

Isotope Based Assessment of Deep Groundwater Resources for Sustainable Management in the Coastal Areas of Bangladesh – Crisis in Overexploitation and Salinization

Nasir Ahmed^{1*} and Pradeep K. Aggarwal²

¹Isotope Hydrology Division, Institute of Nuclear Science and Technology, Bangladesh Atomic Energy Commission, Savar, Dhaka, Bangladesh.

²Isotope Hydrology Section, Department of Nuclear Sciences and Applications, International Atomic Energy Agency, Vienna, Austria.

Abstract

The application of isotopic techniques in Bangladesh over the last few years have proved valuable to improve our understanding on the behaviour of groundwater systems in the coastal areas. Groundwater salinization limits the supply of fresh water to the expanding population, irrigation system and industrial production. Because deeper aquifers in this region generally have low arsenic and chloride concentrations they represent a potential source of safe drinking water. The deep aquifers are subjected to intensive pumping causing large drawdown of piezometric head. The heavily exploited aquifer along the coastal areas is more vulnerable given the relatively longer residence time of the water and salinization processes in this part of the aquifer.

1. Introduction

Groundwater is the main source of drinking water supply for over one hundred million inhabitants in Bangladesh. The withdrawal of groundwater has been increasing over the past three decades. About 95% of the groundwater abstracted is used for irrigation and only 3% is used for drinking purposes (APSU, 2005). Salinization of water resources is one the most widespread processes that degrades water-quality and endangers future water exploitation. In the southern part of the country, groundwater salinization limits the supply of fresh water to the expanding population, irrigation system and industrial production. This problem is intensified in coastal aquifers where human activities result in accelerating water quality deterioration. The young (Holocene) alluvial deposits in the southern part of deltaic basin are mostly affected with high arsenic water. The arsenic contamination (having highest concentration of 401 µg/L) crisis in the shallow aquifers of coastal area (Khulna, Satkhira, Bagerhat, Barisal, Patuakhali, Barguna, Chandpur, Lakshmipur, Chittagong and Cox's Bazar) has engendered a wide variety of responses to the challenge of safe drinking water supply. Because deeper aquifers in this region generally have low arsenic concentrations they represent a potential source of safe drinking water. An assessment of the potential for development is needed, however. The challenges facing the national projects are to identify a source of safe drinking water and to protect it from degradation. In this context, a number of production wells (depth around 305 m) of particularly submersible pump type were installed in 2007-2008 in the well field at coastal area under Bangladesh Water Supply Program Project (BWSPP) of

Department of Public Health Engineering (DPHE) for providing arsenic and saline free water to the community by piped water supply system. Overexploitation can cause problem of water quantity as well as quality problems. The deep aquifers are subjected to intensive pumping causing large drawdown of piezometric head. It sometimes causes the dewatering of confined aquifer and reduces the production section of wells, consequently leading to a decrease in productivity.

A systematic environmental isotope ($\delta^{18}\text{O}$, δD , $\delta^{13}\text{C}$, ^3H and ^{14}C) including geochemical study was carried out by Bangladesh Atomic Energy Commission (BAEC) to understand the groundwater flow system, sources of aquifer recharge and salinization, and possible hydraulic interconnection between aquifers and river waters of this region. Bangladesh Atomic Energy Commission (BAEC) has been actively involved in technical cooperation (TC) and regional cooperative agreement (RCA) programs of International Atomic Energy Agency (IAEA) on isotope hydrology for the last couple of years to promote the use of isotope techniques in understanding the groundwater system in Bangladesh. While portraying the practical applications and active research areas of isotope hydrology in the country, the encouraging results and findings of IAEA-TC and –RCA projects are focused in the following sections.

2. Geography, geology and hydrogeology of the study area

The study area lies in between north latitudes $21^{\circ}05' \text{N}$ to $23^{\circ}42' \text{N}$ and east longitudes $88^{\circ}56' \text{E}$ to $92^{\circ}05' \text{E}$. The annual average temperature ranges from minimum 12.5°C to maximum 33.5°C and the annual average rainfall is 1710 mm. The location map of study area is shown in figure 1.

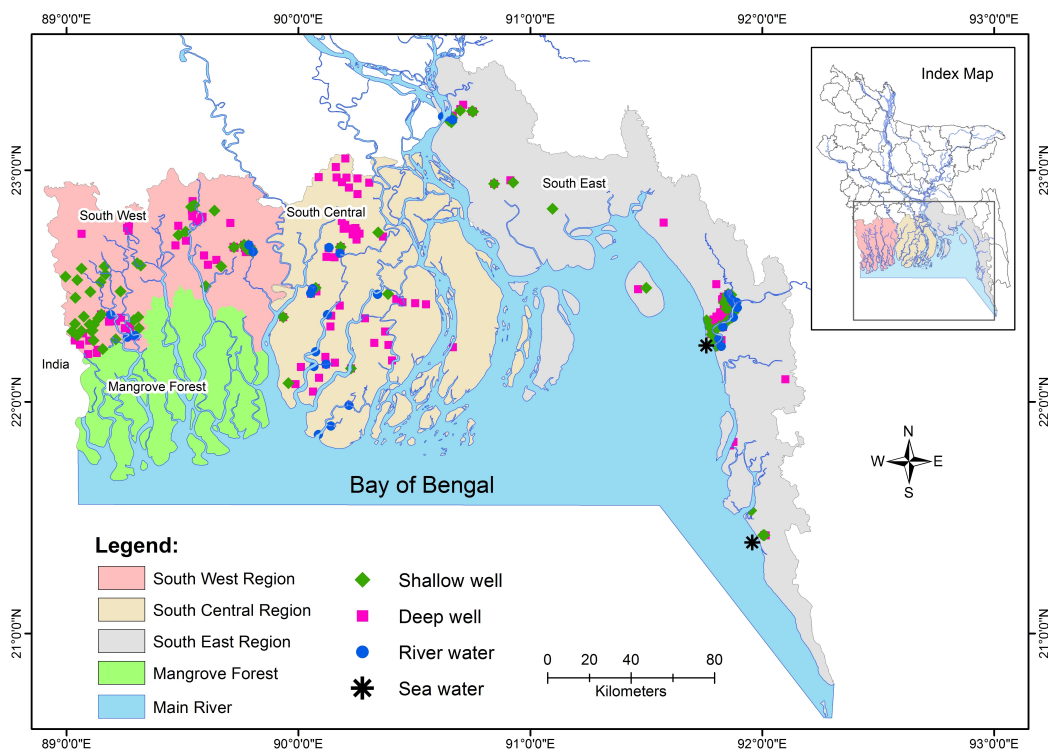


Figure 1: Location of groundwater and surface water sampling points in the study area

For the purpose of effective study and data interpretation, the whole coastal area is divided in three parts, namely, western, central and eastern. Western and central

regions fall within the south-western part of the Faridpur Trough (Gravity low) of the western platform flank of the Bengal foredeep of the Bengal Basin. Geomorphologically the area lies in the Mature Deltaic region of the Ganges Delta. The area has been formed primarily by the deposition of late Holocene to recent sediments carried by the Ganges (Padma). The surface lithology of the area is of deltaic deposits which are composed of recent tidal deltaic deposits, and marshy clay and peat deposits. The subsurface geology of the study area has complex interfingerings of coarse and fine-grained sediments from numerous regressions and transgressions throughout the geologic time. The substratum consists of entirely of the Quaternary sediments (sand and silt), intercalated with salt deposits and clay (Siddiqi, 2001).

The groundwater levels lie within a few meters of the ground surface and fluctuate with the annual dry and wet season conditions. It is recharged during the monsoon season (July–September) when the area receives more than 80% of its annual precipitation (around 2200 mm/year). Huge amounts of annual floodwater standing around coastal area also contribute to the recharge process. Annual fluctuations in groundwater levels are controlled by the local hydrogeological conditions and withdrawal of groundwater for irrigation (Uddin & Lundberg, 1998).

2.1 Aquifer System in the Study Area

Commonly, two hydrostratigraphic units have been determined on the basis of the borelog data and surface geology of the study area. The aquifer system cannot be divided into different zones because of strong heterogeneity in both geometry and permeability of the layers of boreholes; which causes complex groundwater flow in the aquifers. The coastal area of Bangladesh is hydrogeologically complex. The subsurface rock strata up to 400m of depth comprise layers of aquifers and aquitard. Aquifer is composed of very fine sand, fine sand, medium to fine sand and occasionally coarse sand. Aquitards are composed of clay, silty-clay. Figure 2 shows E-W cross section of the southern part of the country.

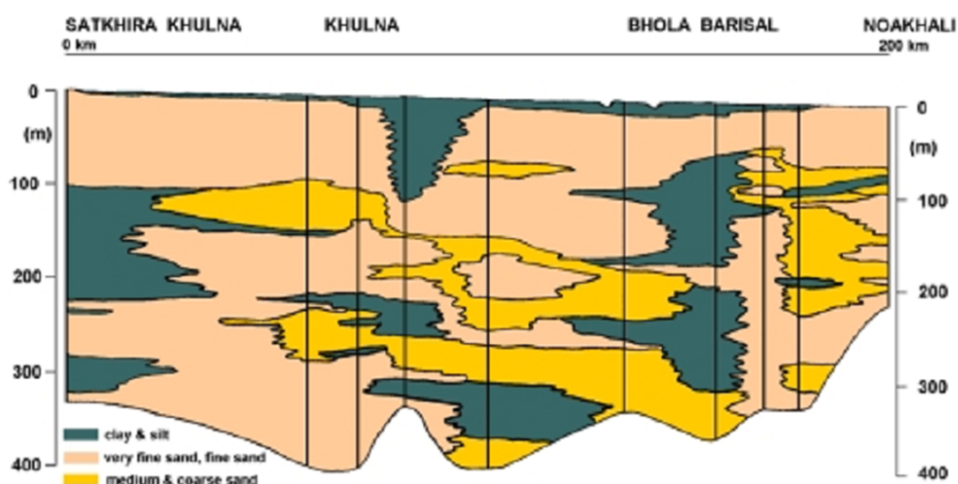


Figure 2: E-W lithological cross section across the coastal areas of Bangladesh

A generalized stratigraphic section across the coastal area reveals alternating sand-dominated and fine-grained sequences. The aquifers in and around the study area are

generally multi-layered varying from unconfined to leaky-confined in the shallow alluvial deposits and confined in the deeper alluvial deposits (Uddin & Lundberg, 1998). The aquifer systems of the study area can be classified into two major classes: the shallow aquifers ranging from depth 10 to 70 m and deep aquifers generally >100 m depth on the basis of lithology.

3. Materials and Methods

The location of sample collection from shallow and deep wells, and also from the adjacent rivers in western, central and eastern part of the coastal area is shown in figure 1. Groundwater samples were collected with a low flow rate (less than 6 L/min) after having purged the wells. Direct measurements of physico-chemical parameters, such as, pH, Eh, temperature, dissolved oxygen (DO) and electrical conductivity (EC) were performed in a flow cell. Alkalinity (HCO_3^-) was determined on-site by point inflection method using 1.6 N H_2SO_4 cartridge. Samples for chemical analysis were filtered through a $0.45\mu\text{m}$ cellulose acetate membrane and collected in 250 mL polyethylene bottles for cation and anion analyses; HNO_3 were added to the cation samples for preventing chemical precipitation. Water samples for stable isotope (^{18}O , ^2H , $^{13}\text{C}_{\text{DIC}}$) and tritium (^3H) analysis were collected in the pre-cleaned, leak tight double stoppered high density polyethylene (HDPE) bottles respectively. In the laboratory all samples were kept refrigerated until analysis. Precipitation of SrCO_3 was collected for Carbon-14 analysis.

Analysis of major cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}), Fe and Mn were carried out with atomic absorption spectrometry (AAS). The anions (Cl^- , Br^- , NO_3^- , SO_4^{2-} , PO_4^{3-}) were analyzed by ion chromatograph. Arsenic was measured in AAS using hydride generation technique. The analyses of stable isotope ($\delta^{18}\text{O}$, $\delta^2\text{H}$) and $\delta^{13}\text{C}_{\text{DIC}}$ were performed by Isotope Ratio Mass Spectrometer (IRMS) in Isotope Hydrology Laboratory, IAEA, Vienna, Austria. The stable isotope data are reported in the conventional delta (‰) notation as a deviation from the V-SMOW for water and from the V-PDB for Carbon-13. Tritium (^3H) analyses were performed by a Low Level Liquid Scintillation Counter (LSC) after electrolytic enrichment. The results were reported as tritium unit (TU). Carbon-14 (^{14}C) analyses were done using the direct absorption technique.

4. Results and Discussion

4.1 Hydrochemistry

The higher EC values exceeding $2000\ \mu\text{S}/\text{cm}$ are seen mostly in the shallow aquifers. These high EC values are also associated with the high salinity in the drinking water. Moreover, in the deep aquifer having depth band 200-300 m the EC values are greater than $2000\ \mu\text{S}/\text{cm}$ associated with higher salinity (exceeding the permissible limit $600\ \text{mg}/\text{L}$ and in some cases exceeding the sea water limit $1000\ \text{mg}/\text{L}$). The deep wells (depth range 150-300 m) of Khulna and Bagerhat areas indicate the intolerable limits of chloride concentration. Among all major ions usually dissolved in water, chloride is the most conservative ion. Concerning the taste and acceptance problem due to high salinity, most groundwaters are rendered non-potable. The chloride concentrations in most of the shallow and deep wells at Khulna and Bagerhat area have exceeded the permissible limit ($600\ \text{mg}/\text{L}$) of DoE, Bangladesh. These are not potable water. High

concentration of Cl^- in deep groundwater suggests they are brackish water. These brackish waters are probably results from relict seawater entrapped in the sediments during the Holocene transgression. The arsenic concentration varies from 0.08-401.0 $\mu\text{g/L}$ with an average of 106.4 $\mu\text{g/L}$. It is observed that shallow groundwater samples (depth <70 m) are highly contaminated with elevated levels of As exceeding the maximum tolerance limit of 50 $\mu\text{g/L}$ setup by Department of Environment (DoE), Bangladesh. In contrast, the deep groundwater samples contain very low level of As.

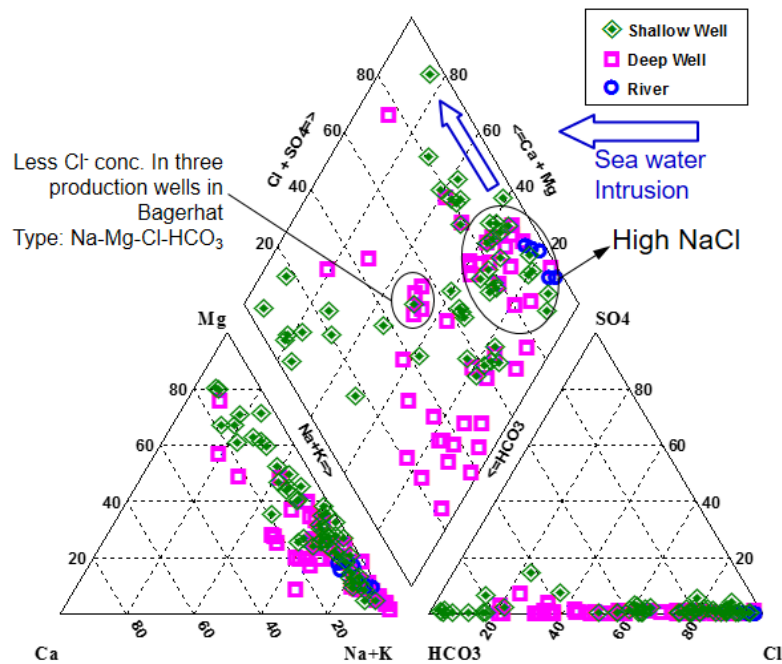


Figure 3: Piper Trilinear diagram showing the spatial evolution of the water chemistry in the shallow and deep aquifers of western part

4.2 Hydrochemical Facies of Groundwater

The concentration of major ions in the samples of western part are plotted on a Piper diagram in figure 3, which identifies the chemical composition of shallow groundwaters as Ca-Mg-HCO_3 , Na-Ca-HCO_3 and Na-Cl-HCO_3 , and deep groundwaters as mostly of Na-Cl-HCO_3 and Na-Cl types. The river waters in the western region are also Na-Cl type with high Cl^- concentrations (1803-3235 mg/L). The Na-Cl-HCO_3 and Na-Cl types of deep groundwaters in Khulna, Bagerhat and its adjoining area may not be influenced by present sea water intrusion as it fall right corner of the upper diamond of the Piper plot (Fig. 3), i.e., the seawater side. These brackish deep groundwaters are probably of remnant seawater trapped within lower-permeability sediments (Clark & Fritz, 1997) having very long residence time (~20,000 years BP, uncorrected age). The water of three production wells (PW3, PW5 & PW6), which falls in the middle of the diamond, is of Na-Mg-Cl-HCO_3 type. Due to low salinity and Arsenic free, the water of these three production wells located at Satgambuj union, Bagerhat is considered to be safe drinking water and the water is supplied to the community people through distribution pipes.

4.3 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ Compositions in Sampled Water

The plots in figure 4 representing groundwaters from the study area fall on, above and below the local meteoric water line (LMWL) as derived from the monthly rainfall of Satkhira (western part), Barisal (Central part) and Chittagong (eastern part) within the study area. This line represents modern precipitation enriched in $\delta^2\text{H}$ with d -excess average value of 11.6‰. This corresponds to present day precipitation over the region and reflects the contribution of vapour masses from Indian Ocean origin. The $\delta^{18}\text{O}$ compositions of western area shallow (<70 m depth) and deep (>90 m depth) groundwaters range from -7.38 to -1.73 ‰ VSMOW and -5.45 to -1.33 ‰ VSMOW respectively, and the $\delta^2\text{H}$ compositions range from -43.0 to -15.04 ‰ VSMOW and -35.0 to -7.2 ‰ VSMOW respectively. The $\delta^{18}\text{O}$ compositions of central area shallow (<70 m depth) and deep (>100 m depth) groundwaters range from -6.10 to -2.84 ‰ VSMOW and -3.80 to -2.40 ‰ VSMOW respectively, and the $\delta^2\text{H}$ compositions range from -53.2 to -10.9 ‰ VSMOW and -24.0 to -11.0 ‰ VSMOW respectively. The $\delta^{18}\text{O}$ compositions of eastern area shallow (<80 m depth) and deep (>100 m depth) groundwaters range from -7.50 to -2.19 ‰ VSMOW and -6.17 to -1.87 ‰ VSMOW respectively, and the $\delta^2\text{H}$ compositions range from -51.0 to -13.9 ‰ VSMOW and -46.5 to -7.1 ‰ VSMOW respectively. Most of the observed groundwater samples in the study area fall on, above and below the Global Meteoric Water Line (GMWL) ($\delta^2\text{H} = 8 \cdot \delta^{18}\text{O} + 10$) (Craig, 1961) which provides convincing evidence that all groundwater is derived from rainfalls and/or flood water and also indicates the effects of evaporation during infiltration.

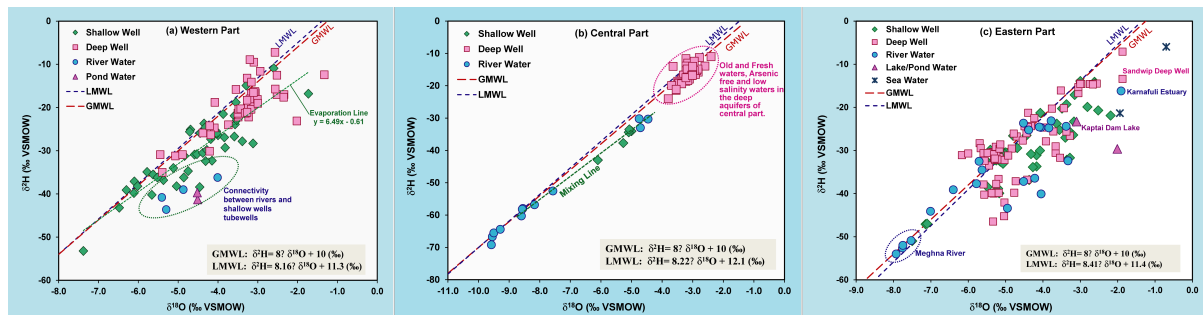


Figure 4: Stable oxygen and hydrogen compositions of shallow & deep groundwater and river water of (a) western, (b) central and (c) eastern parts of coastal area

The results show that the deuterium excesses for groundwater in the western and eastern part vary significantly; these range from -6.94 ‰ to 16.7 ‰ and -5.45 ‰ to 18.25 ‰. It is noted that the deuterium excesses of groundwater in the western and eastern regions have both negative and positive values. Samples that located in the western and eastern regions contain negative values of d -excess suggesting old recharge and greater degree of evaporation (Murad, 2014). It is also observed that the negative values of deuterium excess associated with heavier values of $\delta^{18}\text{O}$ and δD . The d -excess of the groundwater samples of central part is characterized by positive values indicating modern recharge and low degree of evaporation. In addition to that, the shallow groundwater in the central part has deuterium excess less than Craig's value ($+10$ ‰) and there is no shift in the isotopic signatures of hydrogen revealing that Holocene sediments contain small amount of hydrogen which can exchange with water. The isotopic compositions of shallow groundwater in the central part suggests that this water must be of the "juvenile" water with small amounts of meteoric origin.

The deep groundwaters in the central part have d -excess values less (avg. +6.4‰) than +10‰ and greater (avg. +15.12‰) than +10‰ and enriched $\delta^{18}\text{O}$ values. These isotopic features suggest that most of the groundwaters results from a mixing between recent recharge and an older component recharged under climatic conditions cooler than at present. These deep groundwaters in the central are fresh water having arsenic free and low salinity.

In δ -plot for shallow groundwater of western and eastern part, the wide range of shallow groundwater $\delta^{18}\text{O}$ values suggests that these waters are not mixed sufficiently to homogenize variations in the isotopic composition of recharge waters. The $\delta^{18}\text{O}$ values of shallow groundwater are much more depleted than those of the deep groundwater. This effect is attributed to a preferred selection of reduced rainfall in the western region. The selection seems to be based on the amount of rainfall, with recharge occurring preferably from more moderate rains (IAEA, 1981). The stable isotopes of Bhairab river waters are close to those of shallow groundwater at Bagerhat suggesting mixing with river water may be occurring. Both the river and shallow groundwaters have high chloride concentrations associated with high EC values. The salinity of these shallow groundwater samples most probably results from an admixture of marine water, which enters shallow aquifers indirectly by bank infiltration from Bhairab river or by flood water.

All the deep groundwater samples (depth 149–245 m) in the western part except three production wells (PW3, PW5 & PW6) at Bagerhat area have mostly intolerable limits of salinity ($\text{Cl}^- = 656\text{--}1436 \text{ mg/L}$) exceeding the permissible limit 600 mg/L. The isotopic values of these samples are high (-2.02 to -3.74‰ for oxygen) and plot below the meteoric water line, but not towards the sea water. It is assumed that these are pocket saline entrapped during late Pleistocene interglacial period, but they might be evaporated. The three production wells (depth ~ 305 m) installed at Satgambuj union under Piped Water Supply Program are having exceptionally low Cl^- concentrations ranging 260–357 mg/L and enriched oxygen-18 isotope (-2.34 to -3.00‰) indicating the paleo-water. The groundwaters from these three production wells with lower Cl^- contents and arsenic free can be regarded as representative for safe drinking water. The quality of local shallow as well as deep hand tubewells in this area is so saline that the local people are bound to depend on the Piped Water Supply installed by BWSPP, DPHE at Satgambuj, Bagerhat.

In the eastern region, most of the groundwater samples fall on, above and below the LMWL and GMWL (Fig. 4). This indicates that groundwater recharge is mainly sourced from precipitation and/or flood water, and is strongly affected by evaporation. In Madunaghat, Chittagong area, the $\delta^2\text{H}$ vs. $\delta^{18}\text{O}$ fields of deep and shallow groundwater are overlapping. Deep (150–270m depth) groundwater has $\delta^{18}\text{O}$ -3.98‰ to -6.17‰ and shallower (<70 m depth) groundwater has $\delta^{18}\text{O}$ -5.00‰ to -5.41‰ . These isotopic features suggest that most of the groundwaters results from a mixing between recent recharge and an older component recharge under climatic conditions cooler than at present. The isotope data suggest much of the water is derived from similar sources and has undergone evaporation. Overlap of some of the data from shallow groundwater samples and data points from deeper aquifer sources suggests a degree of commonality of source for some sites (Smith & Guitjens, 1998). Both shallow and deep groundwater data sets have trends that diverge from the LMWL and GMWL by a shallower slope suggestive of an evaporative component to the water. It

is difficult to determine if evaporation has occurred during precipitation in the summer months, if evaporation occurred prior to infiltration, or if the evaporation has occurred as a process within the vadose zone (Kendall & Coplen, 2001). Some isotope compositions of the deep groundwater samples with only depleted oxygen isotope values fall above the GMWL and LMWL. This indicates the effect of non-equilibrium fractionation of atmospheric vapour before infiltration. The river samples fall below the meteoric water line showing the evaporation effect.

Spatial distribution of Oxygen-18 of all groundwater samples shows (Fig. 5) some distinction in the groundwater recharge pattern – more enriched water depicted by deep colour.

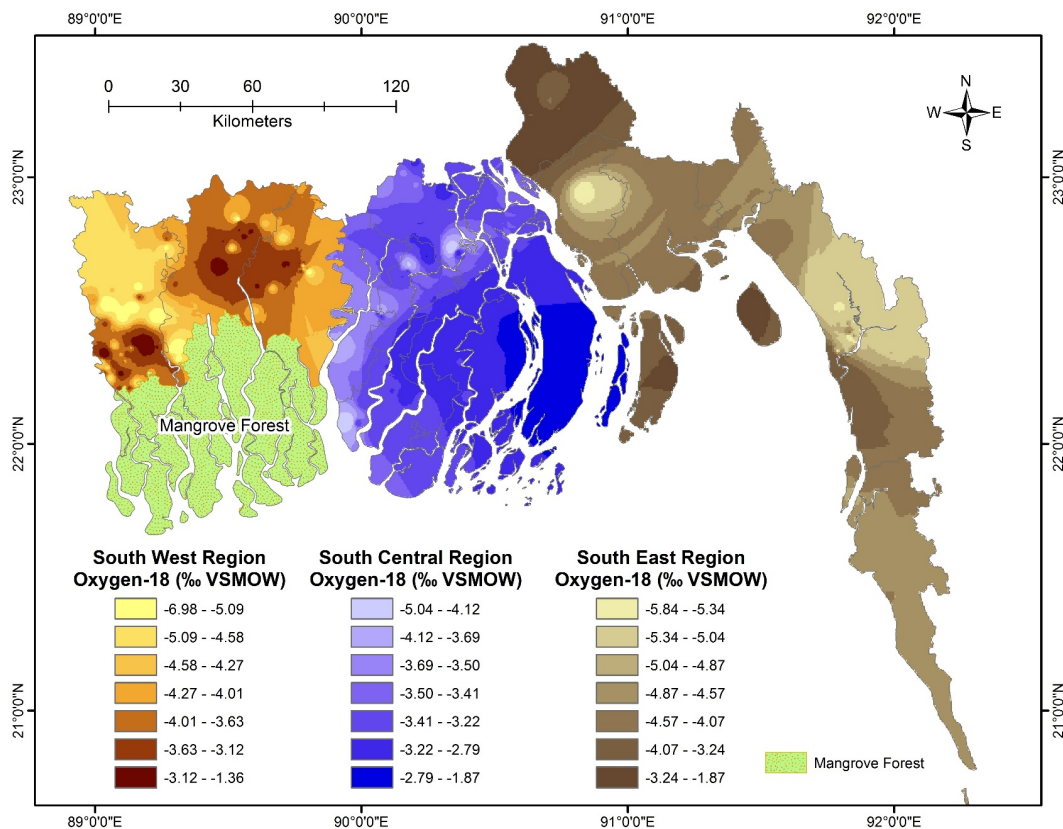


Figure 5: Spatial distribution of Oxygen-18 of groundwater samples are depicted individually in three regions, namely (a) western, (b) central and (c) eastern

4.4 Carbon-13 ($\delta^{13}\text{C}$) on Dissolved Inorganic Carbon (DIC)

Carbon-13 is a stable isotope that is generally sampled and assessed to trace open and closed system evolution of dissolved inorganic carbon (DIC, mainly HCO_3^-) in groundwater. Carbon mass transfers between reservoirs can change the isotopic composition of the DIC. The magnitude of this effect can be traced by the stable carbon isotopic ratio $^{13}\text{C}/^{12}\text{C}$ (Craig, 1957). The $\delta^{13}\text{C}_{\text{DIC}}$ values in groundwater samples of western part (except four +ve $\delta^{13}\text{C}$ samples in Bagerhat) range from -13.34 to -2.31‰ V-PDB with an average value of -6.87‰ V-PDB. The short $\delta^{13}\text{C}$ variations observed in the groundwater reflect derivation of the DIC from dissolution of carbonate minerals and/or mixing with saline water. Meanwhile, methanogenesis are active in the anoxic deep Bengal Delta aquifers (Dowling, 2003), which accounts for the depletion of $\delta^{13}\text{C}$. The positive $\delta^{13}\text{C}$ values ($+1.87$ to $+14.02\text{‰}$) for the samples at Bagerhat are due to high bicarbonate (660, 1448, 839 and 738 mg/L respectively) fraction of groundwater (Clark & Fritz, 1997). The value of the stable carbon isotope ($\delta^{13}\text{C}$) differs from seawater and freshwater. Generally, seawater is close to 0‰ of $\delta^{13}\text{C}$, while the freshwater has a range of -12.9‰ to -24.9‰ VPDB (Izbicki, 1996).

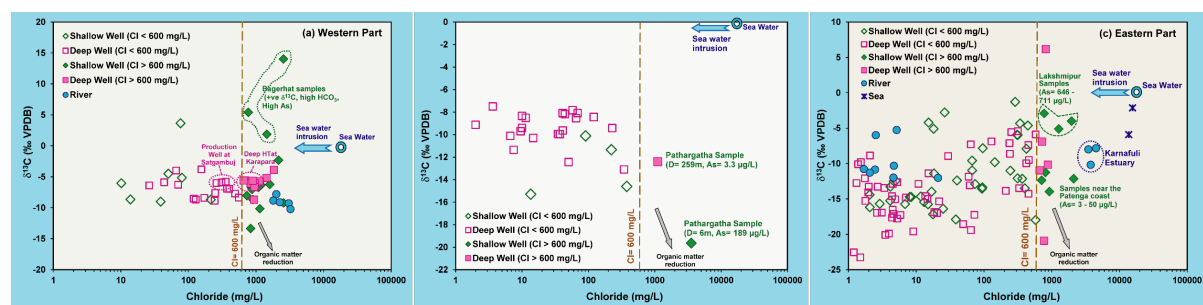


Figure 6: Plot of isotopic properties of $\delta^{13}\text{C}$ versus chloride for groundwaters with low and high salinity in (a) western, (b) central and (c) eastern parts

The results of δD and $\delta^{18}\text{O}$ have indicated that saline groundwaters in the study area are not much affected by seawater. The enriched stable isotope values of only deep groundwaters of coastal area, as plotted on or below the meteoric water line, are not close to seawater. Therefore, considering the compositions of δD and $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ compositions of saline waters are expected to have higher than those of non-saline waters. However, the measured values of $\delta^{13}\text{C}$ for saline groundwaters have ranges of -20.9 to -2.31‰ VPDB and there are similar to those of non-saline waters (Fig. 6).

The $\delta^{13}\text{C}$ values in non-saline groundwater have ranges of -23.3 to -1.29‰ VPDB (Izbicki, 1996). This result suggests that $\delta^{13}\text{C}$ values of saline groundwater mostly in deep aquifer are affected by dissolution of carbonate minerals to enrich the amount of ^{13}C . Moreover, high bicarbonates (738 to 1448 mg/L) fraction of shallow groundwater of Bagerhat contribute to the positive $\delta^{13}\text{C}$ values ($+1.87$ to $+14.02\text{‰}$). Moreover, the positive $\delta^{13}\text{C}$ values of DIC in shallow groundwaters of Bagerhat range from $+1.87$ to $+14.02\text{‰}$ VPDB, which suggests that dissolution of carbonate minerals makes a larger contribution to the DIC. Accordingly, it can be concluded that groundwaters in the coastal site, Bagerhat, are not influenced by contamination of biological productivity.

4.5 Isotopic Signatures of Deep Groundwater

As seen in the figure 7, mostly the deep groundwater samples in the western region have isotopically enriched oxygen-18 values ranging from -2.02‰ to -3.74‰ VSMOW, less negative compared to shallow samples. The carbon-14 contents are in the range of 5.35 to 14.9 pmC with remarkably lower C-14 values (range 5.35 to 8.14 pmC) at the samples of Karapara, Bagerhat. So, the groundwaters at Bagerhat appear to have been recharged from local rains during or soon after the last glacial maximum (about 20,000 years BP) when the oxygen isotopic composition of local rains is likely to have been about 1‰ less negative than the present rains (Aggarwal et al., 2000). The groundwaters at Satgambuj union area are relatively fresh with a few exception of high salinity in the local deep hand tubewells at Karapara union and Bagerhat pourashava area only. Despite the fact, the waters from three production wells (BGPW-3, BGPW-5 & BGPW-6) at Satgambuj, Bagerhat are of good quality with no arsenic and less salinity can be considered safe for drinking purpose. This situation helps to designate two different sources of water in the deep aquifer system of Bagerhat area. TYPE-I has chloride less than 600 mg/L and tritium ranges 0.01–0.45 TU (low salinity and enriched $\delta^{18}\text{O}$ values, which is old and fresh water and depth ranges 90-427 m) and TYPE-II has chloride greater than 600 mg/L, tritium ranges 0.01–0.42 TU and depth 245 m (high salinity indicating brackish water, enriched or slightly depleted $\delta^{18}\text{O}$ values and age sub-modern to old).

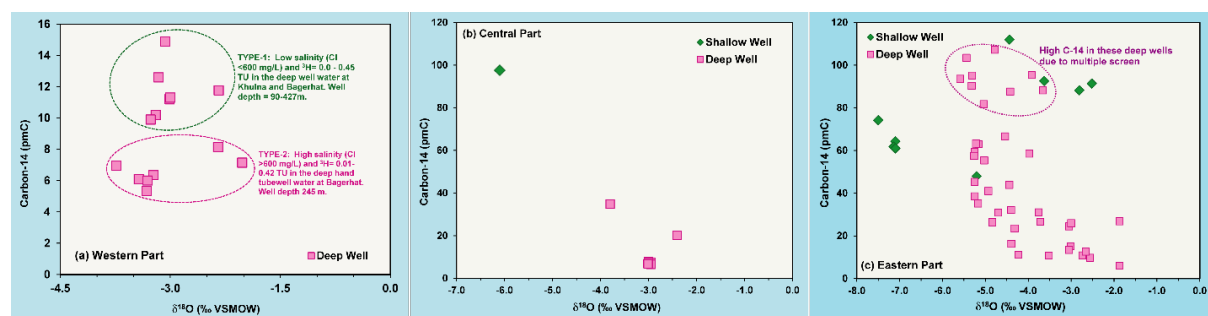


Figure 7: Stable oxygen isotope and carbon-14 compositions of deep groundwater in (a) western, (b) central and (c) eastern parts of coastal area

4.6 Isotopic Evidence of Salinity

The tritium content vs. chloride of the groundwater samples of three parts of coastal region are plotted to see the source of salinity. The negative correlation between tritium content and chloride (Fig. 8) indicates that the deep groundwaters of the coastal area

acquire salinity progressively as its residence time in the aquifer increases, suggesting that gradual dissolution or reaction with aquifer materials is the dominant mechanism. As seen from the figure 8, a few deep groundwaters in the western and eastern part crossing the permissible limit (600 mg/L) of drinking quality have positive tritium values (0.04–23.3 TU) indicating sub-modern to modern recharge. Surprisingly, these groundwaters contain high concentration of Cl⁻ content (960–2830 mg/L) implying the salinity is due to the dissolution of salts in the aquifer during recharge in long time ago. As concerned to high arsenic content, the shallow groundwaters are not acceptable for drinking purpose. The water with low salinity and arsenic free in two production wells (PW5 & PW6) at Satgambuj, Bagerthat has almost zero tritium and low Carbon-14 values, and is considered to be reliable for safe drinking purpose. Presently, these production wells at Satgambuj are being used for community water supply through distribution pipes. It is obvious that the deep groundwaters (depth ~305 m) at Satgambuj are getting relatively fresh recharge from very distant area or the fresh water mixed with low salinity might have entrapped at the time of deposition of the sediments. On the otherhand, presently uncontaminated water from the production wells as well as deep hand tubewells (depth 150–250 m) having positive tritium values have shown some tendency of increasing salinity. However, the potential for groundwater mining is clearly evident and the sustainability of this resource needs to be evaluated properly.

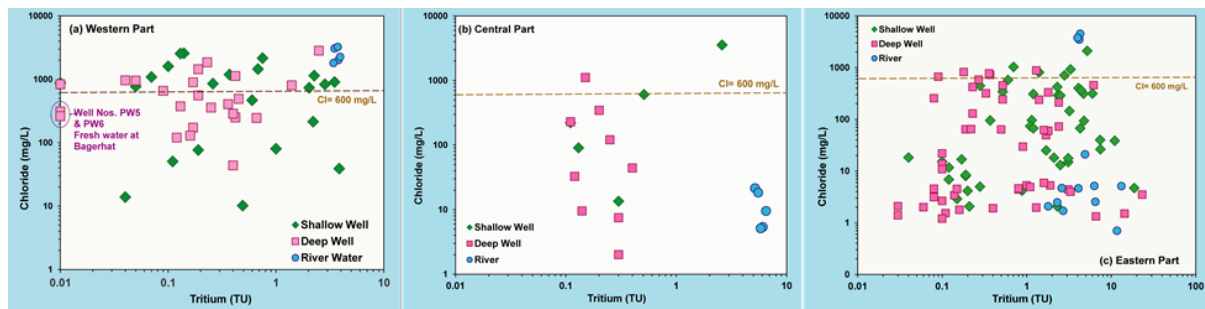


Figure 8: Relation between Tritium and Chloride contents in the groundwater samples of (a) western, (b) central and (c) eastern parts of coastal area

In the Cl- $\delta^{18}\text{O}$ diagram in the figure 9, the mixing line between values of rainwater and seawater are plotted with the measured chemical and isotopic data. The isotopic data of the end members are the weighted mean of Oxygen-18 derived from the rainfall of Satkhira, Barisal and Chittagong stations nearing to sample location points. Sea water is defined by $\delta^{18}\text{O}=0\text{‰}$ and Cl⁻=19,000 ppm (Falkenmark & Chapman, 1989). In most cases, the waters from the deep and shallow wells do not fall on the mixing line, which confirms that the enrichment of the heavy oxygen isotope in these samples is due to evaporation effects (Rozansky & Fröhlich, 2001).

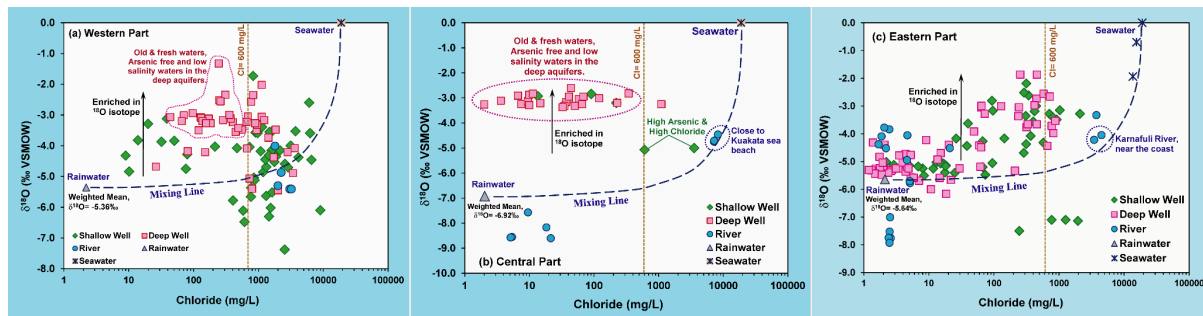


Figure 9: Oxygen-18 and Chloride in the groundwater samples of (a) western, (b) central and (c) eastern parts of coastal area

A few shallow samples of western part (Shyamnagar, Mongla and Batiaghata) having chloride greater than 600 mg/L fall on the mixing line. On the other hand, a few deep samples of eastern part (Chittagong) having chloride less than 600 mg/L fall on the mixing line. The presence of halite within the deposits suggests dissolution of evaporites could be responsible for the high Cl concentration in the groundwaters of coastal area. This fact provides a direct isotopic evidence that the salinity is not of marine origin. The oxygen-18 remains essentially constant for the majority of samples with the increase of chloride contents. This implies that the salinity is due to the dissolution of salts in the soil and aquifer which does not change the deuterium or oxygen-18 contents of groundwater (Sajjad et al., 1993).

5. Conclusions

The multi-layered aquifer constitutes a complex hydrogeological system in coastal area. Increasing exploitation with regards to water demand is of concern for the water authorities to ensure sustainability of this valuable resource. The study provides an understanding of the role of isotopes in groundwater recharge and salinization investigation in the coastal area. The $\delta^{18}\text{O}$ and δD data indicate that all the waters fall below the local meteoric water line and the global meteoric water line, supporting the conclusion that all groundwaters derived from rainfalls and/or flood water are attributed to evaporation during infiltration. The groundwater is also affected by the mixing of various rainfall events and or surface runoff.

An isotopic approach combined with chloride concentration has proved useful in assessing the origin of salinity in the Na-Cl brackish water hosted in the shallow and deep aquifers of Bagerhat. Overall, and in accordance with the geological and lithological features of the study area, the $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, ^3H and Cl^- values in the deep groundwater suggest that dissolution of evaporate deposits is responsible for the composition of Na-Cl brackish water. Nevertheless, some samples show a clear tendency of chloride and oxygen-18 increases indicating that evaporation is an important process, in particular, for near surface groundwater samples. There was no relationship between isotopic enrichment and increasing salinity. The salinity in the groundwater is due to the dissolution of soluble salts in the soil. These salts could have originated from marine aerosols which upon evaporation became solid.

A few shallow groundwater samples show some tendency of mixing with sea water that fed through the marine rivers due to backwater effect. The shallow aquifers are prevalent with arsenic contamination. The water with low salinity and arsenic free in

the deep aquifers at Satgambuj, Bagerhat is considered to be reliable for safe drinking purpose.

Acknowledgements

The supports for environmental isotope analyses were provided by IAEA, Vienna, Austria under the RCA and TC projects. We appreciate BWSPP for providing some financial and logistic support for carrying out field sampling activities. The cooperation of local DPHE office, BWSPP officials, field supervisors and local people during field sampling are highly appreciated. The authors are thankful to the authority of BAEC to take necessary steps for implementation of water quality survey work and isotopic investigation of groundwater.

References

- Aggarwal, P.K., Basu, A.R., Poreda, R.J., Kulkarni, K.M., Froehlich, K., Tarafdar, S.A., Ahmed, N., Rahman M. & Ahmed, S.R. (2000) *A report on Isotope Hydrology of Groundwater in Bangladesh: Implications for Characterisation and Mitigation of Arsenic in Groundwater*. Report No. IAEA-TCR-0159, IAEA, Vienna, Austria.
- ARSENIC POLICY SUPPORT UNIT (2005) *The response to Arsenic contamination in Bangladesh - A position paper*. APSU, Department of Public Health Engineering, Dhaka, Bangladesh.
- Craig, H. (1957) Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. *Geochim. Cosmochim. Acta*. 12, 133.
- Craig, H. (1961) Isotopic Variations in Meteoric Waters. *Science*. 133, 1702-1703.
- Clark, I. D. & Fritz, P. (1997) *Environmental isotopes in hydrogeology*. Lewis, New York, p328.
- Dowling, C. B., Poreda, R. J. & Basu, A. R. (2003) The groundwater geochemistry of the Bengal Basin: Weathering, chemisorption, and trace metal flux to the oceans. *Geochimica et Cosmochimica Acta*. 67(12), 2117.
- Falkenmark, M. and Chapman, T. (1989) *Comparative Hydrology*. UNESCO, Paris, France.
- IAEA (1981) *Stable Isotope Hydrology, Deuterium and Oxygen-18 in the Water Cycle*. Technical Reports Series No. 210, IAEA, Vienna, Austria.
- Izbicki, J. A. (1996) *Seawater intrusion in a coastal California aquifer*. U. S. Geological Survey Fact Sheet, 125-96.
- Kendall, C. & Coplen, T. B. (2001) Distribution of Oxygen -18 and Deuterium in River Waters across the united States, *Hydrological Processes*. 15, 1363-1393.
- Murad, A. (2014) Dueterim excess of groundwater as a proxy for recharge in an evaporative environment. *Geophysical Research Abstracts*. Vol. 16, EGU2014-38.
- Rozansky, K. and Fröhlich, K. (2001) *Surface water, in: Environmental isotopes in the hydrological cycle*. 3, edited by: Mook, W. G., UNESCO/IAEA, Paris.
- Sajjad, M. I., Hussain, S. D., Tasneem, M. A., Ahmad, M. & Akram, W. (1993) Isotopic evidence of the source of groundwater salinity in the Indus Basin, Pakistan. *The Science of the Total Environment*. 129(3), 311.

- Siddiqi, A. B. (2001) *Characteristics of Quaternary sediments*. The Oxford University press limited, Dhaka, Bangladesh, pp. 522.
- Smith, D. L. & Guitjens, J. C. (1998) Characterization of Urban Surfacing Ground Water in Northwest Henderson, Clark County, Nevada. *Environmental & Engineering Geoscience*, Vol. IV, No. 4, 455-477 (1998).
- Uddin, M. A. and Lundberg, N. (1998) Cenozoic history of the Himalayan–Bengal system: sand composition in the Bengal Basin, Bangladesh. *Geological Society of America Bulletin*. 110, 497.