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Original Article

Groundwater flow systems in the Bengal Delta, Bangladesh, inferred from subsurface temperature readings

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Abstract

Borehole temperatures were measured in observation wells to determine the temperature-depth profile, magnitude of temperature and thermal gradient. The observed temperature profiles are classified into recharge and discharge types. The recharge-type wells are located in the northern site of the study area. Meanwhile, discharge-type wells are found in the southern site of the study area. The 2-D cross-section of subsurface temperature shows that the shallow groundwater temperature in the southern discharge area is higher than that of the northern recharge area. The calculated temperature-depth profiles for shallow wells show the recharge rate ranging from 0.04 to 1.35 m/year and discharge rate within the range of -0.2 to -0.79 m/year. On the contrary, the recharge rate is 0.05 to 0.16 m/year and discharge rate -0.15 m/year for the deep well sites. The present study has revealed the existence of shallow and deep groundwater flow systems in Bengal Delta aquifers.

Keywords: temperature, thermal gradient, recharge, discharge, groundwater flow

1. Introduction

Circulating groundwater will acquire geothermal heating along its flow path (James *et al.*, 2000). Subsurface temperature could be used as a tracer for detecting the groundwater movement, because heat in the subsurface is transported not only by conduction but also by advection caused by subsurface water movement (Taniguchi, 1993). Meanwhile, it is generally recognized that the temperature profile in a borehole is affected by both groundwater flow and past climatic change (Uchida *et al.*, 2003). Solid earth scientists seek to remove such effects from a temperature profile for the corrections of terrestrial heat flow values. The distribution of subsurface temperature is affected by groundwater flow. However, those temperature data can be used to evaluate the direction and velocity of groundwater flow. The thermal effects of thermal advection are especially large in shallow sedimentary strata with high groundwater flux (Uchida *et al.*, 2003). The groundwater temperature measured in observation wells is assumed to be the same as the subsurface temperature, because there is thermal equilibrium between water in the borehole and the surrounding subsurface temperature. Temperature profiles are one-dimensional sequential data arrays which can be used to estimate the subsurface water fluxes (Taniguchi *et al.*, 1999a).

A temperature-depth profile without groundwater flow generally has a constant gradient with depth (Figure 1a) and a stratified thermal regime (Figure 1b). Domenico and Palciauskas (1973) analyzed the 2-D groundwater temperature distribution under the condition of regional groundwater flow and found that the temperature-depth profile shows a concave shape in the recharge area where the downward

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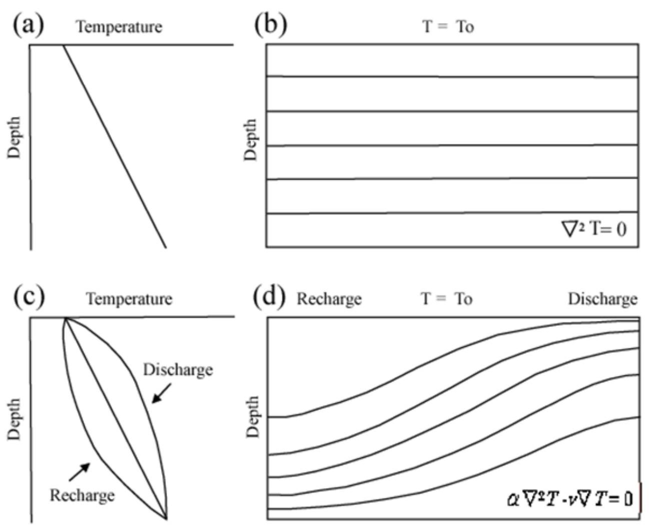

Figure 1. (a) Temperature-depth profile with thermal gradient, (b) stratified thermal regime, (c) concave-convex of temperature-depth profile and (d) isothermal lines in the two-dimensional groundwater flow systems (Taniguchi *et al.*, 1999a).

water flux dominates and a convex shape in the discharge area where the upward groundwater dominates (Figure 1c). They also provided isothermal lines in the two-dimensional groundwater flow systems (Figure 1d) (Taniguchi *et al.*, 1999a). In the present study, we employ temperature measurements to determine the sources and distribution of groundwater flow systems in the Bengal Delta, Bangladesh.

2. Study Site and Methods

The Bengal Delta is formed largely of alluvial and deltaic sediments of the Ganges, Brahmaputra and Meghna (GBM) rivers, and Bangladesh occupies the greater part of the Bengal Delta. Bangladesh extends from latitude 20°43′ to 26°36′N and longitude 88°3′ to 92°40′E; and the present study covers the western, southern and northern regions of Bangladesh.

The alluvial plains of the GBM river system slope from north to south, smooth on a regional scale but interrupted locally by ridges and basins. The altitude of the GBM alluvial plain is about 15 to 20 m above mean sea level (MSL) in the northwest, and decreases to 1 to 2 m above MSL to the south near the coast (Mukherjee *et al.*, 2009). The residual deposits, the Madhupur and Barind tracts, locally interrupt the flat topography of central Bangladesh, rising by up to 20 m above the adjacent floodplains. It is convenient to consider the regional geology in terms of five major subdivisions – Tertiary deposits, residual deposits, alluvial fan deposits, alluvial deposits and deltaic deposits (Figure 2) (Alam *et al.*, 1990). Stratigraphic correlation across the Bengal Basin is difficult (Brunnschweiler and Khan, 1978), and the Quaternary is particularly poorly defined owing to the absence of well-exposed sections. Thus it is difficult to establish absolute ages for the lithologic column (Monsur, 1995). A simplified stratigraphic sequence for Bangladesh is shown in Figure 3.

The deposits of thick unconsolidated Pleistocene and Holocene alluvial sediments of the GBM delta system form one of the most productive aquifer systems in the world (Kinniburgh and Smedley, 2001). The Holocene aquifer grain sizes fine upwards, from coarse sands and gravels at the base, to fine and very fine sands towards the top of the aquifer (MPO, 1987; Davies, 1989; BADC, 1992). Silts and clays predominate in the upper few meters, forming a surficial aquitard, generally less than 10 m thick, with typical specific yield values of 2–3%, and vertical permeability values in the range 3–8×10^{-3} m/d (BADC, 1992). This aquitard is extensive, but may not be continuous across active and recently abandoned riverbeds. The aquifers are mostly medium-to-fine and medium-to-coarse sands (MPO, 1987). The Pleistocene Dupi Tila Aquifer is underlain by the Madhupur and Barind Clay. The yellowish-brown Dupi Tila sand aquifer is tens of meters to more than a hundred meters thick.

In the coastal regions, shallow fresh-water aquifers overlie saline groundwater at depths of 20–30 m. Deeper sands, about below 150 m, form productive fresh-water aquifers which are apparently protected from saline water intrusion by intermediate clay layers (Rus, 1985). Where deep clayey aquitards exist, the sands below are commonly referred

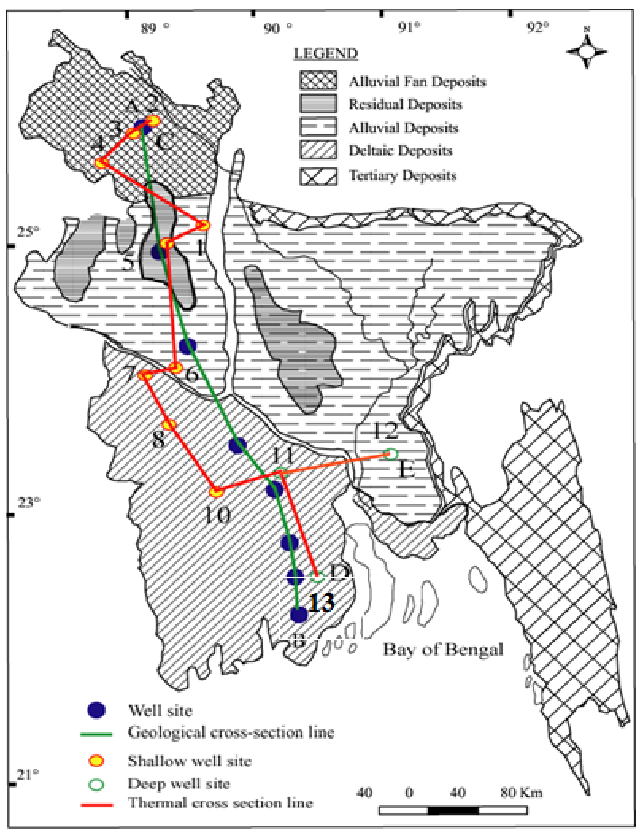

Figure 2. Surface geological distribution (modified after Alam *et al.*, 1990) and logged borehole location in the study area.

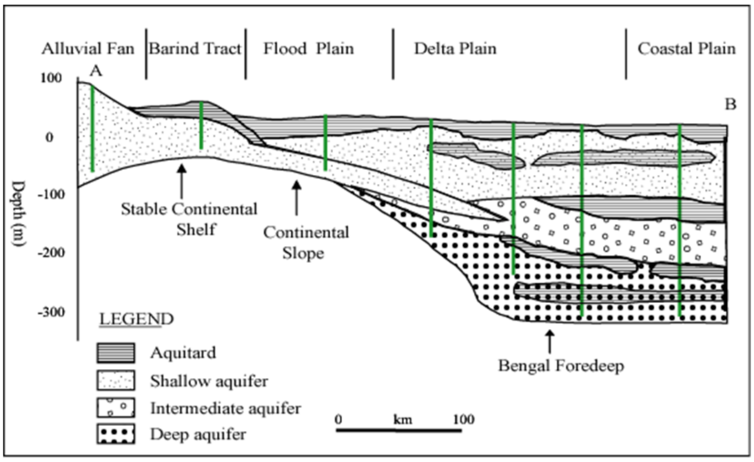

Figure 3. Generalized geological cross-section (cross-section line shown in Figure 2) (modified after Kinniburgh and Smedley, 2001).

to as the 'deep aquifer', although there is no generally agreed definition. Where the aquitards are absent, the deeper sands may be Pleistocene in age, but they effectively constitute deeper regions of the same multi-layered aquifer that at shallower levels is formed of Holocene sands (Ravenscroft and MacArthur, 2004). Across the Holocene floodplain in southern Bangladesh, the deeper levels of the aquifer are exploited for potable water supply to depths of up to 350 m at individual towns (DPHE, 1996). In the north and centre of the country, the aquifer system beneath the Holocene floodplains behaves essentially as a single layer, but to the south and east, layering becomes increasingly important.

The Bengal Basin is drained by the rivers Ganges, Brahmaputra (also known as the Jamuna in Bangladesh), and Meghna, along with numerous tributaries and distributaries. In general, groundwater flow in the basin is strongly influenced by the heavy rainfall caused by the southeast monsoon wind from mid-June to mid-October originating from the Bay of Bengal (Mukherjee *et al.*, 2009). The average annual rainfall in Bangladesh varies from a maximum of 5,690 mm in the northeast of the country to a minimum of 1,110 mm in the west (DPHE, 2001). Up to about 95% of the annual rainfall occurs during the May to September monsoon (Majumder *et al.*, 2011). Bangladesh experiences a tropical monsoon climate with mean monthly minimum temperatures from 10–12°C in January to 20–25°C in June to August, and mean monthly maximum temperatures from 25–28°C in January to 32–35°C in June to August. Temperatures increase during March to May, followed by a hot and very wet period from June to October (Kinniburgh and Smedley, 2001).

During March 2008, borehole temperatures were measured at 1-m depth intervals both in downward and upward directions in 12 boreholes (Figure 4) by means of thermistor thermometer (Technol Seven Ltd., Japan), which can read to 0.01°C. Well diameters are 3.8-15 cm (mostly 3.8 cm) and depths range from 7 to 300 m (mostly 7–80 m). Groundwater levels were measured in wells prior to temperature logging using a dipper. The logged boreholes are cased for groundwater observations by the Bangladesh Water Development Board (BWDB) and were drilled during 1965-1980, and never used for any pumping purposes. Screens are placed at the bottom of all observed wells. In shallow wells 1.0 m screens are used and 3.0 m screens are used for the deep wells.

3. Observation Result

The temperature–depth profiles of shallow and deep wells observed in March-2008 are shown in Figure 4a and 4b, respectively. Depending on the shape of the profile, magnitude of temperature, and thermal gradient, the observed temperature profiles are classified into two types: (a) recharge and (b) discharge. Wells 2, 3, 4, 5, 7, 11 and 12 are classified as recharge type and wells 1, 6, 8, 10 & 13 are classified as discharge type. The recharge type wells are located in the northern site of the study area (Figure 2), where southward groundwater fluxes are expected. Meanwhile, discharge type wells are found in the southern site of the study area (Figure 2).

In Figure 5 the 2-D cross-section of subsurface temperature along line C–D (Figure 2) shows that the shallow

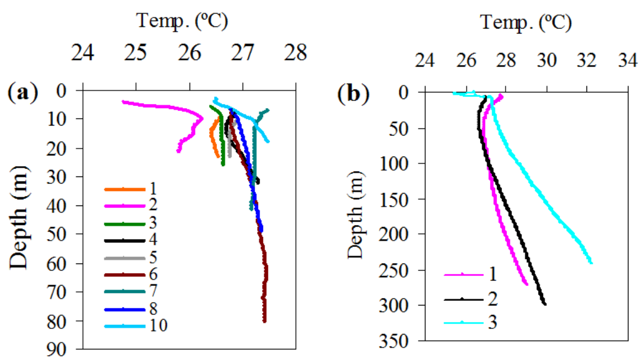

Figure 4. Temperature-depth profiles for (a) shallow wells and (b) deep wells.

Table 1. Well depth, screen length, screen position, hydraulic head and summary of the calculated temperature-depth profiles.

Well No.	Depth (m)	Screen length(m)	Screen position(m)	Hydraulic head from MSL(m)	Flux rate (m/year)	Type
1	23	1	22–23	16.11	-0.20	Discharge
2	21	1	20–21	32.38	1.35	Recharge
3	26	1	25–26	30.40	0.04	Recharge
4	32	1	31-32	29.25	0.30	Recharge
5	23	1	22–23	10.37	0.20	Recharge
6	80	1	79–80	4.41	-0.79	Discharge
7	41	1	40–41	6.22	0.21	Recharge
8	49	1	48–49	4.08	-0.40	Discharge
10	18	1	17–18	0.60	-0.75	Discharge
11	240	3	237–240	1.10	0.05	Recharge
12	272	3	269–272	1.15	0.16	Recharge
13	300	3	297–300	1.20	-0.15	Discharge

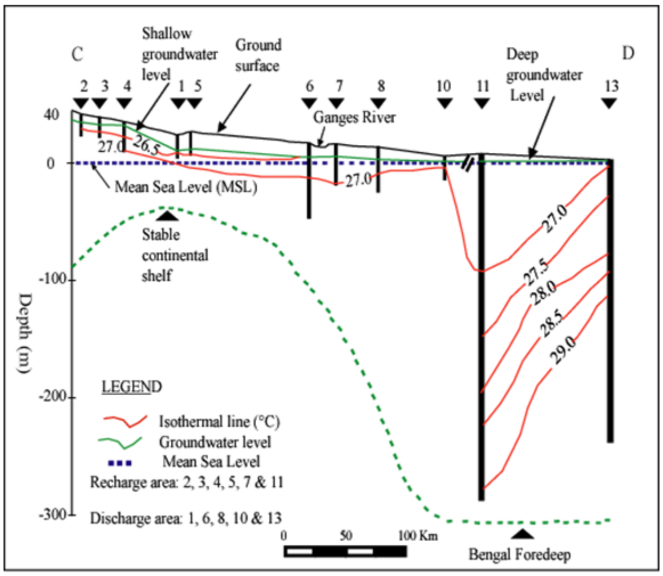

Figure 5. 2-D cross-section showing subsurface temperature variations.

groundwater temperature in the discharge area (well 1, 6, 8 and 10) is higher than that of the recharge area (northern site). As per Domenico and Palciauskas (1973), this is attributed to the effect of heat advection due to shallow groundwater flow (Taniguchi *et al.*, 2003). In Figure 6 the deep well site 11 shows distinct recharge pattern having low temperature; on the other hand the deep well site 13 shows an upward movement of heat due to discharge of deep groundwater along the coastal belt. The 2-D cross-section for deep wells relatively low groundwater temperatures in the well sites 11 and 12, and higher temperature at the well site 13 (Figure 6). It clearly indicates the presence of deep groundwater flow within the Bengal Delta discharging along the regions close to the Bay of Bengal having much higher temperature than that of regional geothermal gradient (2.4°C/100 m after Imam and Hussain, 2002). It is obvious that the subsurface temperature in the study area is affected by the regional and local groundwater flow systems. Among the observed shallow wells, the water table shows a general slope toward the south (Figure 5). There is a local depression of the water table near well 1, where the discharge type of temperature–depth profiles are also found (Figure 5). This indicates the presence of shallow groundwater flow system discharging in the vicinity of this well site.

4. Model Calculation

In order to represent the temperature-depth profiles for different vertical groundwater fluxes, subsurface temperatures have been calculated in the western, southern and

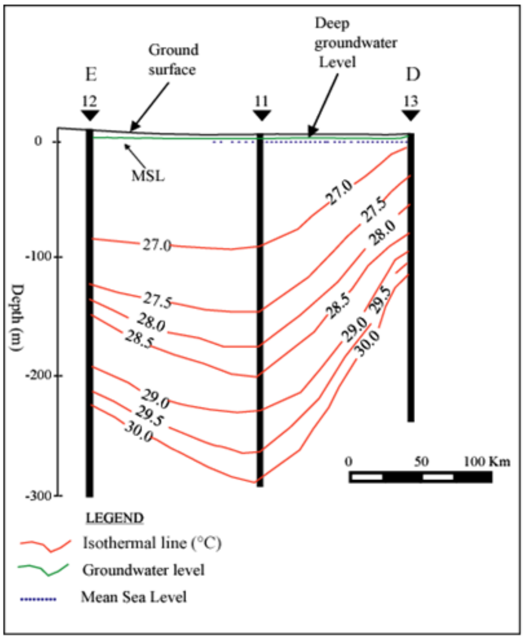

Figure 6. 2-D cross-section showing subsurface temperature variation in deep wells.

northern part of Bengal Delta aquifers. Under the condition of a linear increase in surface temperature, the analytical solution for one-dimensional heat conduction-advection can be shown as (Carslaw and Jaeger, 1959):

$$T(z,t) = T_o + T_G(z\text{-}Ut) + \{(b+T_GU)/2U\} \times [\{(z+Ut)e^{Uz/a}\,\mathrm{erfc}\,\{(z+Ut)/2(\alpha t)^{1/2}\} + (Ut-z)\,\mathrm{erfc}\,\{(z\text{-}Ut/2(\alpha t)^{1/2})\}]$$

where T is temperature, z is the depth from the surface (positive downward), t is the time after semi-equilibrium condition (Taniguchi *et al.*, 1999a, b) and considered as 100 years, T_o is the surface temperature at t = 0, T_G is geothermal gradient, $U = vc_o\rho_o/c\rho$ where *ί* is the vertical groundwater flux, $c_o\rho_o$ is the heat capacity of water, and $c\rho$ is the heat capacity of the aquifer), *erfc* is the complementary error function and α is thermal diffusivity. The modeling is limited to semi-infinite layers with only vertical conduction and convection, and vertical groundwater flux is assumed to be constant with depth (Taniguchi *et al.*, 2003).

Temperature–depth profiles are computed using the above equation for different values of U setting T_G=0.024°C/m (Imam and Hussain, 2002), b=0.0256°C/year (Ramamasy and Baas, 2007), T_0 is considered as the air temperature of well site (because long term ground surface temperature data are not available in Bangladesh), t=100 years and thermal diffusivity α=6.5×10^{-7} m^2 s^{-1} (Taniguchi *et al.*, 1989). The calculated profiles of shallow and deep wells are shown in Figures 7 and 8, respectively. The shallow well profiles with values of U=0.04 to 1.35 m/year are given the best representations of the profiles observed at shallow well sites 2, 3, 4, 5 and 7, which are classified as recharge type (Figure 7). The misfit in the lower part of the shallow well site 4 (Figure 7) might have caused due to result from a difference of thermal properties of the aquifer materials or other factors rather than heat convection because of groundwater flow.

Alternatively, the observed shallow well temperature-depth profiles agree with the calculated temperature–depth profiles with negative U (upward groundwater flow) at well sites 1, 6, 8 and 10 (Figure 7) in the discharge area of the groundwater flow system. The calculated profiles with values of U=-0.2 to -0.79 m/year give the best representations of the discharge type profiles observed in shallow wells. The misfit in the middle and lower parts of the profile in shallow well site 6 (Figure 7) might have happened due to the reflect variation of thermal property of the aquifer materials, which may affect heat convection within the aquifer. The calculated temperature profiles for the deep well sites 11 and 12 (Figure 8) are the best illustration of recharge profiles with U=0.05 to 0.16 m/year, while well site 13 (Figure 8) agrees with the discharge type profile having U=-0.15 m/year. The partial misfit for the calculated deep well profiles for the wells 12 and 13 may be caused by the difference of thermal properties (thermal conductivity, thermal diffusivity) of the aquifer materials, i.e., multiple layering of the aquifer system that may influence the thermal properties. Besides, Taniguchi *et al.* (2003) observed similar types of misfit in their study in Kumamoto Plain, Japan, and they also stated that this misfit between the observed and the modeled curves might be caused by the difference of thermal property of the aquifer materials.

The observed wells in the northern site are characterized by a shallow subsurface thermal regime with low thermal gradients, in contrast to and high thermal gradients in the southern region (Figure 4). The variations created in the thermal-flow field by groundwater movements, as indicated by the observed profiles, suggest the existence of local flow systems and a regional flow system mainly flowing from north to south or northwest to southeast. Results from the temperature-depth simulation modeling show that the specific configuration of the geothermal patterns of this field is due to hydraulic and thermo-physical properties of different sedimentary units (e.g. grain size, multiple layering, etc). The increasing thickness of the Bengal Delta aquifers towards the south may explain the southward increase in the geothermal gradient. It is obvious that an extensive groundwater flow system is developed in the northern Piedmont Plain and Tista Flood Plain sand and gravel aquifers (Figure 3) (Majumder *et al.*, 2011) enhancing the heat-flow redistribution (advective heat transport) from the regional-recharge area of the north to the south regional-discharge area. The sharp increase–decrease observed in temperature profile at the well site 1 (Figure 7) is possibly due to the affect of surface temperature (Kiuchi, 1950; Taniguchi 1993) and/or is due to local thermal regime possibly created by pumping of groundwater for irrigation purposes.

The flow-induced geothermal anomalies can be accentuated by increased flow rates along bedding planes (Toth, 1999). The deep aquifers of the Bengal Delta are char-

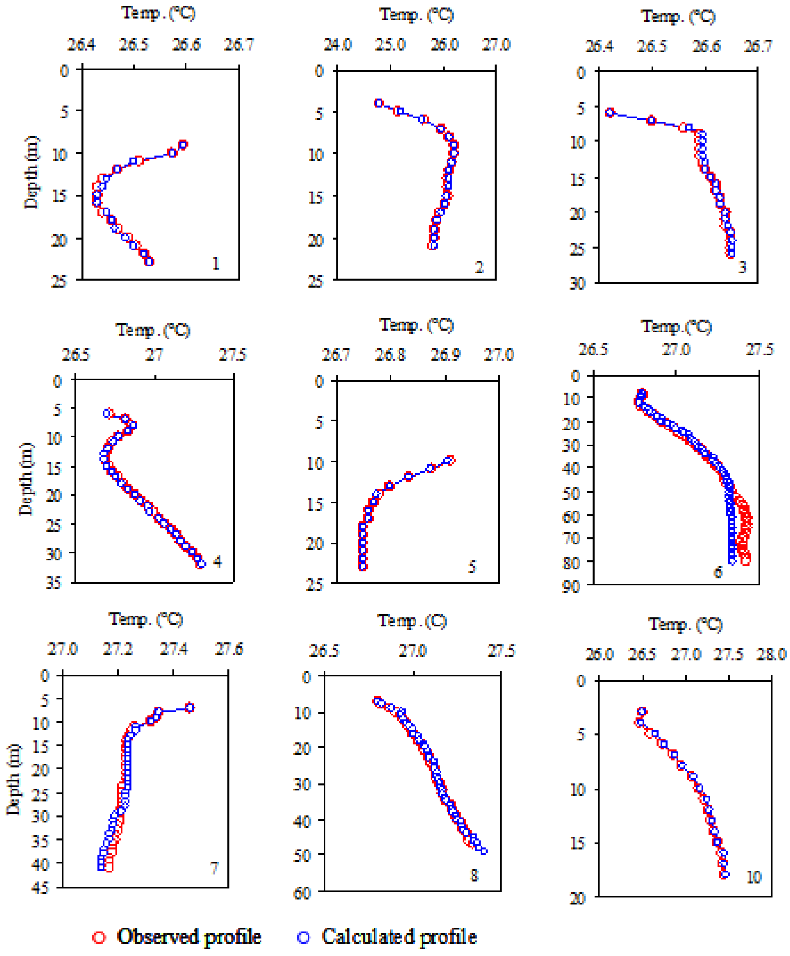

Figure 7. Observed and calculated temperature-depth profiles for shallow wells.

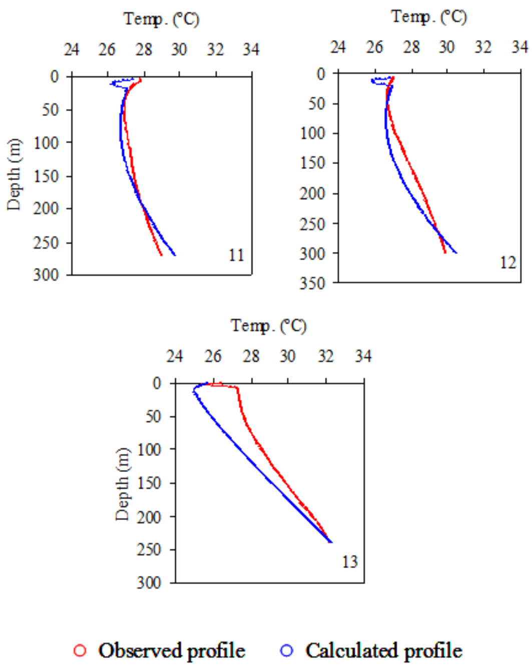

Figure 8. Observed and calculated temperature-depth profiles for deep well.

acterized by layered zones (Kinniburgh and Smedley, 2001), which may possibly cause upward movement of deep groundwater along the coastal region. Meanwhile, each flow system, regardless of its hierarchical position, has an area of origin or recharge, an area of through-flow or transfer, and one of termination or discharge. In the recharge areas, the hydraulic heads, representing the water's mechanical energy, are relatively high and decrease with increasing depth; water flow is downward and divergent. In discharge areas, the energy and flow conditions are reversed; hydraulic heads increase downward, resulting in converging and ascending water flow. In the areas of through-flow, the mechanical energy of the water is largely invariant with depth (isolines of hydraulic heads are subvertical) and consequently the flow is essentially lateral (Toth, 1999).

In Figure 5 and 6, the well 13 shows vertically compressed temperature at shallow depth relative to those expected under pure heat conduction. This is due to predominant upward subsurface flow in the discharge area. The deep groundwater moves up along the coastal region due to high hydraulic head resulting ascending water flow, which is a clear indication of deep groundwater discharge along the coastal region at depth. The upward flow of deep groundwater may also occur when water is squeezed out of compacting clay (Stuyfzand, 1999), which is characteristic of the Bengal Delta coastal aquifers as described by Ravenscroft and McArthur (2004). High recharge rate (1.35 m/year) at well site 2 is due to alluvial fan deposits (Figure 3).

By using the average recharge rate (0.70m/yr) and considering the surface area of the study area (length of 500 km × width of 300 km), the total recharged water is estimated as (total recharge, m^3/year) = surface area, m^2×recharge rate, m/year) (Dowling *et al.*, 2003) = 1.04×10^8 m^3/yr or ~34% of the total annual rainfall considering an annual rainfall >2 m/yr. The calculated recharge rates for the deep well sites 11 and 12 are 0.05 and 0.16 m/year, respectively. At well site 13 the calculated rate of deep groundwater flow is -0.15 m/year, i.e., in the southern site (close to the Bay of Bengal) of study area the deep groundwater moves upward and discharges into the Bay of Bengal, which occurs as submarine groundwater discharge into the Bay of Bengal.

5. Conclusion

Observed temperature–depth profiles are classified into two types depending on the shape of the profile, temperature itself and thermal gradient. Recharge-type wells are mainly located in the northern site of the study area where downward groundwater fluxes are expected. On the other hand, the wells with discharge type are located in the northern alluvial deposits area and southern deltaic deposits area (Figure 3), where upward hydraulic gradients are observed. Groundwater flow systems as estimated from the observed subsurface temperature agree well with the systems evaluated from hydraulic heads in the study area (Figure 6). Subsurface Temperature distributions in the Bengal Delta aquifers have been simulated using heat conduction–advection theory. Calculated temperature–depth profiles with upward and downward fluxes reproduce the observed temperature profiles reasonably. The temperature in Bengal Delta aquifers is affected by groundwater flow. The present study has clearly demonstrated the spatial variations in temperature in the Bengal Delta aquifers, illustrating the presence of shallow and deep groundwater flow systems as stated below. i) A shallow flow system is observed in the west-central and southern coastal regions of the area, where shallow groundwater shows upward heat advection. ii) The deep groundwater flow system has temperatures greater than the normal groundwater temperature gradient because of deeper upward circulation in the coastal region. Presumably, it emerges into the Bay of Bengal in the form of submarine groundwater discharge.

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