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Understanding wetland sub-surface hydrology using geologic and isotopic signatures

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Abstract

This paper attempts to utilize hydrogeoloy and isotope composition of groundwater to understand the present hydrological processes prevalent in a freshwater wetland, source of wetland groundwater, surface water/groundwater interaction and mixing of groundwater of various depth zones in the aquifer. This study considers East Calcutta Wetlands (ECW) – a freshwater peri-urban inland wetland ecosystem located at the lower part of the deltaic alluvial plain of South Bengal Basin and east of Kolkata city. This wetland is well known over the world for its resource recovery systems, developed by local people through ages, using wastewater from the city. Geological investigations reveal that the sub-surface geology is completely blanketed by the Quaternary sediments comprising a succession of silty clay, sand of various grades and sand mixed with occasional gravels and thin intercalations of silty clay. Aquifer within the depths of 80 m to 120 m has the maximum potential to supply water. Groundwater mainly flows from east to west and is being over-extracted to the tune of 65×10^3 m^3/day. $\delta^{18}O$ and δD values of shallow and deep groundwater are similar indicating resemblance in hydrostratigraphy and climate of the recharge areas. Groundwater originates mainly from monsoonal rain with some evaporation prior to or during infiltration and partly from bottom of ponds, canals and infiltration of groundwater withdrawn for irrigation. Relatively high tritium content of the shallow groundwater indicates local recharge, while the deeper groundwater with very low tritium is recharged mainly from distant areas. At places the deeper aquifer has relatively high tritium, indicating mixing of groundwater of shallow and deep aquifers. Metals such as copper, lead, arsenic, cadmium, aluminum, nickel and chromium are also present in groundwater of various depths. Therefore, aquifers of wetland and surrounding urban areas which are heavily dependent on groundwater are vulnerable to pollution and hence surface water-groundwater interaction should be minimized by regulating tubewell operation time, introducing treated surface water supply system and artificially recharging the aquifer.

HESSD

6, 3143–3173, 2009

1 Introduction

Freshwater wetlands are characterized by significant temporal and spatial variations in sediment types. These will reflect the wetland hydrostratigraphy and will produce distinctive aquifer system that reflects depositional history and changes in groundwater source. Such wetlands are characterized by a hydrological cycle in which the groundwater within the wetland may be recycled from local and/or distant areas and will comprise varying quantities of water derived from precipitation, surface water bodies and return flow of groundwater used for irrigation in nearby irrigated land.

Many wetland hydrology studies have described the wetland water table or developed an annual water budget (Owen, 1995; Cooper et al., 1998) to illustrate the link between wetland hydrology and ecology (Drexler et al., 1999). These studies often fail to represent the variability in wetland hydrological process adequately, especially the ever increasing human-induced pressures on groundwater. It is therefore, imperative to identify the depositional condition of wetlands through surface and sub-surface sediment disposition and lithofacies analysis, water level trend and heavy metal concentration in groundwater.

Determining the stable isotope ratios of groundwater (δ^{18}O and δD) and radioactive isotope (Tritium) content may explain wetland hydrological dynamics in a better way. Variation in stable isotope composition can classify patterns of groundwater recharge and flow and have been used to estimate groundwater residence time (Soulsby et al., 2000). Isotopes have also been used to investigate the seasonal dynamics in wetland water storage (Clay et al., 2004). However, comparatively few studies have used isotope to determine inland wetland groundwater sources, to discriminate sources of groundwater recharge and to understand mixing and contamination processes of groundwater. This paper attempts to utilize hydrogeologic and isotopic signatures to understand the present hydrological processes, sources of inland wetland groundwater, surface water/groundwater interaction and mixing and contamination of groundwater of various depth zones.

2 Methodology

This study was undertaken in and around an inland freshwater wetland of India, known as East Calcutta Wetlands (ECW). The ECW is a complex of natural and human-made wetlands lying east of the city of Kolkata (previously known as Calcutta) in Eastern India. This wetland covering an area of 125 sq km comprises intertidal marshes such as salt marshes and salt meadows with significant wastewater treatment areas including sewage farms, settling ponds and oxidation basins and is well known over the world for its multiple uses. It treats about 800×10^3 m^3 of wastewater flowing out daily from Kolkata and has saved the city from constructing and maintaining a wastewater treatment plant. ECW is a perfect example of wise-use wetland ecosystem where city sewage is used for traditional practices of fisheries and agriculture. This wetland ecosystem is one of the rare examples of combination of environmental protection and development management where a complex ecological process has been adopted by the local farmers by mastering the resource recovery activities. Therefore, ECW has been declared as a Ramsar site on 19 August 2002 (Ramsar site no. 1208) (Source: www.ramsar.org/index_list.htm) acquiring an international status.

The study area covers about 334 sq km and is bounded by latitude 22°25′ N to 22°40′ N and longitudes 88°20′ E to 88°35′ E (Fig. 1) and lies between River Hugli in the northwest and River Bidyadhari in the east. The area is a part of the lower deltaic plain of the Bhagirathi-Ganga river system and is entirely covered by fluviatile sediments of Quaternary age. The elevations of the land vary between 3 m and 6.5 m above the mean sea level and slopes gradually towards south and southeast. The solid waste dumping ground of Kolkata city is on the western fringe of ECW at Dhapa (Fig. 1). Solid waste dumping started in 1870 and at present more than 95% of the total waste generated in Kolkata city is disposed here. This area may also act as an important source of contamination of groundwater of the area. Moreover, in the near future, industrial activities in the Calcutta Leather Complex (CLC) project area located just outside the eastern boundary of ECW at Karaidanga (Fig. 1) are likely to increase.

This would require an additional 30×10^3 m^3/day of water from the already stressed aquifer.

Sampling of subsurface sediments was carried out from newly installed eight boreholes (Fig. 2) to understand the grain size distribution of aquifer sediments. These samples were subjected to mechanical analysis by sieving using sieves of ASTM (American Society for Testing Material) standard (sieve size 5, 10, 18, 35, 60, 120, 230 and $\rangle$230). For grain size analysis, Folk's classification (1968), based on phi-scale was followed. Grain size data were used for generating cumulative frequency curves, which in turn were utilized for determining various statistical parameters such as median, inclusive graphic standard deviation, inclusive graphic skewness and kurtosis. A summary of grain size analysis is presented in Table 2.

Sub-surface distribution of the lithounits has been ascertained from 109 lithological logs and 57 Vertical Electrical Sounding (VES) data, collected from different government and private agencies. Depths of the boreholes range from 24 m to 304 m and that of VES data ranges from 25 m to 434 m. Using lithologs and VES data, an isopach map of top silty clay bed (Fig. 2) and a three-dimensional fence diagram (Fig. 3) of the area have been constructed. Depth-wise lithofacies analysis have been done using the technique of Pettijohn and Randich (1966) to understand the spatial extent, thickness and gross lithology of the identified lithofacies units. Five lithofacies maps have also been prepared as a sequence of overlay maps (Fig. 4b–f). Each map represents a unit thickness, that is 40 m, and this thickness has been determined by the average thickness of the topmost aquitard. For the preparation of lithofacies map, the grain size ratio {GSR = (Sand + Gravel)/(Clay + Silt)} plots as horizontal lines on the triangle (Fig. 4a) with zero at the top and infinity at the bottom. The sand-gravel thickness ratio plots as a series of lines converging towards the clay-silt apex with infinity at the left and zero at the right. From the values of GSR, the overall texture of the sediments are visualized. The maximum depth has been kept at 200 m as this is the maximum depth tapped by heavy-duty tubewells and hand pumps of the area.

For stable isotope (oxygen-δ^{18}O and hydrogen-δD) analysis, eight groundwater and four surface water samples were collected from the area during the month of June 2006 from twelve isotope monitoring stations (IMS) (Fig. 1). Among the eight groundwater samples, four were collected from the shallow aquifer (depth <50 m) and rest were collected from the deep aquifer (depth >50 m). Surface water was collected from a fishery tank, Bhangar canal, River Bidyadhari and a pond. At each location, along with two groundwater samples of different depths, any one of the four types of surface water, present in around the same location were collected. Before collecting groundwater samples, the selected wells were purged for 30 to 35 min. Each bottle (100 ml Teflon bottle) was rinsed for several times using the well water to remove any kind of impurities present in those bottles. The bottle was then completely filled with water taking care that no air bubble was trapped within the water sample. Then to prevent evaporation, the double plastic caps of the bottles were sealed. During sampling of surface water proper care was taken to avoid air bubbles and sealing the mouth of the bottle. Stable isotope analyses for the water samples were carried out at the Indian Institute of Technology, Kharagpur using a Finnigan Mat Delta Plus XP continuous flow isotope ratio mass spectrometer and the samples were measured in gas bench. The analyses were standardized against the international references Vienna-Standard Mean Ocean Water (VSMOW), Greenland Ice Sheet Project (GISP), and Standard Light Antarctic Precipitation (SLAP), as well as internal standards STAILIT (IIT Standard).

For radioactive isotope (tritium) analysis, twelve groundwater samples were collected from the isotope monitoring stations during the month of June 2006 (Fig. 1). Six groundwater samples were collected from the shallow aquifer and rest from the deep aquifer. Tritium analysis of groundwater samples was carried out at the isotope laboratory of the United States Geological Survey (USGS). The samples were analyzed by electrolytic enrichment and liquid scintillation counting.

3 Results

3.1 Sub-surface geology and lithostratigraphic correlation

The sub-surface geology of the area is completely blanketed by the Quaternary fluviatile sediments comprising a succession of silty clay, sand and sand mixed with occasional gravel. In some places along with silty clay, sticky clay is also present at the top of the lithological column. Lithologs of deeper exploratory boreholes, drilled by various agencies suggests the existence of underlying Tertiary clay/silty clay at an average depth of 296 m (Sikdar, 2000; Mukherjee et al., 2007). This formation continues up to a depth of at least 614 m below the ground surface. Therefore, the Quaternary aquifer of the area is sandwiched between two aquitards made of silty clay/clay and is more or less continuous in nature. These two fine grained beds are dark gray in colour, sticky and plastic to semi plastic in character and also contain stringers of silt or fine sand. The top aquitard is underlain by a sequence of fine to coarse sand horizon mixed occasionally with gravel. The continuity of the sand layer that forms the aquifer is broken by occasional clay lenses of limited lateral extent. The Quaternary stratigraphy of the area (Table 1) has been compiled on the basis of lithological, floral, faunal and radiocarbon dating (Sen and Banerjee, 1990; Barui and Chanda, 1992; Hait et al., 1996; Sikdar, 2000).

The sands are highly micaceous. The average median diameter (Folk, 1968) of the sands of the upper horizon (<84 m) is 1.29 ϕ while those of the lower horizon (>84 m) is 0.93 ϕ (Table 2). The median diameter indicates that the sands occurring in the lower horizon are coarser compared to those occurring in the upper horizon (Table 2). The average sorting values of the upper and lower horizons are 1.13 and 0.95, respectively and indicate that the sediments are poor to moderately sorted. The average skewness values of the upper and lower horizons are +0.09 to +0.25, respectively, which indicate that sands of the upper horizon are more or less normally distributed while those of the lower horizon are fine-skewed. The sands of the sedimentary column are leptokurtic to very leptokurtic in nature (Table 2). The grain size parameters and the fining upward sequence of the Quaternary sediments reflect a fluvio-deltaic depositional environment (Allen, 1965). Occurrence of peat in the upper horizons of the sediments and occurrence of marsh or salt lakes in the central part of the area indicate prevalence of bog and marshy conditions towards the close of sedimentation.

The yellow colour of the sand (at a depth range of 24 m to 76 m) is thought to be due to oxidation of the sediments generated from the Archean terrain of the Chotonagpur Plateau and brought down by the easterly flowing rivers. The grey to light grey colour of overlying sediments might indicate Himalayan provenance, deposited under reducing condition during the late Quaternary period (Sikdar, 2000).

The lithologs of the deep and shallow boreholes also show the occurrence of a thick silty clay bed at the top of the geological succession. The spatial variation in thickness of this top aquitard in different parts of the area is shown in Fig. 2. The thickness of this bed shows an overall increase from north to south. At places the top silty clay bed is conspicuously absent and in these areas sand occurs from the top of the geological sequence.

A fence diagram, (Fig. 3) correlating the lithologs of favourably located boreholes and VES data, have been constructed to obtain a three-dimensional view of the subsurface disposition of the sediments underlying the area. This fence diagram presents an overall picture of the disposition of sediments down to a depth of 200 m below the land surface. In the western part of the area, top silty clay bed is very thick, generally 40 m and above. At few places in east and south the top silty clay layer is conspicuously absent due to the scouring action of past channels of River Bidyadhari. The top silty clay bed is underlain by a sandy sequence, grading from fine to coarse. Thin intercalations of silty clay are also present within the sandy sequence. The fining upward sequence indicates alluvial environment of deposition.

The fence diagram, however, do not reveal the bottom silty clay bed as their depth is restricted to 200 m. In deeper boreholes a fining upward sequence has been noticed from the bottom silty clay bed. At lower horizon of the sedimentary column, coarse sediments represented by gravel and coarse sand grade into medium to fine sand and

HESSD
6, 3143–3173, 2009

Understanding wetland sub-surface hydrology

P. K. Sikdar and P. Sahu

then to silty clay in the upper horizon (Sikdar, 2000).

A perusal of the lihtofacies map for the depth span of 0 m to 40 m (Fig. 4b) reveals that in the east the dominant lithofacies is clayey sand (GSR in between 1 and 8) followed by sand (GSR>8) whereas in the west clay (GSR in between 0 and 0.25) and sandy clay (GSR in between 0.25 to 1) dominates. The presence of sand lithofacies in the northern and eastern parts of the area indicates the routes of past channels. Lihtofacies map of the 40 m to 80 m depth interval (Fig. 4c) reveals coarsening of the sediments compared to that of the 0 m–40 m depth range. Lithofacies maps indicate that aquifer within the depth range of 80 m to 120 m (Fig. 4d) has the maximum potential to supply water. Lihtofacies distribution within a depth of 120 m to 160 m (Fig. 4e) also reveals the dominance of sand lithofacies. In the depth zone of 160 m to 200 m (Fig. 4f), finer sediments reappear and the clayey sand lithofacies dominates. In the area to the north of the wetlands and in the eastern part of the wetland sandy lithofacies is observed at all depth intervals. Therefore, these zones are highly vulnerable to groundwater pollution and groundwater quality deterioration.

3.2 Groundwater condition

The sub-surface geological set up as discussed above indicates that the groundwater occurs under confined to semi-confined condition. However, in the northern part of the area the thickness of the top confining bed is less than 10 m and at places it is absent and a thick column of sand occurs from the top of the geological succession indicating channel deposition. These pockets, where groundwater occurs under unconfined condition, act as recharge area.

Pumping test carried out at 12 locations by Geological Survey of India (GSI), Central Ground Water Board (CGWB) and Calcutta Leather Complex Project Authority indicates that the aquifer occurring in and around the northern part of the area has greater potentiality with transmissivity ranging from 3447 m^2/day to 6514 m^2/day (average: 5063 m^2/day). The potentiality of the aquifer in the southern part is much lower compared to that of the northern part and the transmissivity ranges between

640 m^2/day and 2318 m^2/day (average: 1567 m^2/day). In the western part the transmissivity value is about 2065 m^2/day. In the eastern part, the aquifer has the highest potential with transmissivity of 9935 m^2/day (Chaterji et al., 1964; Niyogi et al., 1966; Ghosh and Roy, 1996; Banerjee and Khan, 1982; Misra, 2001). Storage coefficient of the aquifer ranges from 3.78×10^{-5} to 3.3×10^{-3} and indicates confined to semi-confined nature of the aquifer.

By applying the predictive method of Masch and Denny (1966), hydraulic conductivity has been determined for 223 samples, systematically collected during drilling operations at regular intervals from 8 boreholes drilled in and around ECW. The hydraulic conductivity of the aquifer material of different depths varies from 6 m/day to about 55 m/day.

Though the topography of the area in and around ECW is more or less flat, local groundwater mounds and troughs have developed due to various rates of groundwater withdrawal at different places. Trend surface analysis of piezometric surface elevation data has been carried out to separate the local flow system from the regional one by fitting a mathematical surface to the piezometric surface elevation data represented on a map. Fourth degree trend surface map of pre-monsoon, 2005 (Fig. 5) indicates that the regional flow of groundwater within the area is from east to west and is controlled by a groundwater trough defined by the 13.7 m below mean sea level contour near south-central Kolkata (Sahu and Sikdar, 2007). Therefore, any leakage of contaminated water from ECW and Dhapa solid waste dumping ground may pollute Kolkata's aquifer.

Long term piezometric surface data collected by different workers during the pre-monsoon period of 1956–1958 (Chaterji et al., 1964), 1980–1981, 1985 (Biswas and Saha, 1986), 1993–1994 (Sikdar, 1996), 1976–1998 (Misra, 2001) and 2004–2005 (present study) indicates that the average recession rate of depth to piezometric surface ranges from 0.10 m/year to 0.21 m/year.

The total quantity of groundwater flowing into the area has been estimated by applying Darcy's equation of flow of fluids through porous media. The total quantity of groundwater that naturally flows into the area is 228×10^3 m^3/day. The total groundwater discharge, (natural outflow=65×10^3 m^3/day and withdrawal for irrigation purpose=124×10^3 m^3/day, for drinking purpose=98×10^3 m^3/day and for industrial purpose=6×10^3 m^3/day) is 293×10^3 m^3/day. Therefore, groundwater in the area is being over-extracted to the tune of 65×10^3 m^3/day. An additional abstraction of 30×10^3 m^3/day of groundwater in CLC project area will increase the stress on the aquifer which may lead to contamination of groundwater and land subsidence due to leakage of water from the overlying aquitard.

The geochemical study of the groundwater suggests that (i) the groundwater can be categorized into four hydrochemical facies which may be assigned to 3 broad types "fresh", "blended" and "brackish" and (ii) mixing of "fresh" and "brackish" water is possibly responsible for evolution of "blended" water. Absence of sodium dominated hydrochemical facies indicates medium flushing of the aquifer by freshwater. Hence, ion exchange of sodium in clay for calcium and magnesium in water by circulating water in the area is limited (Sahu and Sikdar, 2007). Sikdar and Dasgupta (1997), Mitra and Gupta (2000), Ghosh et al. (2001) and Sikdar and Bhattacharya (2003) reported the presence of arsenic, lead, cadmium, chromium, nickel and copper in groundwater of Kolkata city and ECW. Sikdar et al. (2002) also reported high concentration of aluminium (1.2–2.6 mg/l) in groundwater of ECW. This groundwater quality deterioration may be due to leaching of heavy metals from bottom of the sewage-fed fisheries to the aquifer.

3.3 Isotope signature on hydrology

Published studies on distribution of stable environmental isotopes δ^{18}O and δD in the Bengal Basin are very limited. The earliest work on distribution of stable environmental isotopes δ^{18}O and δD in the Bengal Basin was done by Dray (1983), who demonstrated that significant isotopic differences exist between groundwater and the water of the River Ganges (Padma) in Bangladesh. Several other workers such as Aggarwal et al. (2000); Basu et al. (2002); Stüben et al. (2003); Harvey et al. (2005); Klump et al. (2006) etc. have also used stable isotope techniques to understand hydrogeochemistry and groundwater dynamics of the Bengal Basin.

The most recent work relevant to the present area was carried out by Mukherjee (2006) and Sengupta and Sarkar (2006). Mukherjee (2006) collected sixty-four groundwater, seven river-water and fourteen rain-water samples from Gangetic West Bengal during the months of May to August of 2003–2005 and analysed them for δ^{18}O and δD. Using the rainwater data from various parts of Gangetic West Bengal (Murshidabad, Nadia, North 24-Parganas, South 24-Parganas districts and Kolkata) collected during 2004 and 2005, Mukherjee (2006) generated a Local Meteoric Water Line (LMWL). The equation for the LMWL is as follows:

$$\delta\mathrm{D}=7.24\,\delta^{18}\mathrm{O}+7.73\,(r^2=0.93) \quad (1)$$

Sengupta and Sarkar (2006) have also carried out analysis of δD and δ^{18}O of thirty-six numbers of weekly composite precipitation samples at Barasat, nearly 20 km north-east of Kolkata and generated a LMWL. The equation for the LMWL is as follows:

$$\delta\mathrm{D}=7.88\,\delta^{18}\mathrm{O}+8.93\,(r^2=0.99) \quad (2)$$

These LMWLs compare well to the Global Meteoric Water Line (GMWL) of Craig (1961) ($\delta\mathrm{D}=8\delta^{18}\mathrm{O}+10$). Craig's GMWL defines the relationship between δ^{18}O and δD in worldwide fresh surface waters. In the present work, for analyzing the isotope data generated for the area in and around ECW these LMWLs have been used.

3.3.1 Groundwater

In the present area, groundwater of shallow depths have δD (‰ VSMOW) values ranging between −25.04‰ and −32.33‰ and δ^{18}O (‰ VSMOW) values ranging between −2.96‰ and −4.54‰. In deeper groundwater the values of δD and δ^{18}O are in the range of −26.93‰ to −32.36‰ and −3.30‰ to −4.89‰, respectively (Table 3).

To understand the influence of depth on the concentration of δ^{18}O and δD, depth-wise variation of the isotopes have been plotted (Fig. 6a and b). Perusal of these plots reveals that there is apparently no difference between the $\delta^{18}O$ and δD concentrations for both shallow and deep groundwater. This is possibly due to similarity in hydrostratigraphy and climate of the recharge areas of shallow and deep aquifers of ECW.

To understand the influence of depth on the concentration of tritium, a plot of tritium concentration versus depth has been drawn (Fig. 6c). Tritium content of groundwater from shallow and deep aquifer varies from 0.36 TU to 6.6 TU and 0.0 TU to 4.5 TU, respectively (Table 3). Very low tritium content of the groundwater of deep aquifer (0.0 TU to 0.5 TU; Table 3), except for Bamanghata (4.5 TU; Table 3, Fig. 1) suggest that these waters have long residence time and recharge of such water is likely to take place from the recharge area located in North 24-Parganas and Nadia districts (Fig. 1 inset) in the north of the wetlands. The shallow groundwater has higher tritium content indicating local recharge from surface water bodies. At Bamanghata (IMS no. 6) the tritium value of deep groundwater is similar to that of the shallow groundwater indicating the mixing of groundwater of shallow and deep aquifers. This is corroborated by the sub-surface lithological set up where sand occurs continuously from the top of the geological sequence. Therefore, it can be inferred that pumping for domestic and irrigation purposes from various depth levels has resulted in vertical mixing of groundwater in some places.

The plots of δD versus $\delta^{18}O$ (Fig. 7a) for both shallow and deep groundwater of the area, fall slightly below the GMWL and LMWLs. This indicates an origin from rain with some evaporation prior to or during infiltration. The slight deviation of the samples from the LMWLs suggests that some evaporation of rainfall occurs prior to or during infiltration, or there might be some mixing of the infiltrating water with pre-existing soil moisture that has undergone several cycles of evaporation and wetting (Allison, 1982). δD and $\delta^{18}O$ values of shallow and deep groundwater (Table 3) are similar as the recharge area for both are quite close and the local climatic condition is quite similar so as not to cause significant isotopic variation.

Shivanna et al. (1999) reported stable isotopic results for groundwater samples collected from various depths in selected areas of South 24-Parganas district of West Bengal. They inferred that there is limited connectivity between deep and shallow groundwater in South 24-Parganas. According to Misra (2001) stable isotope study of South 24-Parganas reveals that shallow groundwater (depth <70 m) is slightly depleted in δD and δ^{18}O content compared to that of deep groundwater (depth >70 m). In this region, δD and δ^{18}O values ranges from −37‰ to −22‰ and from −6‰ to −3.5‰, respectively and in deep groundwater they range from −16‰ to −9‰ and from −6‰ to −3‰, respectively. The δD versus δ^{18}O plots (Misra, 2001) also indicate that they fall in two different groups and there is no interaction between the two groups of groundwater. But moving further north, towards the present area, plots of stable isotope data indicates a different hydrogeological environment. In and around ECW, the plots of δD versus δ^{18}O for shallow and deep groundwater fall in a single cluster (Fig. 7a). It indicates that there is an interaction between the groundwater of two different depths in the area. This interaction is only possible when the top confining bed of the deeper aquifer is discontinuous or permeable in nature. These conditions allow shallow groundwater to move downwards and mix with the groundwater of deep aquifer.

The groundwater line [$\delta D=3.7964\ \delta^{18}O-13.708$ ($r^2=0.89$)], obtained by least square fit method using the groundwater of present area, has a lower slope than both LMWLs and GMWL (Fig. 7a). This indicates that the isotopic composition of the groundwater of the area is also influenced by evaporation as well as precipitation.

3.3.2 Surface water

All surface water samples (fishery water, canal water, river water and pond water) plot below the GMWL and LMWLs (Fig. 7b) suggesting evaporation. The water sample of Bhangar Canal (IMS no. 5; Fig. 1), with δ^{18}O values of −3.91‰ shows maximum depletion because of short residence time of the water in the canal inhibiting evaporation. The isotopic composition of this canal water is similar to that of the groundwater because this water is the waste water of the city of Kolkata, which is a mixture of groundwater and surface water. The maximum enrichment of δ^{18}O is in pond water (IMS no. 11 having δ^{18}O value 4.69‰) which indicates prolong evaporation from a small area.

The "deuterium excess" values d ($d = \delta D - 8\delta^{18}O$, Dansgaard, 1964) for surface water ranges from −50.45‰ to 4.54‰ with a mean value of −15.09‰. This indicates that evaporation is probably occurring from the surface water bodies and results in the stable isotope compositions lying below GMWL and LMWLs (Fig. 7b).

4 Conclusions

The results described here demonstrates the degree to which the wetland geology and wetland groundwater sources may vary over comparatively short distances and time scale in an apparently small homogeneous wetland illustrating the importance of determining the hydrostratigraphy of inland freshwater wetlands. The variation in the isotope data also demonstrates the potential of isotopes to understand wetland hydrological dynamics, including differences in the recharge area and aquifer vulnerability to groundwater pollution.

This study indicates that absence of the top aquitard at places within the wetland may act as "stratigraphic shortcuts". These "shortcuts" are recharge areas and make easy passage for pollutants to flow from the wetlands and agricultural land into the underlying aquifer and deteriorate the quality of groundwater. The isotope data confirms that in general, the isotope composition of groundwater of the wetland is similar to the mean weighted annual precipitation composition. Variations may result depending on types of soil and vegetation, unsaturated flow through heterogeneous porous media, evapotranspiration, seasonal variations, long-term climatic variations and residence time in the recharge zone (Clark and Fritz, 1997). For the present area, the effect of evaporation before or during infiltration and seasonal variability may be important. In general the ECW recharge is dominated by monsoonal precipitation, although there might be some contribution from the pre-monsoonal rainfall and also from the wetland itself. The effect of these recharges would be most dominant in the shallow groundwater. However, it should be noted that because all groundwater and surface water samples were collected at the same time of the year, no study of seasonal trends was undertaken. The groundwater $\delta^{18}O$ range of the ECW is within the range of monsoon precipitation composition range of Mukherjee (2006) and Sengupta and Sarkar (2006) during 2004–2005. This indicates that groundwater of the area is probably recharged primarily from precipitation with similar isotopic composition to the present. Similarity in δD and $\delta^{18}O$ values of both shallow and deep groundwater indicates that the recharge areas for both are quite close and the local climatic condition of both the areas is quite similar. Present day precipitation in India is estimated to have a tritium content of around 1.33 TU–6.32 TU (estimated at Kozhikode, Kerala; Source: www.isohis.iaea.org) whereas that of Bangladesh is estimated to have a tritium content of around 5 TU–10 TU (Dray, 1983). Similarity of tritium value range in rainwater with that of the shallow groundwater of the area also indicates that the aquifer is directly recharged from monsoonal precipitation.

Generally, the depth-wise variation of tritium data described here illustrates the potential of radioactive isotopes to differentiate recharge areas of groundwater of different depths. Though, depletion or enrichment of $\delta^{18}O$ and δD with depth was not observed, tritium content of groundwater from shallow aquifer is in general more than that of deep aquifer. Exception to this has been observed at one location within the ECW where the tritium content is 4.5 TU. Therefore, shallow groundwater has been recharged from local surface water bodies whereas the deeper groundwater has been recharged from sources located far away from the wetland. Deeper groundwater where tritium content is similar to that of the shallow groundwater indicates absence of any lithological barrier and mixing of groundwater of shallow and deep aquifers due to heavy pumping for domestic and irrigation purposes from various depth levels. The slight deviation of the samples from the LMWLs suggest that some evaporation of rainfall occurs prior to or during infiltration, or there might be some mixing of the infiltrating water with pre-existing soil moisture that has undergone several cycles of evaporation and wetting. Harvey et al. (2005) concluded that the recharge in their study area in Bangladesh is very complex: in addition to direct infiltration from precipitation, recharge may also take place from the bottom of ponds, ox-bow lakes, rivers, and re-infiltration of groundwater withdrawn for irrigation. Such a scenario is probably also true for the present wetland especially in areas where the top aquitard is absent and the piezometric surface is below the water table of the aquitard. The implication of this in the context of the present study is that if the wastewater contains heavy metals, a part of those metals may travel towards Kolkata's well intakes. This is in agreement with the works of Ghosh et al. (2001), Sikdar et al. (2002), Sikdar and Bhattacharya (2003) and Sahu and Sikdar (2007) who reported presence of heavy metals such as cadmium, chromium, nickel, lead and copper in groundwater of both shallow and deep aquifers of the wetland area and Kolkata city. Therefore, surface water and groundwater interaction should be minimized in and around wetland areas by regulating tubewell operation time, introducing treated surface water supply system and artificially recharging the wetland aquifer by roof top rainwater harvesting in high-rise building and in nearby heavy water consuming industries.

In general the results described in this paper have several implications for the study of wetland hydrology. This illustrates the importance of determining the hydrostratigraphy of inland freshwater wetlands and also indicates that the recharge area of wetland may vary over short distances. The variation in the isotope data also demonstrates the potential of isotopes to understand wetland hydrological dynamics especially groundwater mixing and contamination.

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HESSD

6, 3143–3173, 2009

Table 1. Stratigraphy of the area in and around East Calcutta Wetlands.

System	Series	Lithology	Average depth (m)
Quaternary	Holocene	Clay and silt, with peaty intercalation at two depth ranges from the surface (i) 2–5 m dated at 3990±70 years B.P. (ii) 12–12.6 m dated at 7030±70 years B.P.	40
	Pleistocene	Sand, fine to coarse with clay lenses, gravel and calcareous concretions	296
Tertiary	Pliocene	Clay, bluish grey, soft and sticky	To >614

Source: Sikdar (2000).

HESSD

6, 3143–3173, 2009

Table 2. Summary of statistical parameters computed from mechanical analysis of the aquifer material.

Location and borehole number in parantheses	Depth Range (m)	Median (ϕ_{50}) (phi)	Inclusive Graphic Standard Deviation (σ_I) (phi)	Inclusive Graphic Skewness (phi)	Graphic Kurtosis K_G (phi)
Narayanpur (72)	0–84	1.18	1.03	0.09	1.52
	85–256	0.95	0.95	0.29	1.70
Andulgari (65)	0–84	0.71	0.81	0.52	1.38
	85–246	1.34	1.14	0.13	1.39
Shaksaharpukur (71)	0–84	1.16	1.04	0.18	1.14
	85–222	1.08	1.02	0.25	1.34
Binarite (70)	0–84	1.28	1.09	−0.03	1.58
	85–246	0.75	0.78	0.30	2.18
Barjuli (68)	0–84	1.33	1.25	0.15	0.99
	85–234	0.67	0.88	0.37	1.85
Ballypur (66)	0–84	1.35	1.12	0.05	1.29
	85–252	0.76	0.76	0.22	1.55
Borali (69)	0–84	1.86	1.57	−0.13	1.32
	85–234	1.04	0.92	0.12	1.20
Erenda (67)	0–84	1.47	1.10	−0.15	1.45
	85–240	0.85	1.14	0.31	1.55
Average (phi)	0–84	1.29	1.13	0.09	1.33
	>84	0.93	0.95	0.25	1.60
Remarks	0–84	Medium sand	Poorly sorted	Near symmetrical	Leptokurtic
	>84	Coarse sand	Moderately sorted	Fine-skewed	Very Leptokurtic

HESSD

6, 3143–3173, 2009

Table 3. Result of isotope analysis in and around ECW.

Sl. No.	IMS number	Location	Screen depth (m)	Water type	δD_{VSMOW}‰	$\delta^{18}O_{VSMOW}$‰	Tritium (TU)
1	1	Chaynabi	76	Groundwater (Deep)	−28.91	−4.02	0.15+/−0.19
2	3	Trinathpalli	12	Groundwater (Shallow)	−27.57	−3.63	0.36+/−0.20
3	6	Bamanghata	92	Groundwater (Deep)	−26.93	−3.30	4.5+/−0.3
4	4	Bamanghata bazaar	22	Groundwater (Shallow)	−32.33	−4.54	5.5+/−0.4
5	7	Pratapnagar	76	Groundwater (Deep)	−32.36	−4.89	0.5+/−0.3
6	8	Pratapnagar Bazar	30	Groundwater (Shallow)	−28.74	−4.26	0.5+/−0.3
7	12	Dihi Uttar para	305	Groundwater (Deep)	−27.60	−3.96	0.0+/−0.3
8	10	Dihi	28	Groundwater (Shallow)	−25.04	−2.96	3.9+/−0.3
9	2	Goaltala Bheri	–	Surface water (Fishery)	−3.65	0.78	–
10	5	Bhangar Canal	–	Surface water (Canal)	−26.74	−3.91	–
11	9	Kasiadanga	–	Surface water (River Bidyadhari)	−8.97	−0.55	–
12	11	Dihi	–	Surface water (Fresh pond)	12.93	4.69	–
13	13	Dhapa Durgapur	90	Groundwater (Deep)	–	–	0.0+/−0.3
14	14	Saifarabad	28	Groundwater (Shallow)	–	–	0.5+/−0.3
15	15	Kharamba	90	Groundwater (Deep)	–	–	0.1+/−0.3
16	16	Kharamba	15	Groundwater (Shallow)	–	–	6.6+/−0.4

Experimental precision for $\delta^{18}O \sim \pm 0.1$‰ and for $\delta D \sim \pm 1$‰; Tritium data are with one sigma uncertainties for some samples.

HESSD

6, 3143–3173, 2009

Understanding wetland sub-surface hydrology

P. K. Sikdar and P. Sahu

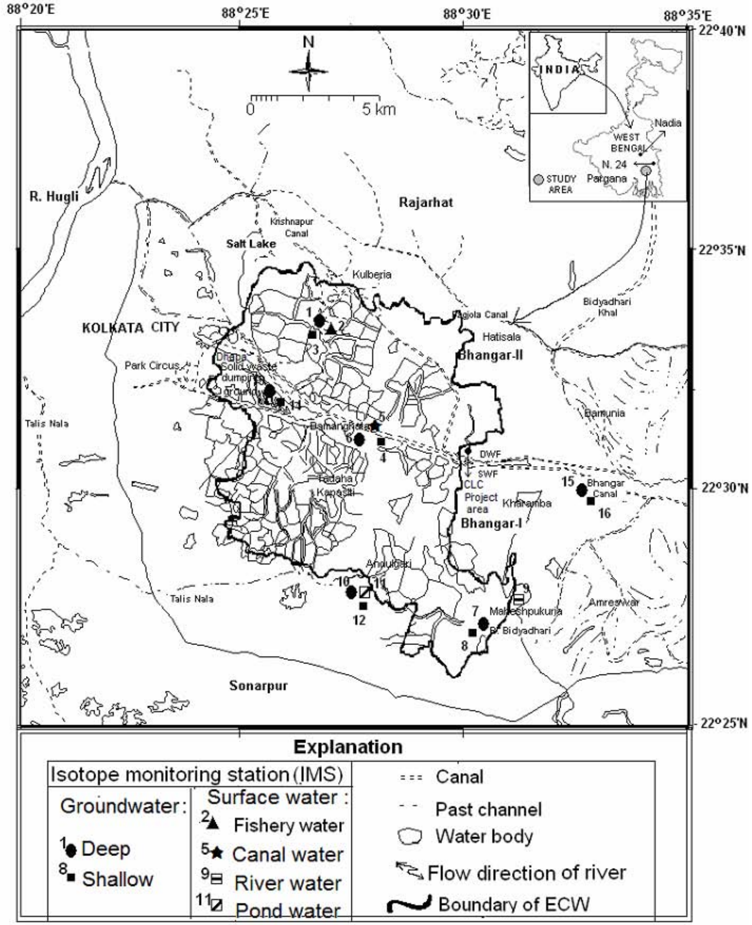

Fig. 1. Location map and drainage pattern of the area.

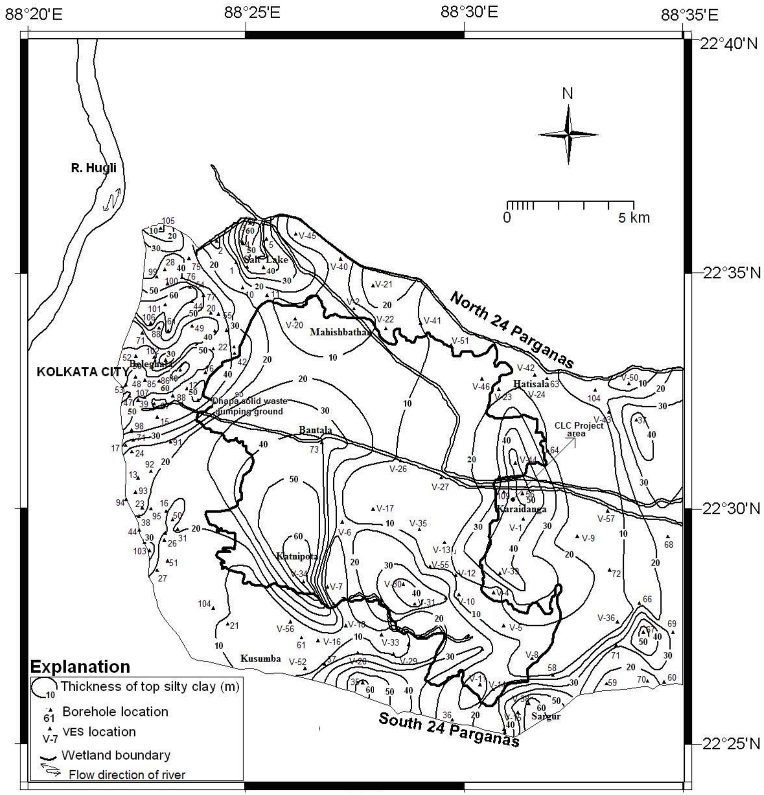

Fig. 2. Isopach map of top silty clay bed of the area in and around ECW.

HESSD
6, 3143–3173, 2009

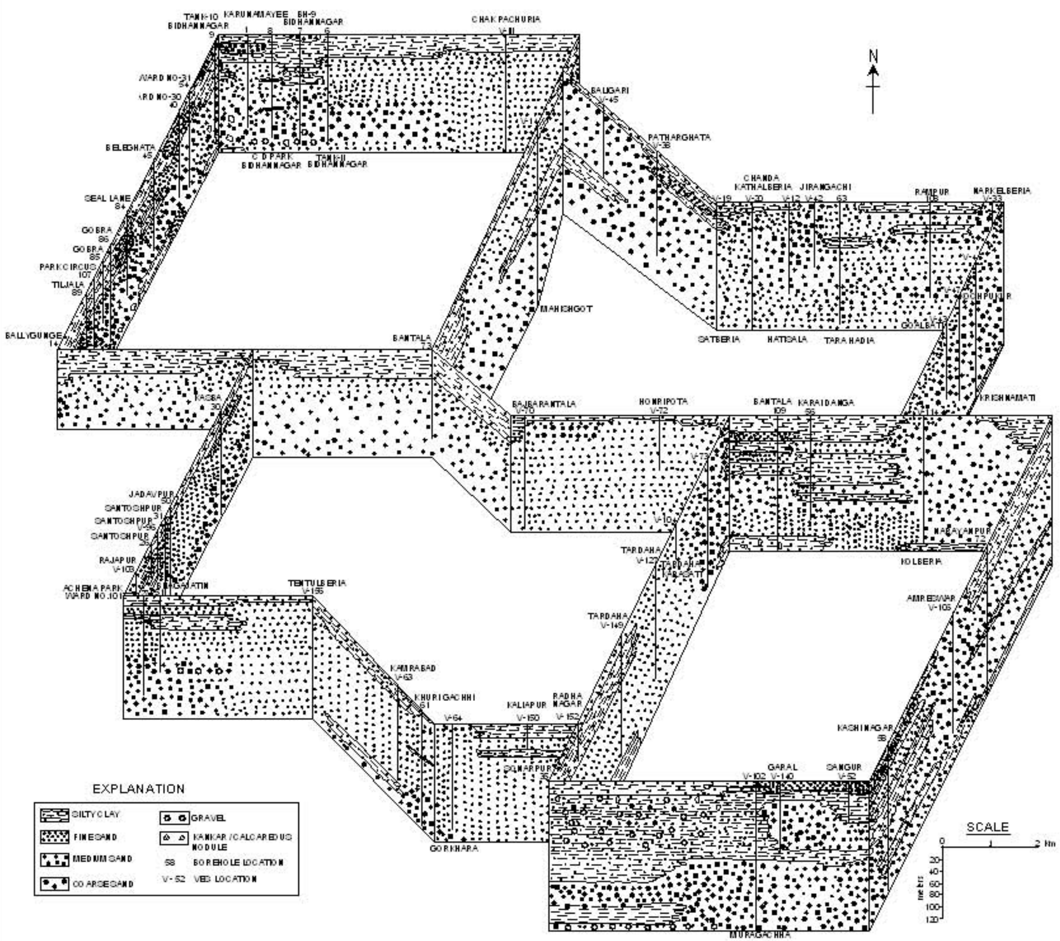

Fig. 3. Fence diagram depicting the subsurface geology of the area in and around ECW.

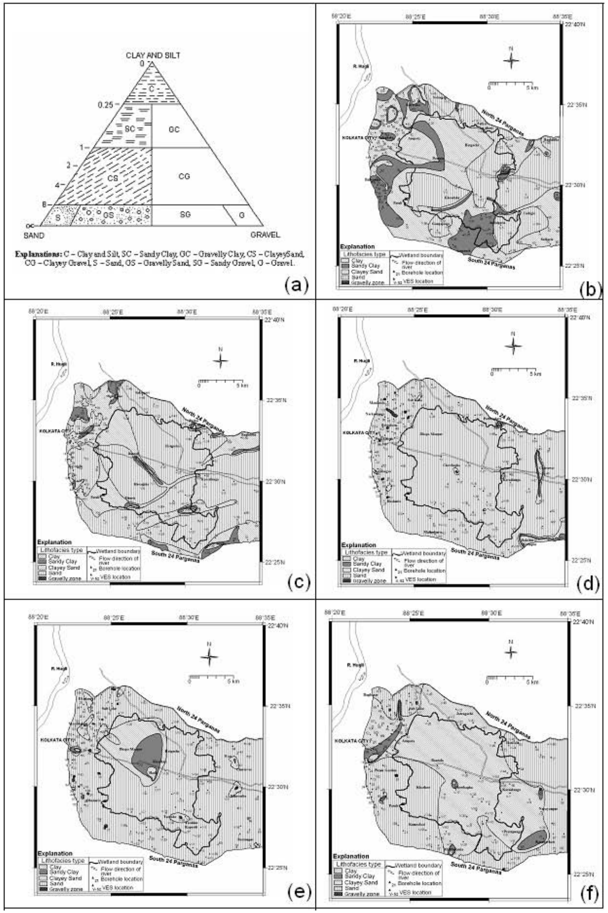

Fig. 4. Lithofacies analysis: **(a)** Lithofacies and grain size triangle (modified by Pettijohn and Randich, 1966); **(b–f)** Spatial distribution of lithofacies for the depth span of 0 m–40 m, 40 m–80 m, 80 m–120 m, 120 m–160 m and 160 m–200 m, respectively.

HESSD
6, 3143–3173, 2009

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

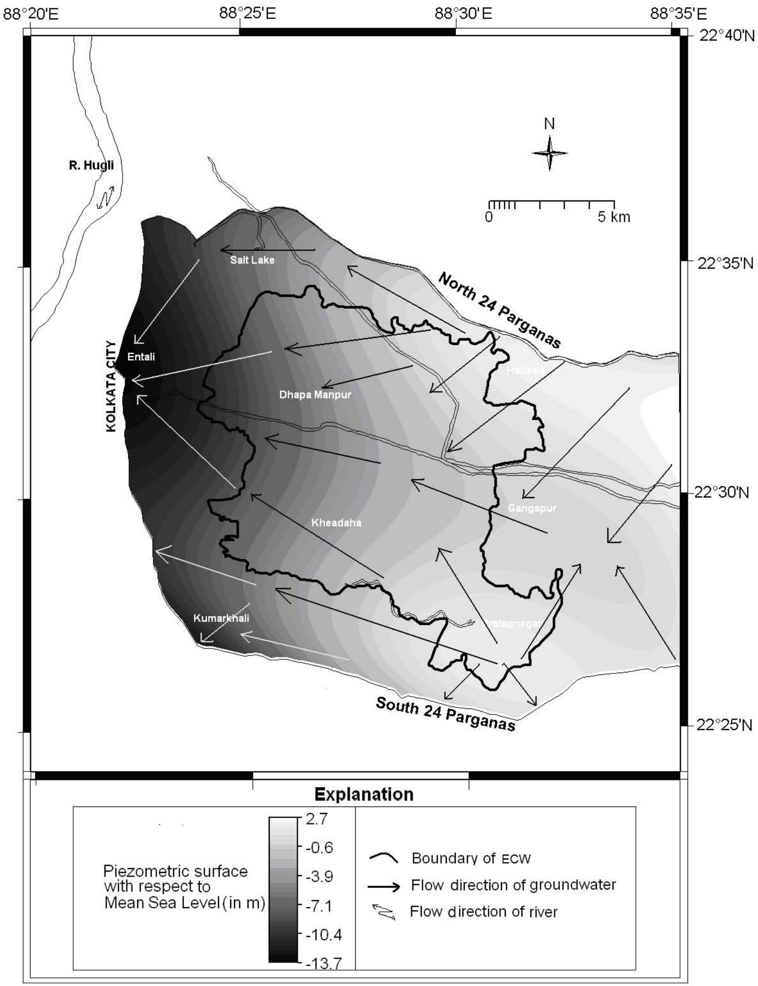

Fig. 5. Fourth degree trend surface map of pre-monsoon, 2005.

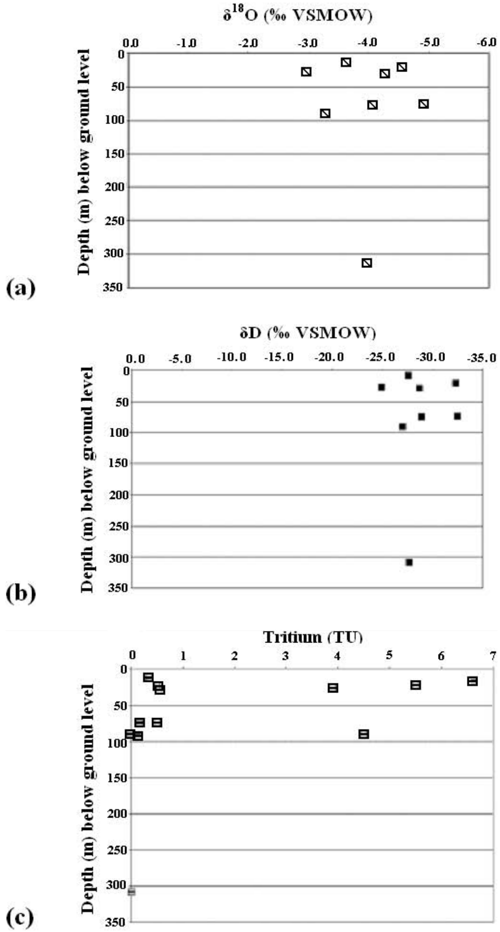

Fig. 6. Depth wise distribution of isotope in groundwater: **(a)** δ^{18}O **(b)** δD and **(c)** tritium.

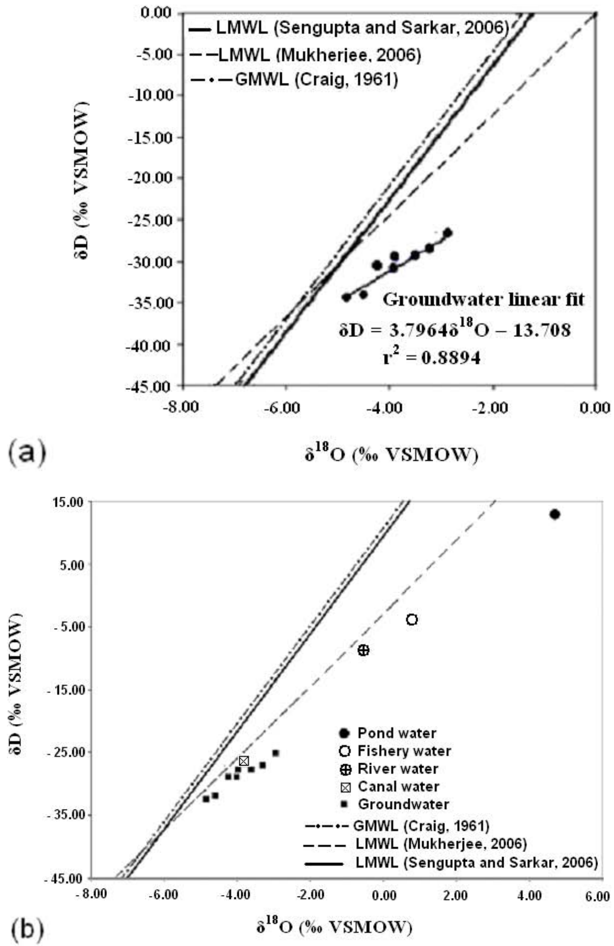

Fig. 7. Plots of δD versus δ^{18}O along with GMWL and LMWLs for **(a)** shallow and deep groundwater and **(b)** surface water and groundwater.

HESSD

6, 3143–3173, 2009

Understanding wetland sub-surface hydrology

P. K. Sikdar and P. Sahu