

**HYDROGEOLOGIC CHARACTERISTICS AND GROUNDWATER POTENTIALITY OF LOWER AQUIFER OF SINGAIR UPAZILA, MANIKGANJ DISTRICT, BANGLADESH**

MAZEDA ISLAM\*, KHAIRUL BASHAR, NASIR AHMED<sup>1</sup>, MD. GOLAM RASUL<sup>1</sup>, SAHADAT HOSSAIN<sup>1</sup> AND MD. MIZANUR RAHMAN SARKER

*Department of Geological Sciences, Jahangirnagar University, Savar, Dhaka*

**ABSTRACT**

The study area is located in the central part of Bangladesh. The aims of this study were to explain the hydrogeological characteristics of aquifers and evaluate the groundwater potentiality. The borehole logs revealed three types of zones: upper aquitard (low permeability clays, silty clays & silts), upper aquifer (very fine sand to fine sand) and lower aquifer (medium to coarse sands and gravels). Both aquifer waters are mainly Ca-Mg-HCO<sub>3</sub> type. Except arsenic (As), most of the ions of both aquifer waters are within the limit of drinking standard of WHO (2004) and Bangladesh (DoE, 1997). Arsenic concentrations of upper aquifer exceed both the WHO (10 µg/l) and Bangladesh standard (50 µg/l) and for lower aquifer exceed only WHO standard. Waters of both aquifers in north western and central part of the study area show high arsenic concentration due to lack of continuous impermeable layer between them as revealed from borelog data. Water quality index map also indicates that north western and central part is not suitable for groundwater development because of inferior quality. The average δ<sup>18</sup>O values for upper and lower aquifer waters are isotopically enriched compared to river water (~10.08‰). Similar isotopic composition of upper (~4.77‰) and lower aquifer waters (~5.50‰) indicates both waters were mixed in the past and mixing may be continued in the future. The mixing may be preferentially from the upper aquifer to lower aquifer because of water abstraction, lack of impermeable layer and high permeability of the upper aquifer etc. Therefore, the potentiality of the lower aquifer may not be suitable for large-scale groundwater development project without any mitigation measure.

Key words: Upper aquifer, Lower aquifer, Hydrochemistry, Stable isotope and WQI

**INTRODUCTION**

Water is abundant due to heavy rainfall for several months each year in the Bengal Basin of Bangladesh and India (Michael *et al.* 2009). The landscape of the study is dominated by the surface water bodies. Because of poor sanitation, use of fertilizers, chemicals for cultivation and inadequate waste management practices, the surface water bodies of the study area are nearly

contaminated with microbial pathogens and anthropogenic pollutants (Michael *et al.* 2009). To avoid contaminated water, 80 deep tube wells and 3070 shallow tube wells are in operation for domestic and agricultural purposes (BADC 2004). Water borne diseases and infant mortality rate has reduced dramatically because of the use of groundwater instead of surface water in

\* Corresponding author: <mazeda@juniv.edu>.

<sup>1</sup> Isotope Hydrology Division, Institute of Nuclear Science & Technology, AERE, Savar, Dhaka.

Bangladesh (Rahman and Ravenscroft 2003). Large proportion of wells have elevated levels of dissolved arsenic undiscovered until 1990s and around 46 million people are at the risk of adverse health effects (Yu *et al.* 2003) in Bangladesh. According Ahmed *et al.* (2006) more than half million of those exposed to arsenic are continuously drinking water with arsenic concentrations higher than worldwide drinking water standards. The released mechanism of arsenic from the sediments is widely variable as shown by study of arsenic concentrations in water wells on both large (BGS and DPHE 2001; NAMIC and BAMWSP 2003) and small spatial scale (van Geen *et al.* 2003; van Geen *et al.* 2006). But the dissolved arsenic concentration is remarkably consistent vertically (Michael *et al.* 2009). In general, highest concentration of dissolved arsenic occur in the shallow aquifer sediments of Holocene age, grey and chemically reducing compared to groundwater in older age, brown or orange oxidized sediments at depth having low arsenic concentration (BGS and DPHE 2001; Ahmed *et al.* 2004). A depth of approximately 100 m is mostly arsenic contaminated in most of the arsenic contaminated areas although this depth varies and contact is not clear. Elevated concentration of arsenic is mainly occurred within the shallow sediments and below the detection limit at greater depth from the results of geological and chemical stratification (BGS and DPHE 2001; Ravenscroft *et al.* 2001; Harvey *et al.* 2002; van Geen *et al.* 2003). A study by Halim *et al.* (2014) in the Singair Upazila of Manikganj district revealed that high concentration of As (23 mg/kg) with elevated concentrations of FeO, MnO and TOC were

found within the upper 15 m of silty clay sediments. The high concentrations of arsenic in groundwater of Bangladesh are occurring naturally and the dominating process is the mobilization of arsenic from arsenic enriched minerals (Lowers *et al.* 2007; Halim *et al.* 2010). A good number of recent studies (Acharyya *et al.* 1999; Nickson *et al.* 2000; Mc Arthur *et al.* 2001) suggested that Arsenic in Bengal Basin was derived from the Himalayan rocks weathering and subsequently the released As was adsorbed by stream sediments and oxides under aerobic conditions during their transportation by surface water. The World Health Organization (WHO) has set a guideline value 10 µg/L for arsenic in drinking water because of its adverse health effect (WHO 2004). Due to water availability most of the water wells for drinking water are abstracting water from the shallow aquifers and the water from the shallow aquifer is contaminated with arsenic. People of the study area are thinking to drill more deep wells to avoid the arsenic contamination. However, the consequence of water abstraction from the deep aquifer of the study area is very poorly studied. This study will simply try to determine the flow pattern and mobilization of arsenic with the help of stable isotope study. Determination of the usability of lower aquifer as a source of fresh water with acceptable arsenic content is made in the present study.

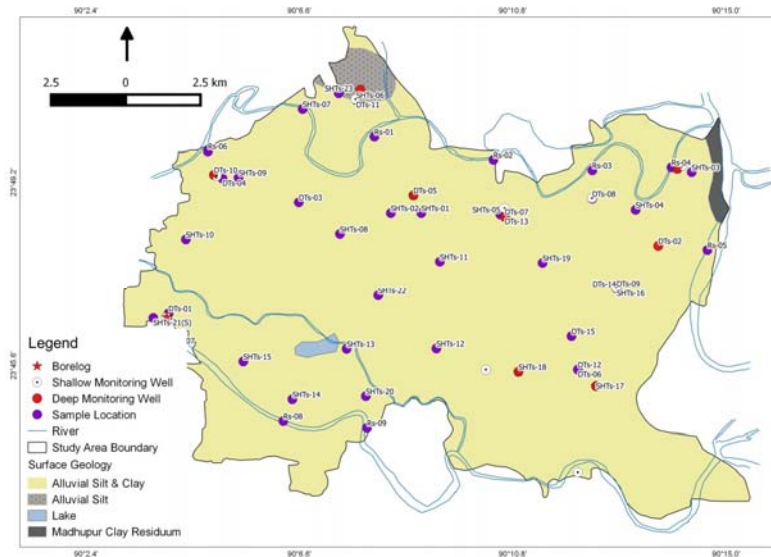
## MATERIALS AND METHODS

### *Description of the Study Area*

The studied area, “Singair Upazila” of Manikganj district, is in the central part of Bangladesh (90°03'E to 90°16'E and

23°42'N to 23°52.3'N), about 20 km away from Dhaka (Fig. 1). Main rivers are the Kaliganga River and Dhaleshwari River. The

Department (BMD). Observation well data for ten piezometers in the study area were collected from BWDB. The maximum



**Fig. 1.** Sample location, borelog, monitoring well and surface geology map of the study area.

Kaliganga River in South and Dhaleshwari River bounded in the Eastern and Northern portion and overflow during the wet season. The Dhaleswari is the main river, which is bounded with the north and east portion of the study area and Kaliganga River flows in the southern part. The study area lies in the tropical monsoon climatic zone, which is subjected to tropical climate and is characterized by the moderate to high temperature (34.5°C), heavy rainfall and often with excessive humidity. Maximum rainfall occurs during May to October in summer. Geological, hydrogeological and meteorological data of different kinds were collected from Bangladesh Water Development Board (BWDB), Department of Public Health Engineering (DPHE), Bangladesh Agricultural Development Board (BADC) and Bangladesh Meteorological

elevation of the groundwater level in the month of September 2006 range from 3.5 to 6.5 mPWD for shallow monitoring well and range from 3.6 to 7.5 mPWD for deep monitoring well. In March 2006, the minimum elevation of groundwater table in the Singair area range from zero or less than zero to 2 mPWD for shallow monitoring well and range from zero or less than zero to 3 mPWD for deep monitoring well. Water table of minimum elevation indicates that flow direction from northwest to southeast is towards the present Kaliganga and Dhaleswari confluence. Water table of maximum elevation indicates that the direction from southeast to northwest direction in both shallow and deep monitoring well respectively. From short-term hydrograph, it is found that the upper and lower aquifer are hydraulically

connected and recharged from the same source. The cross plot of rainfall, groundwater level and river stage indicates that the rainfall is directly involved in the recharge of groundwater level and river stage.

#### *Geology and Hydrogeology*

Topographically, the study area is flat. The geology of the study area can be attributed to Quaternary alluvial sequence, which is a part of Ganges – Jamuna flood plain. The north and western part of the area is covered by the Pleistocene sediments, which are known as Madhupur clay. In general, the stratigraphic sequence is fining upward sequence i.e. from gravels to cobbles, pebbles, sand and finally silts and clays; micaceous are abundant in whole sequence in Pliocene- Pleistocene-Holocene time. From the analysis of the individual log and cross-section sections, the aquifer system of the study area can be divided into three divisions; upper aquitard: comprises a mixed sequence of grey coloured low permeability clays, silty clays, silts and occasional very fine sand layer (Fig. 2). Thickness ranges from 3.05 m to 9.15 m. Upper aquifer mainly composed of grey to light brown color very fine sand to fine sand and thickness ranges

from 39.65 m to 85.41 m. Lower aquifer is composed of medium to coarse sands and gravels. The thickness of this zone ranges from 129.2 m to 173.8 m. Most of the deep tube wells either for irrigation or for domestic and industrial purposes have been installed in this zone. Absence of lower aquitard indicates that the area is susceptible to contamination.

#### *Hydrochemistry Data*

Groundwater samples were collected from active wells and different types of observation wells installed at different aquifers down to the maximum 247 m below ground level (bgl) (Fig. 1). The depth range of upper aquifer water varies from 12 to 70 mbgl and 70 to 247 mbgl for the lower aquifer water. USGS sampling protocols have been followed during the collection of groundwater and surface water samples (Claassen 1982). 0.45  $\mu$ m pore-size disposable capsule filter has been used for more turbid water, especially river water. Anion samples were preserved in labeled as "FU" (filtered unacidified) in the polyethylene bottles. For the cations, HNO<sub>3</sub> had been used and labeled as "FA" (filtered,

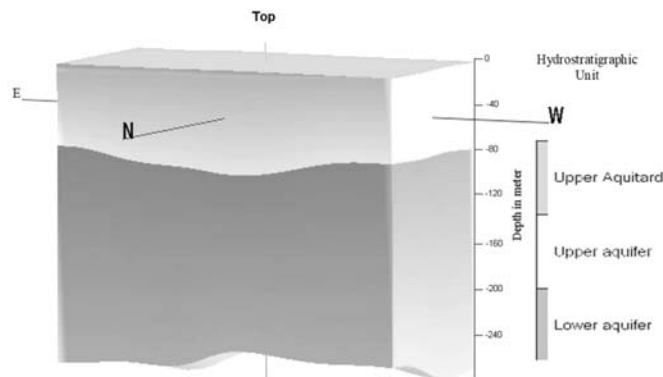


Fig. 2. 3-D hydrostratigraphic model of the study area.

acidified) in the polyethylene bottles. The pH, temperature ( $^{\circ}\text{C}$ ) and electrical conductivity (EC) were measured in the field during sampling. Samples were stored below  $4^{\circ}\text{C}$  and all the laboratory analyses had been carried out in the Isotope Hydrology laboratory, Atomic Energy Research Establishment, Institute of Nuclear Science and Technology, Bangladesh Atomic Energy Commission following the laboratory manual and standard methods for examination of water and wastewater (APHA 1985).  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$  analyses were done by flame atomic absorption spectrometry (FAAS). Concentrations of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{PO}_4^{3-}$  were determined by molecular absorption spectrophotometry. Arsenic was measured with hydride system at FAAS. Titration with HCl was used for the determination of  $\text{HCO}_3^-$ .  $\text{SO}_4^{2-}$  was measured with a turbidimetric method. The trace elements, manganese (Mn), iron (Fe) and silicon dioxide ( $\text{SiO}_2$ ) were determined using spectrophotometer. Aquachem<sup>3,70</sup> software (Calmbach 1997); the (Piper 1953) diagram have been used to classify water. The Piper diagram was used to plot the major ions as

percentages of milli-equivalents. The drinking water quality has been assessed against the standard of DoE (1997) and World Health Organization (WHO 2004). Sodium adsorption ratio (SAR), electrical conductivity (EC), soluble sodium percent (%Na), and other parameters such as chloride and sulphate were used for irrigation suitability assessment. The US Salinity Laboratory (USSL) (1954) diagram has been used to determine the groundwater suitability for agricultural purpose. QGIS software has been used for the preparation of different geological, hydrogeological and piezometric maps and spatial distribution of water chemistry data. Statistical software such as R and Microsoft excel were used for statistical analysis.

## RESULTS AND DISCUSSION

### *Basic Statistics and General Chemistry*

pH has no positive correlation with other constituents except As and has a strong negative correlation with stable isotopes (Table 1).  $\text{Na}^+$  has very good correlation with  $\text{HCO}_3^-$ , EC and  $\text{Cl}^-$ , EC has strong correlation with  $\text{HCO}_3^-$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Cl}^-$  and stable isotope.

**Table 1: Cross-correlations among major chemical constituents of the waters. Substantially large correlation values ( $>0.50$ ) are bolded.**

	pH	EC	$\text{HCO}_3^-$	$\text{Cl}^-$	$\text{Na}^{2+}$	$\text{K}^+$	$\text{Ca}^{2+}$	$\text{Mg}^+$	As	$^{18}\text{O}$	$^2\text{H}$
pH	1.00										
EC	<b>-0.65</b>	1.00									
$\text{HCO}_3^-$	<b>-0.66</b>	<b>0.95</b>	1.00								
$\text{Cl}^-$	-0.41	<b>0.61</b>	<b>0.50</b>	1.00							
$\text{Na}^+$	-0.44	<b>0.64</b>	<b>0.66</b>	<b>0.53</b>	1.00						
$\text{K}^+$	-0.27	0.44	0.36	0.20	0.33	1.00					
$\text{Ca}^{2+}$	<b>-0.61</b>	<b>0.89</b>	<b>0.85</b>	<b>0.63</b>	<b>0.59</b>	<b>0.53</b>	1.00				
$\text{Mg}^{2+}$	<b>-0.68</b>	<b>0.94</b>	<b>0.91</b>	<b>0.53</b>	0.50	0.37	<b>0.86</b>	1.00			
As	0.13	0.15	0.19	-0.19	0.00	-0.03	0.11	0.01	1.00		
$^{18}\text{O}$	<b>-0.72</b>	<b>0.78</b>	<b>0.81</b>	0.43	<b>0.58</b>	0.26	<b>0.71</b>	<b>0.82</b>	0.11	1.00	
$^2\text{H}$	<b>-0.73</b>	<b>0.77</b>	<b>0.80</b>	0.42	<b>0.57</b>	0.27	<b>0.71</b>	<b>0.82</b>	0.06	<b>1.00</b>	1.00

Dissolution of dolomite and calcite can be inferred from the strong positive correlation between  $Mg^{2+}$  and  $Ca^{2+}$ . Because of calcium removal from water due to precipitation of calcite, the calcium concentration is mostly less than the chloride ( $Cl^-$ ) concentration. The cation exchange process is responsible for precipitation of calcite. The strong positive correlation of  $HCO_3^-$  with  $Ca^{2+}$  can be interpreted as fresh recharge water. Very strong positive correlation also exists between  $^{18}O$  and  $^2H$ .

The basic statistical summary of the water chemistry is given in Table 2. The EC of the analyzed water sample ranges from 349 to 985  $\mu S/cm$  for deep water and 144 to 1054  $\mu S/cm$  for shallow waters. In both waters are within the suitable range prescribed by WHO (2004). Generally alkaline to acidic type waters are common in both deep and shallow waters. The average  $HCO_3^-$  value of shallow waters (322 mg/l) is lower than the deep waters (324 mg/l). The chloride concentration of shallow waters is higher than the deep waters. This may be the leaching from the upper soil layers derived from domestic activities and industrial activities. Average  $SO_4^{2-}$  concentration of shallow aquifers (10 mg/l) is also higher than the deep waters (2 mg/l) may be due to leaching and anthropogenic activities. The concentration of  $K^+$ ,  $Ca^{2+}$ ,  $Mg^{2+}$  and  $NO_3^-$  is within the permissible limit (WHO 2004). Average arsenic concentration (60.45  $\mu g/l$ ) of shallow aquifer is higher than the deep waters (46.25  $\mu g/l$ ).

#### *Water Type Classification Based on Piper Diagram*

The hydrochemical concepts can be used to identify the groundwater water transport and

flow mechanisms and also unravel the paleoenvironmental information (Pierre *et al.* 2005; Ophori and Toth 1989; Hem 1992 and Vasanthavigar *et al.* 2010). Piper plot (Piper 1953) is widely used to determine the hydrogeochemical facies of groundwater. The diamond part of a Piper diagram may be used to characterize different water types.

Piper divided waters into four basic types according to their placement near the four corners of the diamond. Water that plots at the top of the diamond is high in both  $Ca^{2+} + Mg^{2+}$  and  $Cl^- + SO_4^{2-}$ , which results in an area of permanent hardness. The water that plots near the left corner is rich in  $Ca^{2+} + Mg^{2+}$  and  $HCO_3^-$  and is the region of water of temporary hardness.

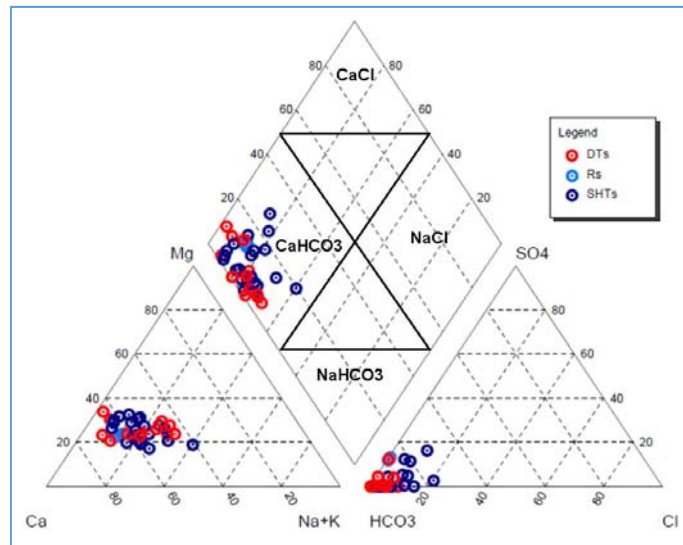
Water plotted at the lower corner of the diamond is primarily composed of alkali carbonates ( $Na^+ + K^+$  and  $HCO_3^- + CO_3^{2-}$ ). Water lying near the right-hand side of the diamond may be considered saline ( $Na^+ + K^+$  and  $Cl^- + SO_4^{2-}$ ). All the water chemistry data of the study area has been plotted in the Fig. 3.

From the observation of Fig. 3 of lower aquifer samples DTs-2, DTs-5 and DTs-11 belong to Ca-Mg- $HCO_3$  type water and the samples DTs-3, DTs-4, DTs-7, DTs-13 and DTS-15 belong to Ca-Mg-Na- $HCO_3$  type water of temporary hardness. The upper aquifer sample SHTs-1, SHTs-2, SHTs-3, SHTs-4, SHTs-6, SHTs-7, SHTs-9, SHTs-11, SHTs-16, SHTs-17, SHTs-18, SHTs-20, SHTs-21(s) and SHT-22, belongs to Ca-Mg- $HCO_3$  type water of temporary hardness and the samples SHTs-3, SHTs-5, SHTs-8, SHTs-6, SHTs-10, SHTs-12, SHTs-13, SHTs-14, SHTs-15, SHTs-19, SHTs-21 and SHTs-22 belongs to Ca-Mg-Na- $HCO_3$  type water of temporary hardness.



All of these samples have low to negligible chloride content and secondary alkalinity exceeds 50%. These are all pure meteoric waters, which have not undergone any much specific chemical changes. All the river

average composition of  $\delta^2\text{H}$  of shallow, deep and river samples is -29.95‰, -30.65‰, -77.84‰ respectively (Fig 6). The analyzed samples are plotted with respect to the Global Meteoric Water Line (GMWL) of Craig



**Fig. 3.** Piper diagram with major ions and water types.

waters are Ca-Mg-HCO<sub>3</sub> type water. From the piper plot, it is evident that Ca-Mg-HCO<sub>3</sub> and Ca-Mg-Na-HCO<sub>3</sub> type of water are the characteristics of the study area.

#### *Stable Isotope Analysis*

The results of the stable isotopes are discussed below. The stable oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta^2\text{H}$ ) isotope ratios of shallow groundwater samples vary from -6.94 to -3.19 and -44.5 to -17.43 respectively. For deep wells the value ranges from -6.15‰ to -4.04‰ and -39.22‰ to -19.76‰ respectively and the river samples range from -11.68‰ to -10.23‰ and -83.28‰ to -72.82‰ respectively. The average composition of  $\delta^{18}\text{O}$  of shallow, deep and river samples is -4.77‰, -5.5‰, -10.08‰ respectively (Fig 5). The

(1961) and local meteoric water line (Fig. 4). All samples plot on or to some extent below the local and global meteoric water line. The stable isotope values are also compared with the stable isotope of precipitation samples from Barisal District, a 180 km south to the study site. River waters are similar to the average precipitation value (Fig. 4) indicating the origin of river water is directly from precipitation. The average  $\delta^{18}\text{O}$  values for shallow and deep groundwater are isotopically enriched compared to rainwater. The average  $\delta^{18}\text{O}$  values for shallow and deep groundwater are very similar to each other. Although the depth is different but their similar isotopic composition indicates that both waters were mixed after some time intervals and are continuing. The mixing may be preferentially



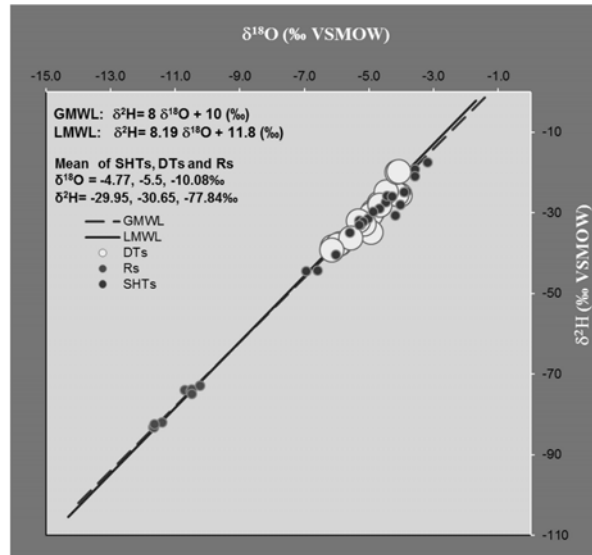


Fig. 4. Relation between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  with reference to Global Meteoric Water Line (GMWL) & Local Meteoric Water Line (LMWL).

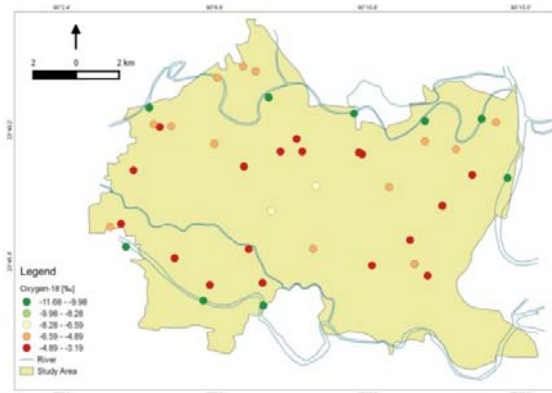


Fig. 5. Spatial distribution of stable oxygen-18 ( $\delta^{18}\text{O}$ ) of the study area.

from the shallow aquifer to deep aquifer either because of the location of the pump or greater permeability of the shallow aquifer. According to surface geology and subsurface geology, there may be a hydraulic connection between shallow and deep aquifer as there is no low permeable zone. Based on isotopic values of rainfall and EC values of the

analyzed water samples, it can be said that the shallow and deep groundwater are mainly recharged during a cooler period, probably the last glacial period. The more enriched value of both shallow and deep waters is located in the north-western to eastern part where arsenic concentrations of both aquifer waters are also high.

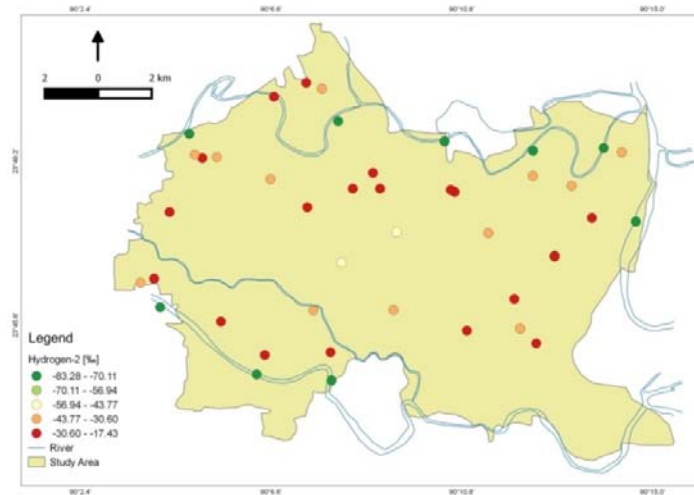


Fig. 6. Spatial distribution of stable hydrogen-2 ( $\delta^2\text{H}$ ) of the study area.

#### *Arsenic Distribution*

In Bangladesh, As concentrations are low near the water table, rise to a maximum typically 20-40 m below ground, and fall to very low levels between about 100 and 200 m. Aquifers at more than 200 m below the floodplains offer good prospects for long-term arsenic-free water supplies, but may be limited by the threats of saline intrusion and downward leakage of arsenic (Ravenscroft *et al.* 2005). Due to arsenic contamination, in some part of the Singair Upazila has been restricted for the use of groundwater from upper aquifer for drinking purposes. The arsenic concentration in the upper aquifer range from 0.003 to 217  $\mu\text{g/l}$  and average concentration is 60.45  $\mu\text{g/l}$ . In the lower aquifer, arsenic concentration ranges from 5 to 122  $\mu\text{g/l}$  and average concentration of arsenic is in the lower aquifer also 46.25  $\mu\text{g/l}$ . 73% deep aquifer samples exceed the maximum allowable limit (10  $\mu\text{g/l}$ ) of WHO standard. Samples DTs1, DTs3, DTs6, DTs7, DTs11 exceed the Bangladesh standard (50  $\mu\text{g/l}$ ). Out

of 23 upper aquifer samples, 16 samples exceed the WHO (2004) provisional drinking water limit and 11 samples exceed the Bangladesh standards limit (DoE 1997). Concentration of arsenic in upper aquifer is higher than the lower aquifer and most of the sample exceeds WHO standard. Minimum concentration of arsenic groundwater is found in north-eastern part of the study area. From spatial distribution of arsenic concentration, it reveals that high concentration of arsenic is present in the central part and north-western part of the study area (Fig.7). The depth and spatial distribution of arsenic concentration in both shallow and deepwater wells has already been mixed in some parts of the study area because of over exploitation and abstraction for drinking and agricultural purposes (Fig. 8). This will continue after having a huge abstraction proposed by DWASA. The mixing of arsenic rich shallow aquifer water with deep aquifers water is confirmed by the interpretation of stable isotopic composition of both aquifers water in the study area.

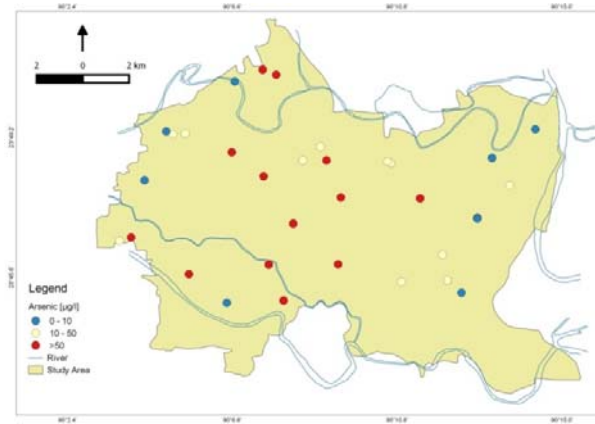


Fig. 7. Spatial distribution map of arsenic (As) of the study area.

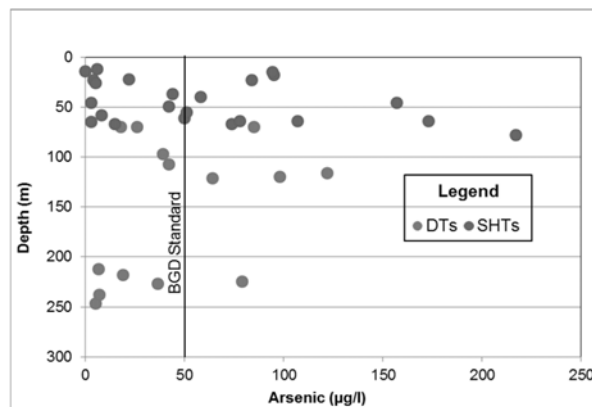


Fig. 8. Depth distribution of arsenic (As) of the study area.

*Groundwater Quality for Domestic and Drinking Purposes*

Drinking water standards are especially important for evaluating groundwater quality because many consumers utilize untreated groundwater that is pumped directly from a well (Fetter 1994). Quality classification is necessary for potential use of water. The construction of water wells in the study area without proper investigation and unregulated withdrawal of groundwater have accelerated the degradation of water quality.

*Classification based on Total Hardness*

Hardness is the sum of Ca and Mg concentrations expressed in mg/L of calcium carbonate. Classification of water based on hardness was given by Sawyer and McCarty (1967). Total hardness of groundwater and surface water samples has been calculated by using the following formula, where concentrations are in meq/l.

$$\text{Total Hardness as CaCO}_3 \text{ in mg/L} = \Sigma (\text{Ca} + \text{Mg}) \times 5.$$

In the study area, about 72% water from shallow and 94% water from deep aquifers are very hard resulting in unsuitable quality.

#### *Classification based on TDS*

Total dissolved solid (TDS) is calculated by adding the mass of all ions plus silica. TDS in water includes all solid material whether ionized or not, but it does not include suspended sediments, colloids or dissolved gases. All the waters of the study area are fresh.

#### *Quality as Drinking Water*

In terms of drinking water quality standard, most of the ions of shallow and deep aquifer water are within the limit of drinking water quality standard of both Bangladesh (DoE 1997) and WHO (2004). Most of the upper aquifer water exhibits higher arsenic concentrations. Most of the upper aquifer samples exceed WHO (2004) standard limit (0.01mg/l) except SHTs-04, SHTs-07, SHTs-15 and SHTs-19 and eleven upper aquifer samples exceed Bangladesh drinking water standard limit (0.05 mg/l). In lower aquifer, maximum water exceeds the arsenic concentration of WHO standard and water samples DTs-07, DTs-08 and DTs-11 exceed Bangladesh standard of drinking water limit. Northwestern and central part of the study area show higher arsenic concentration due to lack of continuous impermeable zone between upper and lower aquifer. The concentration is fairly exceeding the guide line limit, other than arsenic, some other constituents iron and manganese are worthy to observe, though most of them are not

problematic for health concern. High concentration of arsenic is the single most health concern in the Singair Upazila. The severely arsenic contaminated groundwater is dominantly Ca-Mg-HCO<sub>3</sub> type water with neutral to basic pH, often hard to very hard hardness with much bicarbonate concentrations. Most of the ions of river water are within the limit of drinking water quality standard of Bangladesh (DoE, 1997) and WHO (2004).

#### *Ground water Quality Index Mapping*

Different water quality parameters on the suitability for drinking purposes can be determined by using groundwater quality index (GWQI) (Sahu and Sikdar 2008). The following equation has been used to determine the GWQI (Vasanthavigar *et al.* 2010) with respect to WHO and Bangladesh standards.

$$GWQI = \sum SI_i = \sum w_i \times q_i$$

$$= \sum \left[ \left( \frac{w_i}{\sum_{i=1}^n w_i} \right) \times \left( \frac{C_i}{S_i} \times 100 \right) \right]$$

Weight (Wi) is computed from the following equation:

$$W_i = w_i / \sum_{i=1}^n w_i$$

where

Wi is the relative weight, wi is the weight of each parameter, n is the number of parameters

Calculated relative weight (Wi) values of each parameter are given in Table 3 where qi is the quality rating, Ci is the concentration of each chemical parameter in each water sample in milligrams per liter,

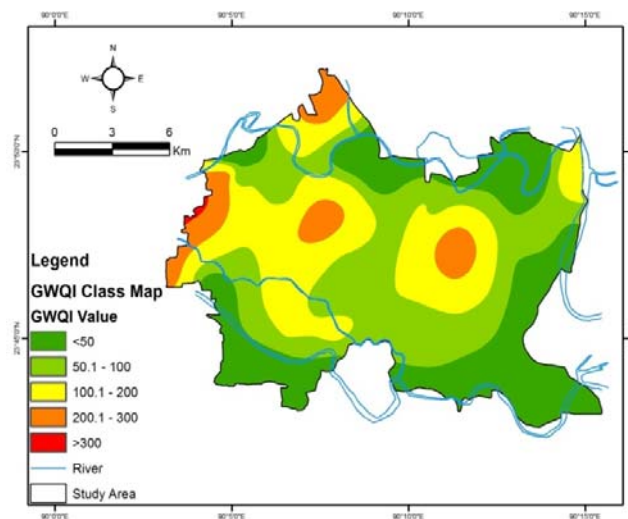
**Table 3. Parameters, weight factors, and limit values considered for the water quality index according to Nabizadeh *et al.* (2013) and Vasanthavigar *et al.* (2010).**

Parameters	Weight ( $W_i$ )	Relative Weight ( $W_i$ )	Limiting values (DoE1997)
pH	4	0.105	6.5-8.5
Na <sup>+</sup> (mg/l)	4	0.105	200
K <sup>+</sup> (mg/l)	2	0.053	12
Ca <sup>2+</sup> (mg/l)	2	0.053	75
Mg <sup>2+</sup> (mg/l)	2	0.053	30
Cl <sup>-</sup> (mg/l)	3	0.079	250
NO <sub>3</sub> <sup>-</sup> (mg/l)	4	0.105	10
SO <sub>4</sub> <sup>2-</sup> (mg/l)	4	0.105	400
As (μg/l)	4	0.105	50
Fe (mg/l)	4	0.105	1000
Mn (mg/l)	4	0.105	300
HCO <sub>3</sub> <sup>-</sup> (mg/l)	1	0.026	600

Si is the drinking water standard for each chemical parameter in milligrams per liter according to the guidelines of the DoE (1997).

The WQI range and type of water can be classified as below: Range Type of water  
 <50 Excellent water; 50-100 Good water;  
 100-200 Poor water; 200-300 Very poor

water; >300 water unsuitable for drinking purposes. The computed WQI values ranges from 23.76 to 257.18. Finally, a GWQI spatial map has been drawn (Fig. 9). The map indicates that unsuitable drinking waters are found in the north-western part of the study area. Poor to very poor-quality waters are observed mostly in the central to northern

**Fig. 9.** Ground water quality index map of the study area.

part of the study area. 43% of groundwater samples represent “excellent water”, 24% indicate “good water”, 21% shows “poor water”, and 9% shows “very poor water”. More degraded quality water in the central to northern part of the study area may be due to ions leaching, over drafting and agricultural impact (Sahu and Sikdar 2008). The arsenic distribution map of the study area also indicates that the central portion has arsenic concentration above the recommended limit.

#### CONCLUSION

Lower aquifer waters are mainly Ca-Mg-HCO<sub>3</sub> and Ca-Mg-Na-HCO<sub>3</sub> type of water. The arsenic contaminated groundwater is dominantly Ca-Mg-HCO<sub>3</sub> type water with neutral to basic pH, often hard to very hard hardness with much bicarbonate concentrations. As the reducing condition is prevailing in groundwater, it is likely to be the reason of arsenic mobilization. Surface water is Ca-Mg-HCO<sub>3</sub> type of water and is all pure meteoric waters, which have not undergone much specific chemical changes. The source of major ions of most of the lower and upper aquifer sample are derived mainly from weathering of silicate or carbonate, limestone-dolomite and especially plagioclase weathering. Most of the ions of upper and lower aquifer water are within the limit of drinking water quality standard of both Bangladesh (DoE 1997) and WHO (2004). Maximum upper aquifer water exhibits higher arsenic concentrations. North-western and central part of the study area show higher arsenic concentration due to lack of continuous impermeable zone. Most of the ions of surface water are within the limit of drinking water quality standard of Bangladesh

(DoE 1997) and WHO (2004). The average  $\delta^{18}\text{O}$  values for shallow and deep groundwater are very similar to each other. Although the depth is different but their similar isotopic composition indicates that both waters were mixed after some time intervals and mixing is continuing. The mixing may be preferentially from the shallow aquifer to deep aquifer either because of the location of the pump or greater permeability of the shallow aquifer. According to surface geology and subsurface geology, there may be a hydraulic connection between shallow and deep aquifer as there is no low permeable zone. Based on isotopic values of rainfall and EC values of the analyzed water samples, it can be said that the shallow and deep groundwater are mainly recharged during a cooler period, probably the last glacial period. The more enriched value of both shallow and deep waters is located in the north-western to eastern part where arsenic concentrations are also high.

#### RECOMMENDATION

Detail isotope study of groundwater for determination of age, recharge mechanism, groundwater abstraction, studies on the economic feasibility of different possible alternatives and public awareness are urgently required to overcome this arsenic problem.

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