this Research:

The overall goal of this research was to understand the processes that gives rise to arsenic concentration in the groundwater as a consequence of lowering of water level.

3. Methodology

The main hypothesis of this study was based on the idea that less oxygen is in the ground water , at and below the water table due to the extension of the unsaturated zone by over pumping of irrigation well. Pumping at a rate greater than that of aquifer recharge causes the water table to lower farther and reduces the rate of oxygen diffusion to deeper layers.

To accomplish the purpose of the study, **three analytical approaches are used:**
1. Statistical approach 2. thermodynamic or geochemical analysis and 3. 3-D mathematical models.

4. Results and Discussions:

4.1 Statistical analysis of the arsenic distribution pattern and its relationship with surface geology, depth of aquifer, dissolved iron content.

Islam (2003) conducted research to understand the interaction between the lowering of the water table position, decreased amount of dissolved oxygen content in recharging water and the triggering of the arsenic contamination problem in Bangladesh's groundwater.

On the basis of the availability of water resources and hydrological variation, Bangladesh is divided into six different water resources zone **(MPO 1987**): NE (North East), NC (North Center), NW (North West), SE (South East) and SW(South West) (**Figure and Table 1**). The distribution patterns of arsenic concentration data of about 4000 wells collected by the British Geological Survey (BGS) were statistically analyzed within the boundary of each group.

At first, the probability of arsenic levels exceeding 10 ppb (WHO **Standard**), 25 ppb (**Bangladesh'**s Target, 50 ppb (**Current Bangladesh Standard**), 100 ppb and 250 ppb were computed for each classification zone using **Exponential and Gumbel distribution** methods. Gumbel distribution was used because the arsenic concentration distribution pattern does not satisfy the condition of **Normal distribution**. The Probability of exceedance of threshold arsenic levels was computed by using exponential distribution equation s. Statistical analysis including probability of exceedance , correlations analysis was done. And presented in Table 1. and figure 1.

Table 1. Probability of exceedance of Arsenic concentration in different hydrologic zone of Bangladesh

Hydrologic Zone	Total **Sample Wells** **(DTW)**	Avg. Arsenic Conc. (ppb)	Stnd. Dev.	***Probability of exceedance (%)***				
				10 ppb (WHO)	**25 ppb BD-Targ**	**50 ppb (BD-Std)**	**100 ppb**	**250 ppb**
North East **(NE)**	1039	34 (0.5- 572)	67.9	58.73	48.7	34	14.9	**< 1**
North Cntr **(NC)**	192	28.64 (0.5-284)	51.4	53.99	48.8	39	24.45	4.98
North West (NW)	1072	12.26 (0.5-708)	47.1	44.93	32.74	18.1	5	0.3
South East **(SE)**	295	174.13 (0.5-1090)	199	80.13	76.26	71.4 *	59.55	29.1
South West **(SW)**	474	84.8 (0.5 -1660)	145	66.26	61.41	53.3 *	38.74	12
South Centr **(SC)**	295	38.61 (0.5-862)	113	53.99	48.05	38.9	24.42	4.98

In Table 1, the probabilities of arsenic exceeding 10, 50, 100 and 250 ppb in the upper 150 m of the aquifer were computed. These values were superimposed on the hydrologic zone maps of Bangladesh (Figure 1) in order to reveal the distribution patterns of arsenic and its relationship with the hydrologic zone. The probability of arsenic in exceedance of the threshold value (>50) strongly correlate with hydrologic zones

The probability of arsenic exceeding the threshold level(50 ppb) was greater than 50% in the SE(South East) and SW (Souithwest) zones (**Red Color**) and less than 50% in the NW (Northwest and North Center and South Center (SC) (Green Color) (**Table 1**.).

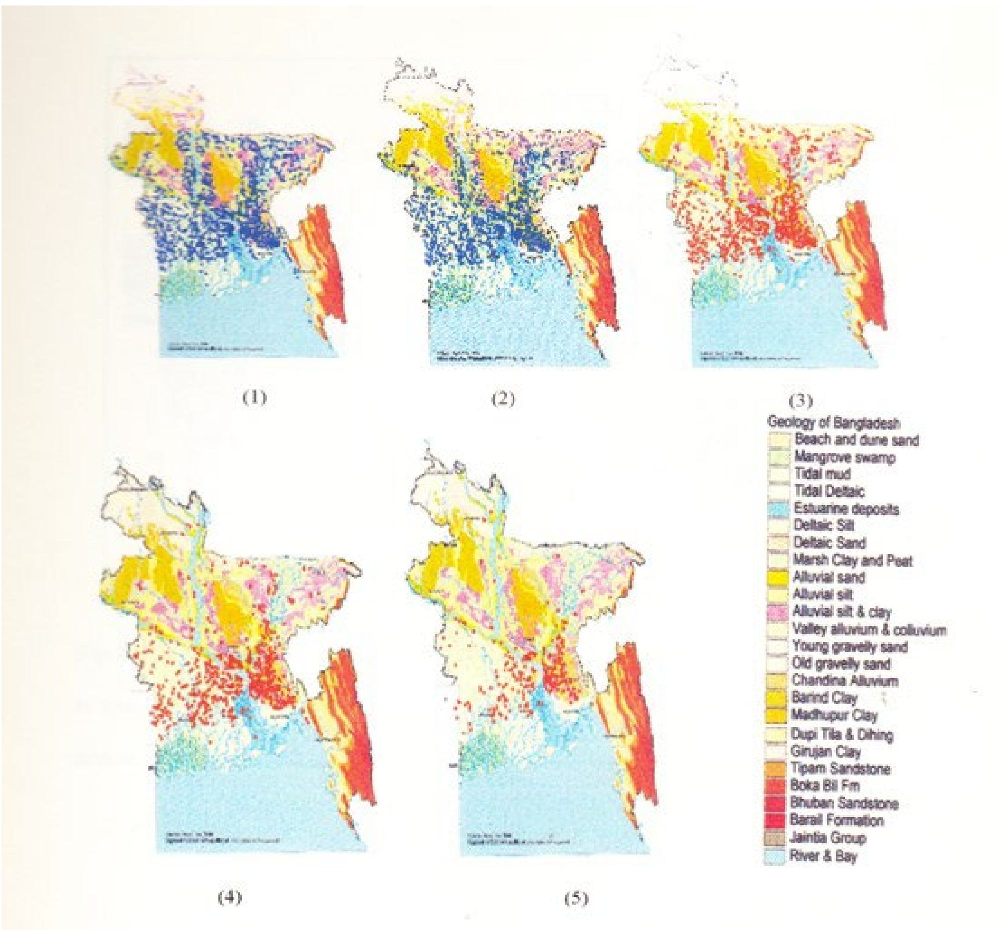


Figure 2. Blue dots on the upper maps (1 & 2) indicate arsenic contaminated Tube Wells with probability of arsenic concentrations greater than (>10 ppb) and (>25 ppb) respectively. **Red dots on the map** (3,4, & 5) indicate Tube Wells with arsenic concentration greater than (> 50 ppb) ,(> 100 ppb) and >(250 ppb) respectively.

Groundwater Irrigation Coverage and Arsenic contamination problem:
The geochemical analysis of about 4000 irrigation Wells data indicated that the probability of exceeding the threshold level of arsenic concentration (50 ppb) is less than 50% in North West (NW) and North Center zone (NC) . Fortunately, 40 % of groundwater irrigation is covered in the North West and North Center zone , however , the chance of release of arsenic into the groundwater is less than 40%. Apparently, in the

NE, NC and NW region , extensive groundwater irrigation does not have significant impact on arsenic contamination problem in Bangladesh. It does needs further investigation why these regions (NW, NC, NE) have been less affected by arsenic contamination.

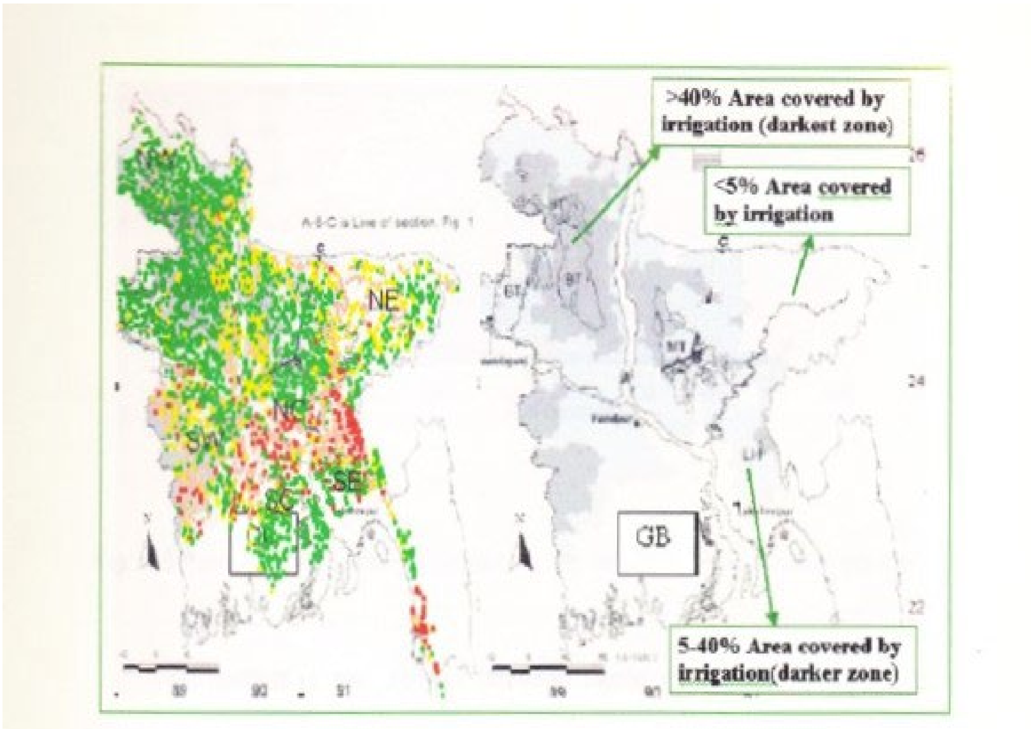


Figure 3. Distribution of groundwater irrigation coverage and the likelihood of arsenic contamination problem in different hydrologic zones .

The darkest areas use more than 40 % groundwater for irrigation, darker area use 5 to 40% and the white area use less than 5% groundwater for irrigation (**Figure 3**) . With data from the real heterogenic world, one would not expect a high correlation between aquifer depth and arsenic concentration . However, a R^2 value of about 58 to 72% at a regional scale was obtained (**Table.2**).

Table 2. Regression analysis between aquifer depth and arsenic pollution distribution in Bangladesh's groundwater system.

Geological Zones	Depth Range	Regression Equation	R2 Value (%)
Regional Surface geology (NW, NE, SW, SE)	0 to 10 m	Y=5.09 x	**58**
SE and SW regions	9 to 30	Y= 0.3428+1.79 log(x)	**60**
All regions (NW, NE, SW,SE)	**50 to 350** **100 to 350**	Y= -33.178 Ln (x) + 196.29 Y=-52.64 Ln (x) +301.83	**67** **85.17**

Source: (Islam, 2003)

Arsenic Concentration range over the depth of aquifer in Bangladesh:
To determine the relation between depth of the aquifer and arsenic concentration for the study area, a band regression analysis was performed. The average depth and arsenic concentration within the selected band or group was estimated by the method known as **Ensemble Average.**

The general patterns of arsenic concentration distribution over the aquifer depth were plotted for 3500 sampled wells distributed over Bangladesh (Figure ***3***.) In table 2, One would expect higher R^2 values if the arsenic concentration were related to the depths of the aquifer (0 to 50 m and 100 to 350 m of the aquifer. The concentration records were totally based on **stratified random variables** ,such as the depth, hydraulic conductivity , vertical permeability , storage coefficient etc.

4. 2. Geochemical Analysis of 3500 sampled well water:

The stability limit of arsenic species in the contaminated groundwater was plotted and calculated. It was revealed from the geochemical analysis that shifting of thermodynamic equilibrium in the aquifer was related to the gradual lowering of water table. Eventually it helps develop reducing environment in the aquifer and increase the risk of arsenic release into the groundwater of Bangladesh.

4.3 A 3-D Mathematical Model was analyzed with assuming a homogeneous, isotropic and steady-state Aquifer system.

Influence of over Pumping on the flow to and from the Rivers :

The river in the study was assumed to be the only outflow and the aquifer system was 400 m thick.

In general, pumping conditions provided more flow through the deeper layers than the natural groundwater flow condition did. The groundwater over extraction has a significant influence on the flow through the deeper layers of the aquifer system . When the extraction rate was greater than the aquifer recharge (SAR) rate, it increased the flow through deeper layers when the aquifer was connected to the river system.

But When the aquifer recharge rate (SAR) was greater than the pumping rate, it reduces the flow through the deeper layers aquifer (Islam 2003).

Computation of Flow patterns in the 3-D Uniform model and movement of arsenic contamination:

Doubling (1230 mm/Yr) or halving (635 mm/Yr) the shallow aquifer recharge rate (SAR) had no or very little impact on the groundwater flow patterns , however, increasing the conductivity, drew more water to the deeper layers. It implies that over pumping groundwater from an aquifer with more permeable layers increase the risk of arsenic movement into the deeper layers (Islam 2003).

Conclusions

- Lowering of the water table to deeper layers after introducing well fields did not increase the oxygen concentration in aquifer water, rather it decreases the oxygen supply to the aquifer water.
- The amount of surplus volume (SUR) available for aquifer recharge was found less when high volume of water consuming varieties were grown in study area of large irrigation projects. Whereas, the amount of SUR available with rainfed rice growing was found 3 times higher than growing HYVs. So, without knowing the influence of aquifer recharge on groundwater fluctuation, movement and flow patterns , it is simply a misleading approach to formulate irrigation development policy.
- It was evident from this research that over extraction from an aquifer at a rate greater than the aquifer recharge rate (SAR) can cause many environmental problems. It appears that arsenic release in groundwater is triggered by a misguided groundwater extraction policy.; including the risk of arsenic movement into the deeper layers of the aquifer.
- Arsenic concentration was found to increase with aquifer depth from 9 to 30 m below the ground surface but to decrease with depth from 100 to 350 m below the ground.
- A 3-D mathematical model results clearly demonstrated that placing well screen at deeper layers would increase the downward flow and arsenic might move with the groundwater to the deeper layers. Also, there is evidence that extraction at a rate greater than the aquifer recharge rate (SAR) increases downward flow through the deeper layers of the aquifer system.

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