Asian Journal of Water, Environment and Pollution, Vol. 14, No. 2 (2017), pp. 1–12.
DOI 10.3233/AJW-170011

Methodology for Groundwater Extraction in the Coastal Aquifers of Purba Midnapur District of West Bengal in India under the Constraint of Saline Water Intrusion

Prabir Kumar Maity, Subhasish Das* and Rajib Das
School of Water Resources Engineering, Jadavpur University, Kolkata 700032, India
✉ subhasishju@gmail.com

Received October 5, 2016; revised and accepted March 6, 2017

Abstract: The objective of this paper is to assess the field-based study on the sub-surface characteristics and groundwater quality variation in the coastal region of Purba Midnapur district, West Bengal, India. The fact that the coastal area receives inadequate surface water, the use of groundwater has become increasingly important for domestic, irrigation and industrial purposes; however threat exists associated with groundwater over-exploitation that leads to the intrusion of seawater. Hydro-geochemical site characterizations at individual locations were selected and detailed investigations were carried out on subsoil condition and groundwater quality assessment. Based on the field test results, contour lines were plotted for chloride concentration. Three dimensional views of piezometric surface of pre-monsoon, monsoon and post-monsoon depth to groundwater level and pre-monsoon piezometric surfaces contours had also been developed. This paper presents a mathematical analysis for estimating the safe yield from shallow vertical well and the qanat well structures coupled with vertical risers are presented as a viable solution to the problem of upconing below deep vertical wells. The vertical wells may not be feasible in several situations and qanat coupled with vertical risers may be successfully used in Purba Midnapur geology context.

Key words: Coastal structures, chemical analysis, geotechnical investigation, hydrogeology, saline water intrusion.

Introduction

The country of India has a significantly long coastal belt of 5700 km. It has been observed that the intrusion in the east coast is severe in comparison to the west coast except the state of Gujarat and a limited portion of the state of Maharashtra. All parts of the east coast of India do not have the same susceptibility to saline water intrusion. The east coast of India has a number of deltaic regions, for example, the Ganga delta, the Mahanadi delta, the Godavari delta, the Krishna delta and the Cauvery delta. In all of these deltas, there is significant recharge in to the aquifer from the upstream; this counteracts to some extent saline water intrusion. Saline water intrusion is of great importance in locations having diverse characteristics, viz., the Purba Midnapur District of West Bengal which lies on the western fringe of the Ganga delta; the Sundarban area of West Bengal which is incised by several tidal channels allowing seawater to proceed deep inland (Dhar et al., 2009; Das et al., 2014; Maity et al., 2017). The district of Purba Midnapur of West Bengal lying on the western fringe of the Ganga delta is studied in details. The significant research and development has already been carried out by various scientists, engineers and researchers at different parts of the world in the field of analysis and control of saline water intrusion into coastal aquifers and other relevant areas. Amongst the important works, the most significant contributions are briefly reviewed, starting from the year 1968 till 2015.

*Corresponding Author

These contributions are broadly classified into three categories, viz., theoretical contributions (analytical and numerical studies), laboratory-based experimental works and field-based studies.

As observed, the different types of theoretical works that have been done are broadly based on two categories such as: (i) using the sharp interface concept viz. Mahesha (2009), Goswami (1968), and (ii) using the brackish interface concept e.g. Li and Yeh (1968) and Xue et al. (1995). Laboratory-based experimental works were carried out by Fand et al. (1987), Kececioglu and Jiang (1994).

Field-based studies have been conducted by various researchers such as Goswami (1968), Barlow (2003), Papadopoulou et al. (2005), Olufemi et al. (2010), Sappa and Coviello (2012), Ayolabi et al. (2013), Mandal (2013), Hashish et al. (2014), Gopinath et al. (2015) and Adedotun et al. (2015). Only Goswami (1968) studied the nature and position of the interface and delineated the fresh and saline groundwater bodies within the aquifer of Digha beach, Purba Midnapur, India. The depth of the interface was found to be much less than that calculated on the basis of the Ghyben-Herzberg principle. However, the work is very old and the prescribed model is in need of updatation. Gaps do exist in knowledge regarding the modelling of the hydrogeology, aquifer system, subsurface stratification, water quality parameters, pre-monsoon, post-monsoon depth to water level and pre-monsoon piezometric surface contour of the study area of Purba Midnapur. Papadopoulou et al. (2005) proposed different management scenarios to prevent further ingress of the saline water intrusion front in the industrial zone of the City of Herakleio in Greek islands. Artificial recharge of fresh water is proposed as part of the solution.

From the brief review of these past researches, it is observed that there are apparent shortcomings in the work of various researchers done so far and there is substantial scope for a thorough and detailed investigation to study the basic phenomenon of saline water intrusion into coastal aquifers of Purba Midnapur district.

Geology of Purba Midnapur District

The Purba Midnapur district of West Bengal is located to the southwest of Kolkata and shares the western border of the state of Orissa. The district comprises 6724 km^2 area and bordered by Paschim Midnapur and Bankura districts of West Bengal in the North, Hooghly, Howrah and 24-Paragnas districts of West Bengal in the east, Bay of Bengal in the south and Mayurbhanj and Balasore districts of Orissa in the Southwest. The district lies roughly between 21°31′ to 23°00′ N and 86°45′ to 88°00′ E. The district is very much populous, population being 25,09,247 persons enumerated in 1971 census. The district is subdivided into five subdivisions namely Haldia, Contai, Tamluk, Egra and Panskura. The district head quarter is located at Tamluk town. Several major and minor rivers traverse the district. River Kasai traverses through the Panskura town and the industrial town of Haldia. Kasai River after its confluence with Kalaghai River is known as Haldi River and it ultimately joins the river Hooghly. Rupnarayana River flows in Eastern border of the district and joins Bay of Bengal. The other major river Subarnarehka passes through the south-western periphery of the district. The groundwater basins of the district mostly to the Ganga basin except for area covering the Subarnarehka River which forms the separate basin. Purba Midnapur district has been formed in the last few thousands of years by the continuous supply of sediments loaded from huge catchments which is deposited into a subsiding basin, partly fluvial and partly marine, under varying energy conditions.

The coastal part is covered by unconsolidated sediments of recent age (Table 1) and it is represented by vast plains of fluvial and marine deposits. In the coastal region the recent sediments are characterized by a group of yellow or brown coloured sediments. Again yellowish or brown sediments are underlain by greyish white sand sequence. The similar types of sediments are also reported from inland areas.

Table 1: Stratigraphic succession of Purba Midnapur district

Rock type	*Geological age*
Alluvium	Recent
Older Alluvium	Pleistocene
Siwalik Group	Miocene-Pliocene

Lithology of bore holes have been drilled in the Purba Midnapur district in the Digha, Contai, Ramnagar, Haldia, Sutahata, Nandigram, Bhupatinagar. Then soil log data have been analyzed. It is observed from the lithology of bore holes that the same group of aquifers continued from the inland part of the district up to the coast. It is also seen that there is considerable lateral variation, i.e. the individual layer of sand, laterally changes its grade from sandy to silt/clay and it is also observed that the three different types of formations encountered in various bore holes in different part of the district belong to different geological ages, from tertiary to the recent (Mukherjee et al., 2015). The unconsolidated recent sediments are essentially a sequence of clay, sand and gravel exhibiting wide variation in grade and colour. Usually these sediments are characterized by shades of grey, brown and yellow colour. The sand is of quartz feldspathic material often associated with gravel, calcareous shelly material. The unconsolidated sediments are very thick (300 m) close to the coast. These horizons occurring at different depths form the aquifers. The aquifers are regionally extensive. Unconsolidated recent sediments are mainly in the eastern and coastal parts of the district and are seen to reduce in thickness towards inland. The thickness of recent sediments are about 25 m at Panskura, 50 m at Tamluk, 30 m at Nandigram, 35 m at Contai, 50 m at Haldia, 80 m at Khejuri and 90 m at Dariyapur. On the coastal side thick sand horizons are met at Khejuri and Dariyapur but these thick sand horizons laterally discontinue towards southeast, i.e. Haldia, Sutahata etc.

Towards Daxin Danki, Bodra and Digha (south-eastern part) a thick sand horizon is divided into several small horizons by intervening clay lenses (Table 2 and Figure 1). The information available from the bore holes identified different type of sediments down to a depth of 300 m. Greyish white sand clay belonging to upper tertiary is encountered from 121 m to 200 m below ground level (bgl) at Marisda, from 102 m to 200 m at Sarda, 66 m to 300 m at Digha, 82 m to 200 m at Khejuri and 105 m to 200 m below ground level at Egra, in the eastern part, 142 m down to a depth of 300 m at Tamluk, 66 m to 300 m below ground level at Sutahata. These greyish white sand and clay horizons are overlain brownish yellow and grey coloured sand and clay horizons. These sediments occur from 15 m to 121 m below ground level at Marisda, 12 m to 102 m below ground level at Sarda, 21 m to 66 m below ground level at Digha, 06 m to 139 m below ground level at Bhupatinagar, 0 to 75 m below ground level at Egra, 63 m to 66 m below ground level at Sutahata and 93 m to 142 m below ground level at Tamluk.

It is found that the upper soil horizon of Purba Midnapur is of quaternary origin and consists of alternating deposits of clay and sand of marine origin. As with all marine deposits, rounded grains and high porosity are dominant characteristics. The northern part of the district consists of a mixture of alluvial and marine deposits. Also there is a great spatial heterogeneity in the aquifer, which makes any predictive method for calculating the depth of saline water intrusion.

Table 2: Aquifer positions at different Bore Hole locations

Stratum	*Tapping zone bgl (m)*	*General features*	*Quality of water*
		Bore Hole-1: Egra	
I	47-50	Sand fine to medium grained, yellow in colour	Fresh water
II	104-107	Sand very coarse with few pebbles and feldspar frgts grey in colour	Fresh water
III	175-178	Sand to medium to coarse with block mineral frgts	Fresh water
		Bore Hole-2: Daxin Danki	
I	191-194	Sand fine to medium with mica and mineral frgts grey in colour	Brackish
II	237-240	-Do-	Brackish
		Bore Hole-3: Sarda	
I	45-46	Sand very fine to fine with mica, yellowish in colour	Saline
II	86-89	Sand a mixture of fine medium and coarse grained brownish colour	Saline
III	170-172	Sand fine to coarse grained, Greyish white in colour	Saline
		Bore Hole-4: Marisda	
I	106-107	Sand fine to medium grained, grey in colour	Brackish
II	155-168	-Do-	Saline
III	187-189	-Do-	Saline
		Bore Hole-5: Nilpur	
I	20-23	Sand medium to coarse grained, yellow in colour	Saline
II	99-102	Sand fine to medium grained, yellow in colour	Saline
III	159-162	-Do-	Brackish
IV	195-198	-Do-	Brackish

(*Contd.*)

Table 2 (*Contd.*)

Stratum	*Tapping zone bgl (m)*	*General features*	*Quality of water*
		Bore Hole-6: Balgeria	
I	49-52	Fine to medium sand	Brackish
II	105-108	-Do-	Brackish
		Bore Hole-7: Digha	
I	45-48	Sand fine to coarse grained with mica yellow in colour	Brackish
II	103-106	Sand, clay, quartz, feldspar, mica, grey colour	Saline
		Bore Hole-8: Chandipur	
I	74-79	Sand fine to medium with feldspar, mica greyish white colour	Saline
II	116-119	Sand fine to coarse grained with feldspar, mica brownish yellow colour	Brackish
III	194-197	Sand fine to coarse grained	Brackish
		Bore Hole-9: Sutahata	
I	68-71	Sand fine to medium grained grey colour	Brackish
II	108-111	-Do-	Saline
III	159-162	-Do-	Saline
		Bore Hole-10: Tamluk	
I	92-95	Sand fine to coarse grained with Quartz, feldspar, mica brownish colour	Brackish
II	122-125	Sand fine to coarse yellow colour	Fresh
III	161-164	-Do-	Fresh
		Bore Hole-11: Khejuri	
I	30-33	Sand very fine grained yellowish grey colour	Brackish
II	59-64	-Do-	Fresh
III	195-198	-Do-	Fresh

Hydrology of Purba Midnapur District

Groundwater development and management studies in parts of Purba Midnapur district has been undertaken to study the extension of saline aquifers and effect of high tidal waves on phreatic aquifers and to study the impact of large scale groundwater development on groundwater regime including saline water ingression. The water level in Purba Midnapur district varies from 3 to 15 m below ground level during pre-monsoon period (Figure 2) and 4-12 m below ground level in post-monsoon period (Figure 3); below the dune sand clay bed occur down the depth of 70 m below ground level. Alteration of sand and clay bed occurs down to a depth of 450 m below ground level. Generally brackish water found in all the aquifers below sand dunes up to the depth of 450 m below ground level over a small area around Contai. Fresh water aquifer occurs within 120 to 300 m to below ground level towards south east of contai in Mukundpur, Baijapur and Sophiabad.

For the year 2014 and 2015 (Figures 4-5), the pre-monsoon piezometric surface contours show depressions near Ramnagar, Bhagbanpur and Sutahata. In the prevailing climatic scenario in the area, the pre-monsoon condition is far more critical as compared to post-monsoon condition. Therefore, evaluation of the potential for salinisation is carried out considering the pre-monsoon position. It is very clear that the Ramnagar area which includes the tourist resort of Digha and the town of Contai is highly prone to saline water intrusion as is the Sutahata area which includes the industrial town of Haldia. Immediate and urgent measures are needed to push back saline water encroachment in these areas.

Geochemical Investigation

The water samples have been collected from the wells at Block Contai-I, II and III area of Purba Midnapur district (Figure 6). Based on chemical analysis (Table 3) conducted, the data obtained from chloride concentration (ppm) has been plotted in the Block Contai-I, II and III area and relevant contours have been drawn (Figure 7). As observed, the chloride concentration varies from as high as 17122 ppm at Ghatua, 16081 ppm at Contai Saline Zone II, 2261 ppm at Nayaput and 2870 ppm at Bhajachawli to as within permissible limit as 300 ppm at Dulalpur. It has been found that the Contai town with its surrounding rural areas of about 116.5 sq. km forms a *saline zone*. The variations of the chloride concentration in the aquifer at the depth taken were

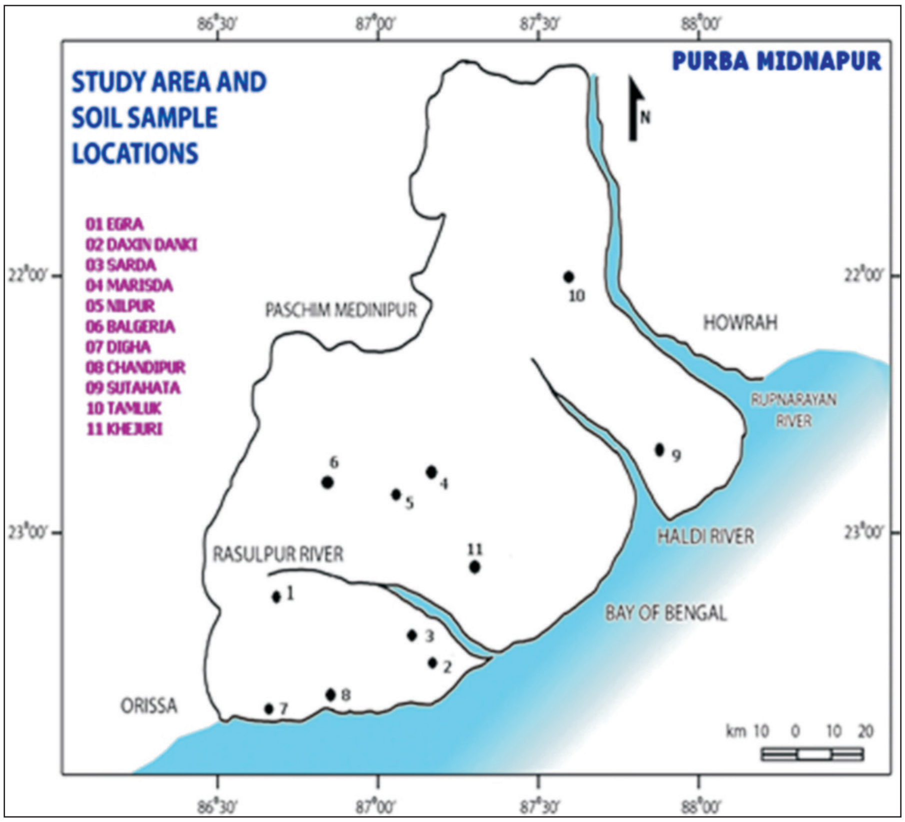

Figure 1: The study area and soil sample locations.

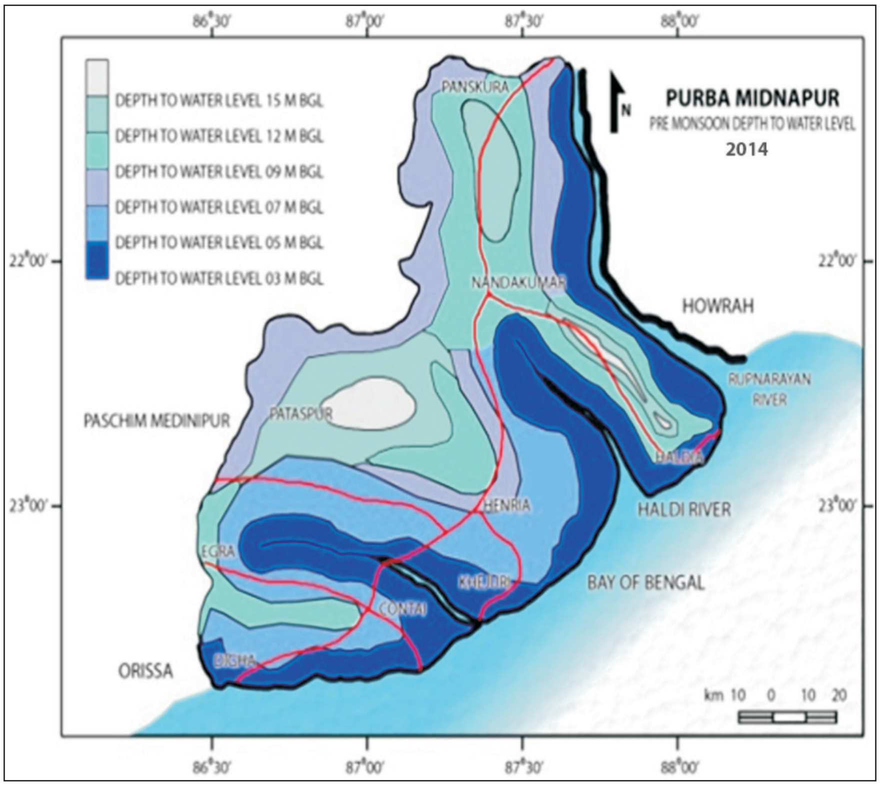

Figure 2: Pre-monsoon groundwater water level contour.

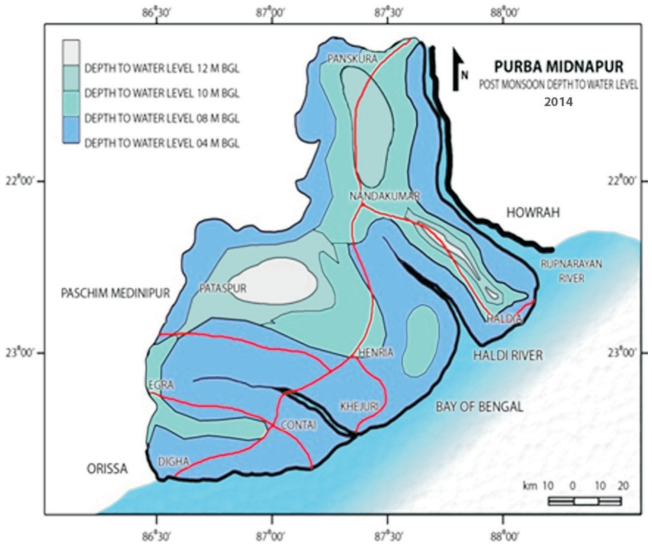

Figure 3: Post-monsoon groundwater level contour.

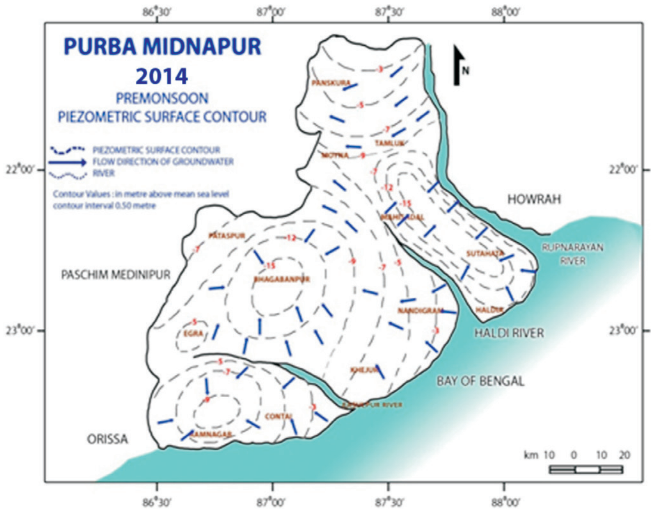

Figure 4: Pre-monsoon piezometric surface contour.

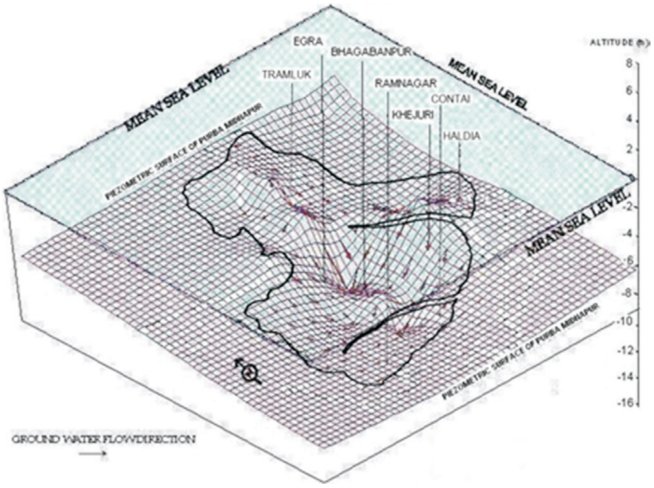

Figure 5: Three dimensional view of piezometric surface.

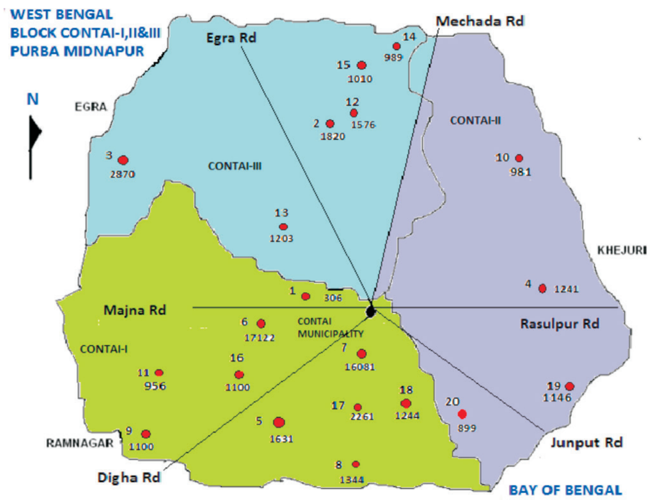

Figure 6: Water sampling points in 20 wells at Contai-I, II and III blocks.

found to be quite irregular pattern. At some locations the chloride concentration is quite high such as at Kudai (1631 ppm), Paschim Kamarda (1576 ppm), Sabajput (1344 ppm), Bamunia (1146 pmm), Mahishagote (1100 ppm), Kanaidighi (1010 ppm), Chandiveti (981 ppm), Jamua Rampur (950 ppm) and Uttar Dauki (899 ppm). Conversely, at few locations, the chloride concentration is within permissible limit like Mukundapur (587 ppm). Within the Block Contai-I, II and III area wide variations in salinity concentration is observed which can be, at least partially, attributed to the high degree of spatial heterogeneity of the aquifer underlying the area.

Theory of Upconing

In coastal aquifers, where fresh water lying above saline water is pumped by a well, the interface rises below the well due to drawdown of groundwater table around the well due to which pressure on the interface is reduced and saline water rises as a conical mound beneath the well (Figure 8). This phenomenon is known as upconing. If the top of the conical mound reaches the well, saline water will flow out of the well, which is a very undesirable phenomenon.

Dagan and Bear (1968) gave a mathematical expression for determining the height of the cone Z_t below the well. The formula is as follows (Eq. 1):

$$Z_t = \frac{\rho_f Q}{2\pi(\rho_s - \rho_f)K_x d}\left[1 - \frac{2\rho_f \theta h_f}{2\rho_f \theta d + (\rho_s - \rho_f)K_2 t}\right] \quad (1)$$

where Z_t = rise of cone at time t; Q = discharge of well; d = depth of interface below the bottom of the well, before pumping; K_x = hydraulic conductivity of aquifer in horizontal direction; K_s = hydraulic conductivity of aquifer in vertical direction; θ = porosity of aquifer and t = time since start of pumping or $t = \infty$. The equilibrium height, Z_∞ of the cone (Eq. 2) is given by

$$Z_\infty = \frac{\rho_f Q}{2\pi(\rho_s - \rho_f)K_x d} \quad (2)$$

The Dagan and Bear (1968) equation holds for $Z/d < 1/3$, but in field situation the inland aquifers are suffering from the maladies of over-exploitation of groundwater by way of unscrupulous pumping. The coastal aquifers encounter the danger of sea water intrusion and saline water upconing. The critical value of z, the interface of saline water upconing touching the bottom of the well, will lead to depression of water table with associated hazards like putting the well out of use and rendering the abstraction uneconomic with increased lift.

If Z_∞ is equal to d, i.e. if the well is to discharge saline water, putting value of $Z_\infty = d$ in Eq. (2), Eq. (3) is obtained.

$$d = \sqrt{\frac{\rho_f Q}{2\pi(\rho_s - \rho_f)K_x}} \quad (3)$$

From Ghyben-Herzberg relation, the depth of interface below the well, before pumping is given by

Table 3: Test result of water samples collected from 21 numbers of pump houses and tube wells within the area of Contai

Sl. No.	*Source/Location*	*pH*	*Turbidity mg/l*	*Total hardness mg/l*	*Chloride mg/l*	*Iron mg/l*	*TDS mg/l*	*EC µS/cm*
01	Tube well/Dulalpur, Contai-I	7.1	9.51	470	306.47	1.32	509	795
02	Pump House-I/Paschim Kamarda, Contai-III	7.2	21.5	700	1820.74	1.7	2508	3420
03	Pump House-II/Bhajachawli, Contai-III	7.2	72.7	790	2870.92	2.2	2200	4720
04	Pump House-I/Mukundapur Zone IV, Contai-II	72	5.51	620	1241.43	0.2	1809	2780
05	Pump House-I/Kudai Padima High School, Contai-I	7.0	0.65	670	1631.99	0.80	2280	3090
06	Pump House-I/Ghatua W/S Scheme, Contai-I	7.4	17.55	1580	17122.50	1.08	15260	28700
07	Pump House-II/Contai Saline Area-II, Contai-III Contai-I	7.3	86.0	2260	16081.59	2.4	18229	27900
08	Pump House-I/Sabajput High School, Contai-I	7.2	0.66	660	1344.98	1.2	2250	3260
09	Pump House-I/Mahishagote High School, Contai-I	7.2	1.15	600	1100.67	1.00	1655	2560
10	Tube Well-I/Chandiveti W/S Scheme, Contai-III Contai-II	7.2	5.31	600	981.64	1.00	1518	2380
11	Tube Well/Contai Jamua Rampur Primary School, Contai-I	7.0	8.23	590	956.32	1.00	1950	1452
12	Tube Well-I/Paschim Kamarda, Contai-III	7.3	2.66	690	1576.69	0.70	2340.55	3140
13	Tube Well-I/Contai Saline Area Zone-III, Contai-III	7.20	17.65	630	1203.96	1.50	1595	2500
14	Tube Well-I/Uttar Kanaidighi S.S.K., Contai-III	7.00	1.18	630	989.88	0.80	1556	2430
15	Tube Well/Kanaidighi Paschim Khudiram S.S.K., Contai-III	7.10	1.08	640	1010.20	0.60	1559	2440
16	Tube Well-II/Contai Saline Area Zone-III, Contai-I	7.10	7.08	620	1100.94	1.00	1646	2570
17	Tara Pump/Nayaput Primary School, Contai-I	7.20	9.71	650	2261.90	1.5	2520	4150
18	Tube Well/Contai Saline Zone-III, Contai-I	7.2	3.66	610	1244.08	1.40	1610	2480
19	Tube Well/Bamunia W/S Scheme, Contai-II	7.20	6.79	600	1146.59	0.90	1517	2330
20	Tube Well-II/Uttar Dauki S.S.K., Contai-II	7.20	3.53	580	899.50	0.70	1759	2750

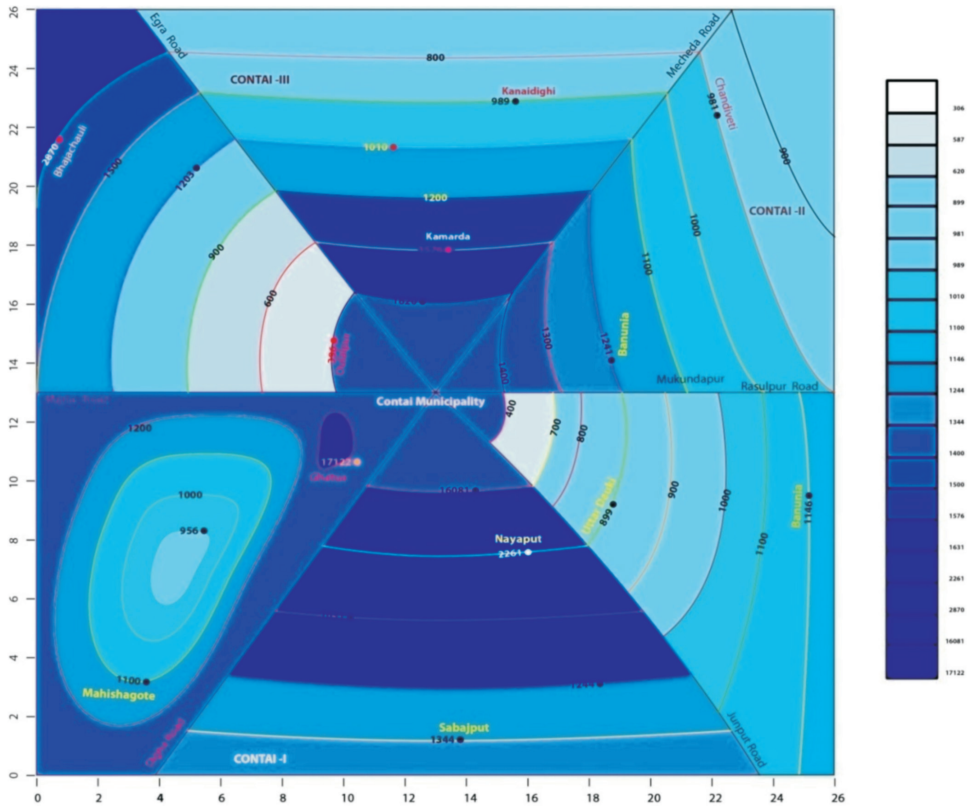

Figure 7: Map showing contours of chloride of well in Contai-I, II and III blocks.

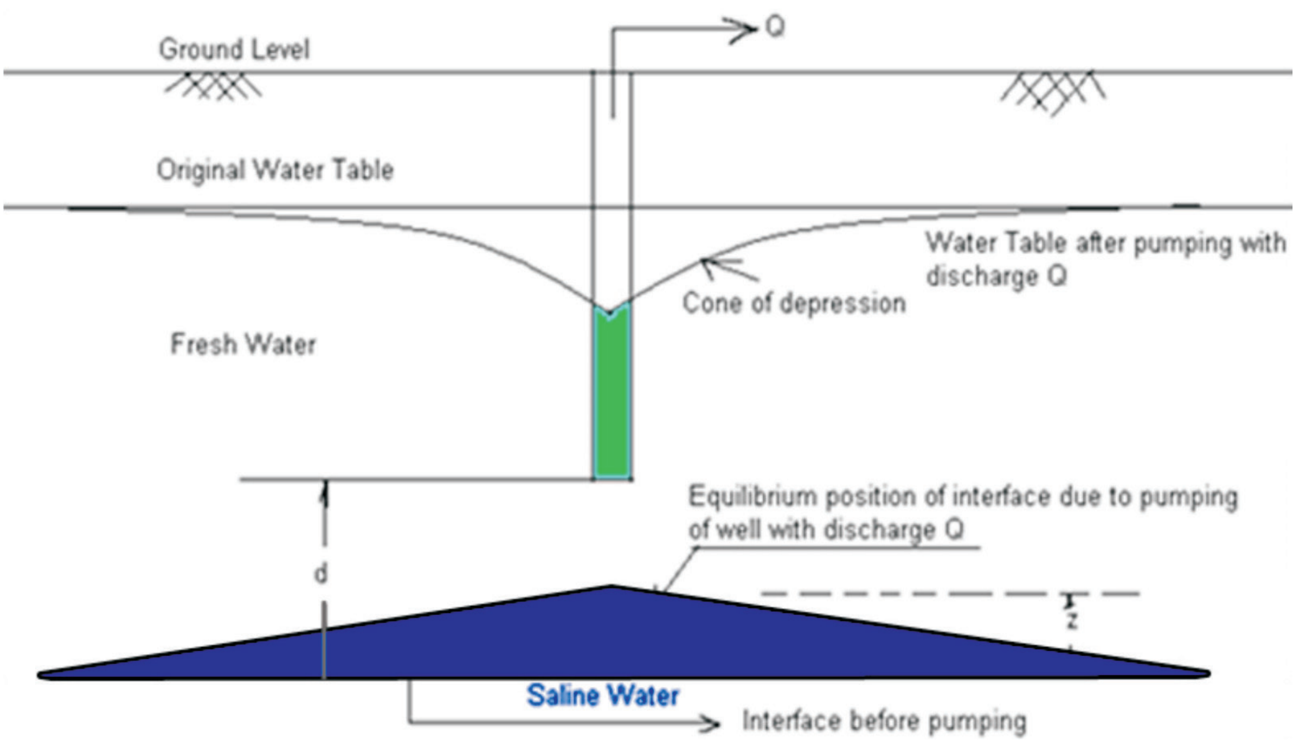

Figure 8: Upconing of saline water beneath a pumped well.

$$d = h_f\left[\left(\frac{\rho_f}{(\rho_s - \rho_f)}\right) + 1\right] - d_w \qquad (4)$$

Equating the right-hand-sides of Eq. (3) and Eq. (4)

$$\sqrt{\frac{\rho_f Q}{2\pi(\rho_s - \rho_f)K_s}} = h_f\left[\left(\frac{\rho_f}{(\rho_s - \rho_f)}\right) + 1\right] - d_w \qquad (5)$$

where d_w = depth of well from original undisturbed water table.

Putting for ρ_f = 1000 kg/m^3 and ρ_s = 1025 kg/m^3 in Eq. (5), making Q the subject of the formula, the Eq. (6) is obtained.

$$Q = 0.157\ K_x\ (41h_f - d_w)^2 \qquad (6)$$

From Eq. (6), it is seen that for a homogeneous aquifer the safe discharge from the well is increased with increase in fresh water head h_f above mean sea level, and the safe discharge from well is increased with decrease in depth of well (d_w) below the original undisturbed fresh water table. The results as mentioned in Table 4 have been obtained by applying Eq. (6) in the computer program.

Safe Yield Analysis

Using the theory developed, a case study based on field data have been carried out. The depth of fresh water zone varied from 5 m to 120 m below the original undisturbed fresh water table, keeping in view the subsoil condition in the district of Purba Midnapur.

The Purba Midnapur district coastal part is covered by unconsolidated sediments of recent age and it is represented by vast plains of fluvial and marine deposits. In the coastal region the recent sediments are characterized by a group of yellow or brown medium to fine sand. And below the dune sand clay bed occurs down the depth of 130 m below ground level. Alteration of sand and clay bed occurs down to a depth of 450 m below ground level. Generally brackish water was found in all the aquifers below sand dunes up to the depth of 450 m below ground. The hydraulic conductivity of the subsoil in the horizontal direction is taken as an average value of (K_x = 3.512 × 10^{-4} m/sec, from laboratory test) 30.34 m/day. The output results obtained using the computer program is documented in Table 4.

From the results in Table 4, the figures are plotted and it is concluded that initially well discharge increases as fresh water head above mean sea level increases when depth of well from original undisturbed water table is 5 m, 10 m, 20 m, 40 m curves respectively as shown in Figure 9. In this figure, the opposite observation is noted, the discharge attends maximum initially at minimum fresh water head, after that the well discharge decreases, as fresh water head increases, attends zero discharge after that the well discharge increases as fresh water head above mean sea level increases, but in small magnitude as for 60 m, 80 m, 100 m and 120 m curves respectively.

As regards the developed formulations for safe yield of vertical well considering upconing in coastal regions, it may be concluded that initially the well discharge increases with fresh water head above mean sea level following fairly a parabolic pattern. Also, at zero discharge, the variation of the depth of well with the fresh water head above mean sea level follows parabolic pattern with positive gradually increasing slope.

Table 4: Safe yield from well at different fresh water head for various values of the depth of well (d_w) (Hydraulic conductivity of soil, K_x = 30.34 m/day)

dw (m)→ *h_f (m)↓*	*05*	*10*	*20*	*40*	*60*	*80*	*100*	*120*
0.0	119.1	476.3	1905.2	7620.8	17146.8	30483.2	47630.0	68587.2
0.4	619.0	195.1	61.7	2652.8	9054.3	19266.1	33288.4	51121.1
0.8	3681.0	2476.0	780.4	246.9	3523.9	10611.2	21508.9	36217.1
1.2	9305.2	7319.0	4061.1	403.1	555.6	4518.4	12291.6	23875.2
1.6	17491.5	14724.2	9904.0	3121.5	149.4	987.7	5636.3	14095.4
2.0	28239.8	24691.4	18309.0	8401.9	2305.3	19.1	1543.2	6877.7
2.4	41550.3	37220.8	29276.1	16244.5	7023.3	1612.6	12.2	2222.2
2.8	57422.9	52312.2	42805.3	26649.2	14303.5	5768.2	1043.3	128.8
3.2	75857.6	69965.8	58896.6	39616.0	24145.7	12485.9	4636.5	597.5
3.6	96854.5	90181.5	77550.0	55144.9	36550.1	21765.8	10791.8	3628.3

Crossed Qanats-Well Structures

In coastal regions, deep tube wells are not desirable because of possibility of upconing of saline water. Shallow tube wells or deep tube wells with low discharge may be used, but the discharge being low may not suffice to meet projected needs. In this context, horizontal infiltration galleries called qanats coupled with vertical risers can be constructed in the fresh water zone to avoid problems associated with upconing.

The qanats are stone wares or pvc pipes having perforations (5 mm diameter) arrangement of 0.2 m to 1.5 m diameter, set at a depth of 1 m to 5 m with gravel packing and wire nets at close intervals so that water can seep with low velocities into the gallery. This water can be pumped out and utilised while effectively preserving the quality of groundwater (Figure 10).

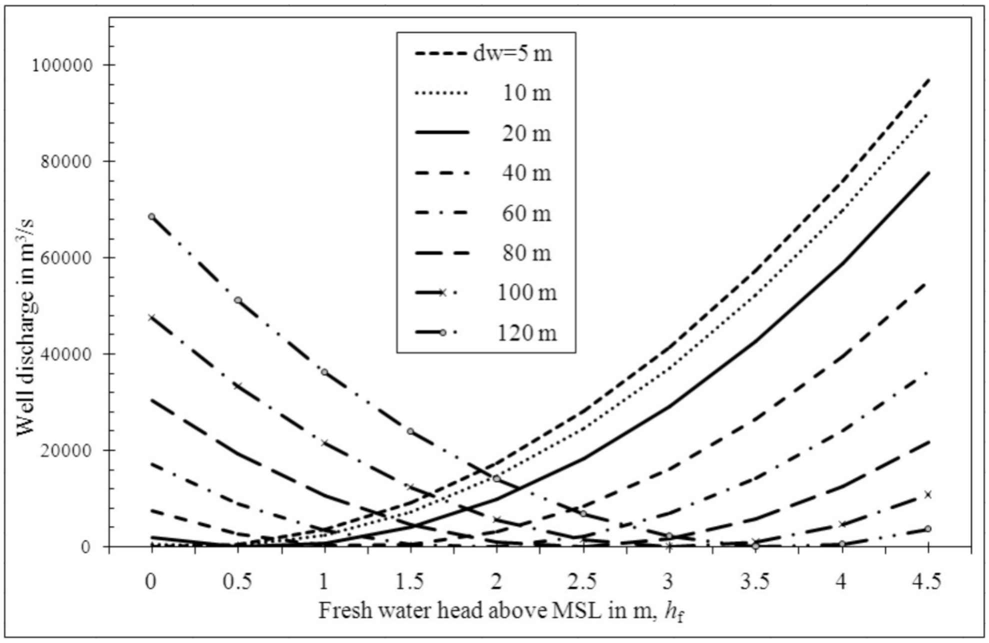

Figure 9: True curves for variation of well discharge versus fresh water head.

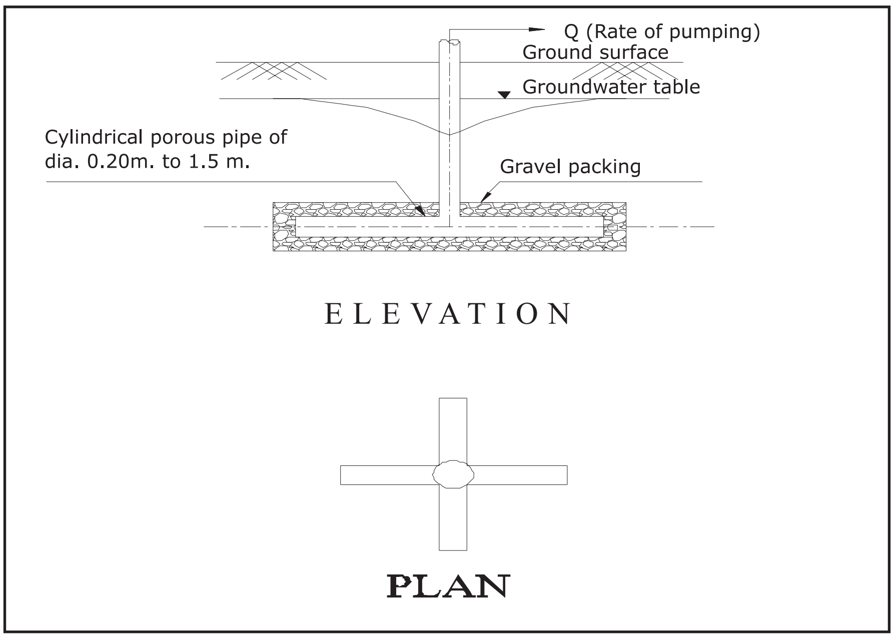

Figure 10: Plan and elevation of a four-legged qanat-well structure.

The qanat-well structures coupled with vertical risers are a viable solution to the problem of upconing below deep vertical wells. The deep vertical wells may not be feasible in several situations and qanats coupled with vertical risers can be successfully used in Purba Midnapur sandy soil texture condition.

Conclusions

- A coastal area Purba Midnapur of West Bengal, India, has been chosen as the study and relevant hydro-geological investigations and groundwater assessments have been conducted. The observed wide variation in saline concentration revealed high degree of spatial heterogeneity of the aquifers.
- The depth to piezometric surface is within 8 m below ground level due to large scale withdrawal of ground water in Sutahata, Mahishadal and Haldia sector; drawdown of piezometric head to the tune of 1.6 m over the last ten years has been noted. In Contai area in the southwest, groundwater occurs under water table conditions in the sand dunes overlying the upper clay blanket.
- For the year 2014 and 2015 (Figures 4-5), the pre-monsoon piezometric surface contours show depressions near Ramnagar, Bhagbanpur, and Sutahata. In the prevailing climatic scenario in the area, the pre-monsoon condition is far more critical as compared to the post-monsoon condition. Therefore, evaluation of the potential for salinisation is carried out considering the pre-monsoon position. It is very clear that the Ramnagar area which includes the tourist resort of Digha and the town of Contai, is highly prone to saline water intrusion as is the Sutahata area which includes the industrial town of Haldia. Immediate and urgent measures are needed to push back saline water encroachment in these areas.
- The artificial recharge by rainwater harvesting through percolation pond, injection well and optimisation of pumping location will also help in reducing the saline water intrusion in the area.
- As regards the formulations developed for safe yield of vertical well considering upconing in coastal regions, it may be concluded that the well discharge initially increases with fresh water head above mean sea level following a fairly parabolic pattern. Also, at zero discharge, the variation of the depth of well with the fresh water head above mean sea level follows parabolic pattern.
- Horizontal infiltration galleries are presented in this paper as a viable solution to upconing below vertical wells. As the analysis presented in this paper has shown, vertical wells may not be feasible in several situations and horizontal infiltration galleries can be successfully used in such cases**.**

References

Ayolabi, E.A., Folorunso, A.F., Odukoya, A.M. and A.E. Adeniran (2013). Mapping saline water intrusion into the coastal aquifer with geophysical and geochemical techniques: The University of Lagos campus case (Nigeria). *SpringerPlus*, **2:** 433.

Adedotun, I.A., Gregory, O.O. and A.A. Obasanmi (2015). Hydrochemical Investigation of Saline Water Intrusion into Aquifers in Part of Eastern Dahomey Basin, Southwestern Nigeria. *Journal of Environment and Earth Science*, **5(11):** 138-153.

Barlow, M. (2003). Freshwater-Saline Water Environments of the Atlantic Coast. U.S. Geological Survey Report (USGS).

Das, S., Nayek, M., Das, S. Dutta, P. and A. Mazumdar (2014). Impact on Water Quality in Piyali River, Sundarbans, India due to Saline Water Intrusion. *Indian Journal of Environmental Protection*, **34(12):** 1010-1019.

Dagan, G. and J. Bear (1968). Solving the Problem of Local Interface Upconing in a Coastal Aquifer by the Method of Small Perturbations. *Journal. Hydraulic Research*, **6(1):** 15-44.

Dhar, S., Das, S. and A. Mazumdar (2009). Salinity Intrusion Impact on the Piyali River of the Sundarbans. International Conference on Emerging Technologies in Environmental Science and Engineering, Aligarh, Uttar Pradesh.

Fand, R.M., Kim, B.Y.K., Lam, A.C.C. and R.T. Phan (1987). Resistance to the Flow of Fluids through Simple and Complex Porous Media whose Matrices are Composed of Randomly Packed Spheres. *Journal of Fluids Engineering*, **109:** 268-274.

Goswami, A.B. (1968). A Study of Salt Water Encroachment in the Coastal Aquifer at Digha, Midnapore District, West Bengal, India. *Bulletin, International Association of Scientific Hydrology*, **13(3):** 77-87.

Gopinath, S., Krishnaraj, S., Saravanan, K. and L.P.P. Devi (2015). Hydrogeochemical characteristics of coastal groundwater in Nagapattinam and Karaikal aquifers: Implications for saline intrusion and agricultural suitability. *Journal of Coastal Sciences*, **2:** 1-11.

Hashish, H.A., El-Ghandour, H.A. and A.A. El-Nimr (2014). Simulating the Effects of Spatial Layout and Pumping/Recharging Rates of Wells on Saltwater Intrusion. *International Water Technology Journal*, **4(3):** 152-166.

Kececioglu, I. and Y. Jiang (1994). Flow through Porous Media of Packed Spheres Saturated with Water. *Journal of Fluids Engineering*, **116:** 164-170.

Mahesha, A. (2009). Conceptual Model for the Safe Withdrawal of Freshwater from Coastal Aquifers. *Journal of Environmental Engineering*, **135(10):** 980-988.

Maity, P.K., Das, S. and Das, R. (2017). Assessment of Groundwater Quality and Saline Water Intrusion in the Coastal Aquifers of Purba Midnapur District, West Bengal, India. *Indian Journal of Environmental Protection*, **37(1):** 31-40.

Mandal, M. (2013). Digha Sankarpur Littoral Tract: A Geographical Case Study. *International Journal of Humanities and Social Science Invention*, **2(4):** 46-54.

Mukherjee, B., Das, S. and Mazumdar, A. (2015). Environmental Study and Analysis of Silts Deposition at Maithon Reservoir. *Indian Journal of Environmental Protection*, **35(3):** 177-187.

Olufemi, A.G., Utieyin, O.O. and O.M. Adebayo (2010). Assessment of Groundwater Quality and Saline Intrusions in Coastal Aquifers of Lagos Metropolis, Nigeria. *Journal of Water Resource and Protection*, **2:** 849-853.

Papadopoulou, M.P., Karatzas, G.P., Koukadaki, M.A. and Y. Trichakis (2005). Modeling the Saltwater Intrusion Phenomenon in Coastal Aquifers – A Case Study in the Industrial Zone of Herakleio in Crete. *Global Nest Journal*, **7(2):** 197-203.

Sappa, G. and M.T. Coviello (2012). Seawater Intrusion and Salinization Processes Assesment in a Multistrata Coastal Aquifer in Italy. *Journal of Water Resource and Protection*, **4:** 954-967.

Xue, Y., Xie, C. and J. Wu (1995). A Three Dimensional Miscible Transport Model for Seawater Intrusion in China. *Journal of Water Resources Research*, **31(4):** 903-912.