Groundwater management in a coastal aquifer in Krishna River Delta, South India using isotopic approach

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Groundwater conditions in the multi-aquifer system in the Krishna River Delta, India, were studied through an integrated approach using hydrochemical, hydrogeological and isotopic techniques. This study was taken up because of the reported seawater intrusion into the groundwater system of this agriculturally rich region. The results, of hydrochemistry and environmental tritium including the radiocarbon dates, indicate that the origin of salinity in the aquifer systems is due to palaeo-geographical conditions. The salinity front is observed to be at 25, 30 and 50 km distance in shallow, intermediate and deeper aquifers respectively from the coast. The modern irrigation practices using intensive canal network has led to refreshening of the aquifer systems. The extent of refreshening has been mapped using hydrochemistry and environmental tritium. The recharge of groundwater by the canal system can be expedited by developing the canal network in the area having high potential for groundwater recharge. This will result in further reduction of salinity in the Krishna delta region. Further, Cl^-/Br^- ratio and stable isotopes ($\delta^{18}O$ and δD) have been used to study the aquifer–aquifer interconnectivity and to identify perched aquifers within the study area.

Keywords: Coastal aquifers, environmental isotopes, hydrochemistry, river delta, salinity, seawater intrusion.

KRISHNA and Godavari districts of the Andhra Pradesh have a flourishing agricultural production. In recent years, groundwater is increasingly being used for irrigation in addition to the surface water supplied through the canal network, which offtakes from the Prakasam Barrage located across the River Krishna in Vijayawada. Several tubewells have been installed in the northern part of the delta region. In the southern coastal region, due to the geological set up, wells have been drilled up to a depth of 120 m to meet domestic needs and for the purpose of prawn culture activities.

The Andhra Pradesh Ground Water Department (APGWD), on the basis of the water quality data obtained from public water supply wells, had reported that the salinity front in the groundwater is moving landwards[1]. The above study by APGWD was based on limited data pertaining mainly to the shallow dugwells in the southern part of the study area, which has led to a concern regarding the sustainability of the valuable groundwater resources. Under a World Bank-aided hydrology project, a research work was carried out to examine the status of salinity problem in the study area and to identify the source of salinity in the groundwater.

This was the first study being carried out in the Krishna Delta using a combined approach with hydrogeological, hydrochemical and isotopic techniques. The objectives of this study were to identify the cause of groundwater salinity, and to identify active hydrological processes including the present day seawater intrusion, if any.

Seawater intrusion near a coastline occurs when fresh water is withdrawn faster than it can be recharged. Seawater generally intrudes upwards and landwards into an aquifer and around a well, though salinity occurs 'passively' without any general lowering of the water table near a coastline. The transition zone (the interface where freshwater naturally mixes with seawater as it is discharged to the sea) naturally descends landwards as a wedge within aquifers along the coastline.

Study area

Krishna Delta forms the southeastern part of the Krishna–Godavari alluvial basin complex along the east coast of India. The delta complex has been built by two major river systems, viz. Krishna and Godavari with a narrow strip of inter-deltaic plain. The Krishna Delta comprises an area of 4600 sq. km bounded by north lat. 15°44′–16°40′N and east long. 80°20′–81°30′E (Figure 1). The northernmost part of the study area is drained by the Budameru River, which joins the Kolleru Lake located in the north-east (not shown in Figure 1).

The delta is a gently rolling low lying plain with a maximum altitude of 19 m above mean sea level (msl) near Vijayawada. The general slope of the terrain is towards south and south-east. The region is influenced by tropical semi-arid type climate. The mean annual temperature is about 28°C. The area receives rainfall mainly

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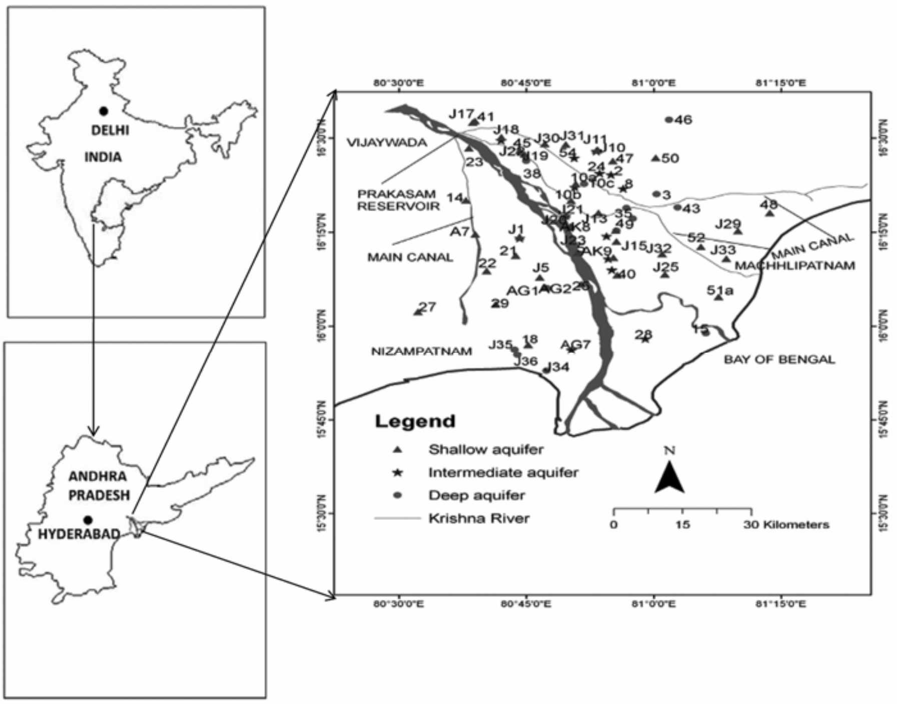

Figure 1. Map of study area showing sampling locations from different aquifers.

from south-west monsoon (June–September) and from north-east monsoon (October–December). The mean annual precipitation is about 1250 mm.

The Krishna Delta has varied lithological formations (Figure 2) ranging in age from Archean crystallines to Recent alluvium. Most of the delta region is overlain by the river alluvium (clay, sand and gravel) and beach alluvium (sand). Although at some places, there are rare exposures of Archean Basement, Gollapalli Sandstone and Tertiary Rajahmundry Sandstone. The Archean group of rocks includes Kondalite, Peninsular gneiss, Charnockite, Dharwar and Dolerite dyke, which are found in the extreme north and northwestern part of the delta area. In the rest of the area, a thick pile of Quaternary sediment is found overlying the Archeans. While moving from north to south, the basement depth varies from 27 m to 5 km. The Quaternary sediments are resting mostly over Rajahmundry Sandstones, at some places on Gollapalli Sandstones, and at some places directly on the crystalline basement. The thickness of the sediment varies from 40 to 450 m and is more towards the sea.

The soils of the Krishna Delta are very deep, moderately drained and very dark greyish brown in colour. Hydrogeologically, soils differ in their infiltration capacity in different parts of the delta depending upon the kind of soil. The alluvial soil, which occupies the deltaic plain, is fertile with very high clay content. The soil of the coastal tract is occasionally saline and deep, coarse textured with sandy sub-soils.

The delta comprises sediments of both fluvial and marine origin. The oscillating depositional environments, fluvial to marine, have led to a complex hydrogeological setting with heterogeneous sediments. The palaeochannels with coarse sediments and flood plains with alternations of coarse and finer clastics form the repository of groundwater. Sand dunes and beach ridges also form aquifers of limited extent. The individual permeable sand beds and the thick confining impermeable clay zones constitute a multi-aquifer system in the Krishna Delta. The laterally extensive and lens-shaped bodies of granular zones, and often interconnected layers comprising sand and gravel form the potential shallow, medium and deep aquifers. Groundwater occurs under water table conditions in shallow aquifers at depth up to 30 m bgl, semi-confined to confined conditions in intermediate aquifer at depth 30–60 m bgl and deep aquifer at depth > 60 m bgl. The groundwater level contours (Figure 3) prepared from msl values, indicate recharge from the river to the surrounding region in case of shallow aquifers. In intermediate aquifers, the flow is from north-west to south-east direction, whereas in case of deeper aquifers it is from north-east towards south-west direction.

The exploitation of groundwater is being carried out by means of shallow and deep tubewells. At present, the development of groundwater is confined to an area of about 1600 sq. km, which occupies the river alluvium with fresh water zones. The groundwater quality varies widely both laterally and vertically in the alluvial formations. By and large, the most potential fresh water aquifers occur as isolated pockets and their extent is more in the upper deltaic plain, whereas in the coastal tracts fresh water occurrence is limited to sand dunes and beach ridges at shallow

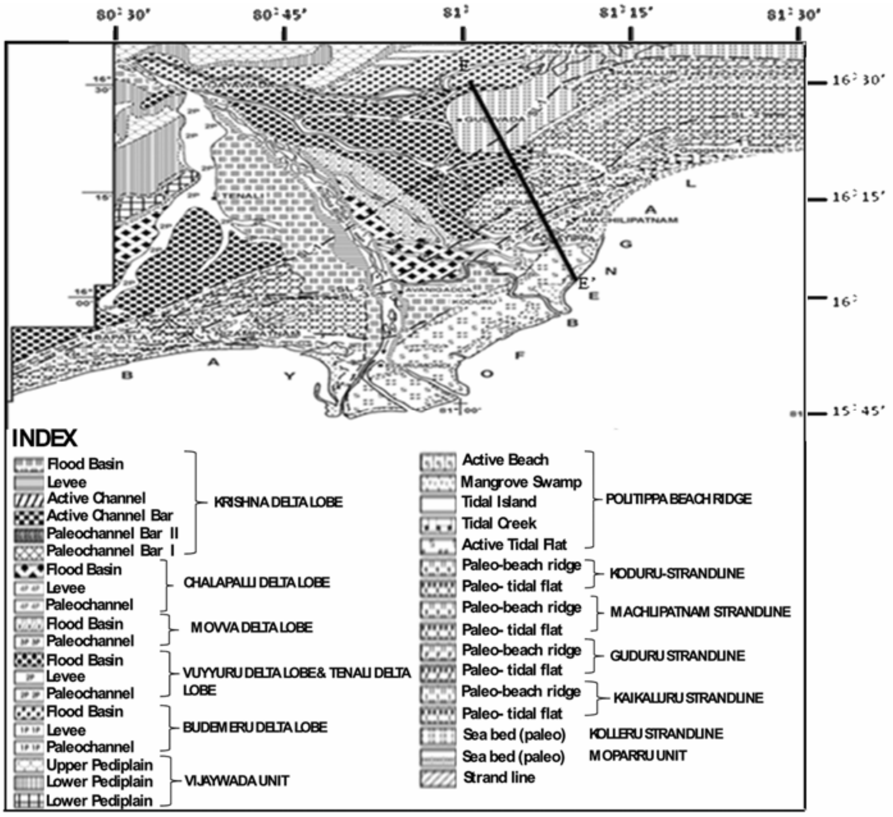

Figure 2. Quaternary geological and geomorphological map of Krishna Delta, AP.

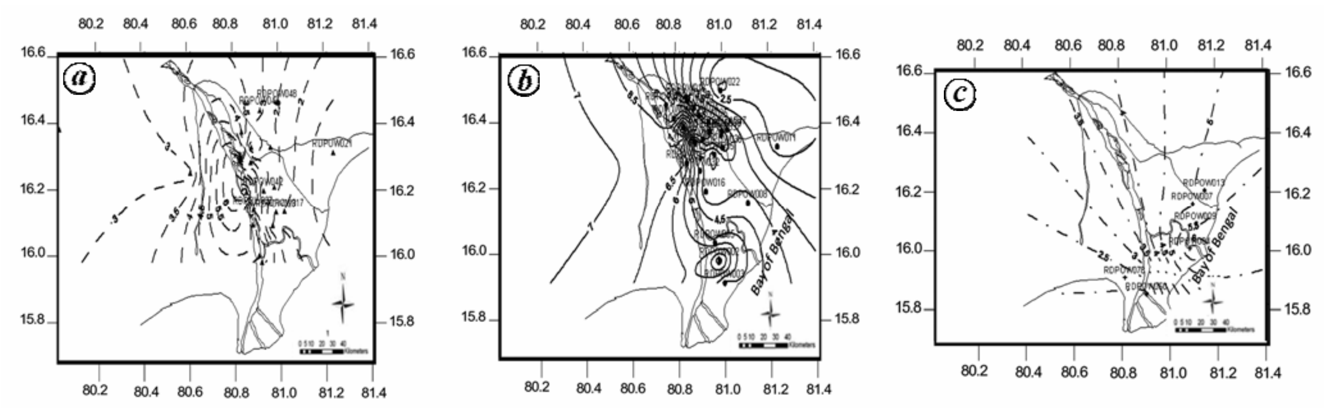

Figure 3. Groundwater level contours of (***a***) shallow; (***b***) intermediate, and (***c***) deep aquifers.

depth up to 14 m. The water quality of deeper aquifers, down to about 200 m, is generally brackish to saline in the deltaic region except in some pockets[1].

Methodology

Isotopes are the atoms of an element with the same atomic number but different atomic weight. Isotopes are presently used in a number of hydrological investigations/ studies. Application of isotopes in hydrology are based on the general concept of 'tracing', in which either intentionally introduced isotopes or naturally occurring (environmental) isotopes are employed.

In this study, environmental isotopes ^{14}C, ^{3}H, D and ^{18}O have been used in conjunction with hydrochemistry including Sr^{2+}, I^-, Br^-, Cl^- and F^- and hydrological data. Sampling of the groundwater from the study area (Figure 1) was carried out in three separate campaigns between November 1999 and April 2002. Groundwater samples were collected from tubewells of shallow, intermediate and deeper depths for which construction details were

Table 1. Details of sites' name and assigned codes (as indicated in various figures) from where water samples were collected during the period from November 1999 to April 2002

Shallow aquifers	Depth < 30 m			Shallow aquifers	Depth < 30 m			Deep aquifers	Depth > 60 m		
Site name	Code	Depth (bgl)	Type	Site name	Code	Depth (bgl)	Type	Site name	Code	Depth (bgl)	Type
Amudrla Lanka[3]	25	11	BW	Praturu	23	8	BW	Bhatiprolu	AG2	104	BW
Avanigedda[2]	31	10	BW	Srikakulam[1]	5	30	HP	Bhatiprolu	AG3	140	BW
Bhatiprolu	AG1	9	BW	Tadepalli	1a	30	HP	Etimoga[3]	J24	61	BW
Chhadlavada[1]	J1	20	BW	Tenali[1]	20	0	Canal	Etimoga	AK2	61	BW
Chinnapulipakka[1]	J19	20	BW	Tenali (West Canal)	A7	13	BW	Gandigunta	10c	90	HP
Chintalapudi[2]	27	11	BW	Tenneru[1]	J31	8	BW	Hamsala Devi[3]	15	80	BW
Devarapalle[1]	J20	9	BW	Vakkala Gedda[1]	40	4	HP	Inampudi[2]	3	75	BW
Duggirala[1]	14	7	HP	Vemuru[1]	21	9	BW	Kammavaripalem	AG4	171	BW
Edlanka[2]	13	10	HP	Vijayawada (DM)[1]	44	11	BW	Kona[3]	51a	100	BW
Edupugallu[1]	39	22	BW	Vijayawada (Singh Nagar)[3]	41	28	BW	Konaphalem[3]	J36	98	BW
Gandigunta[1]	10a	15	BW					Kuchipudi	A6	70	BW
Garuvapalem[1]	18	5	BW	Intermediate Aquifers	Depth > 30 m and < 60 m			Lanka Doddi[3]	43		HP
Guduru	52	3	BW	Bollapadu[1]	24	38	BW	Mollagunta[2]	32	125	AW
Gullapalli[2]	29	6	BW	Chhadlavada	A4	44	BW	Mukteshwarpuram[3]	J34	204	BW
Gunadhala[1]	J17	8	BW	Chitturupu[2]	42	35	BW	Munjuluru[3]	48	65	BW
Iluru[1]	J23	17	BW	Devarapalle	AK8	50	BW	Nagapatnam[2]	9	65	BW
Indupalli[1]	J11	24	BW	Elamaru[1]	8	50	BW	Nizampatnam[3]	J37	128	BW
K.River Near Vekanur[1]	11		River	Emani	A2	31	BW	Pamarru[1]	34	67	HP
Kanakavalli[1]	J21	9	BW	Gandigunta[1]	10b	56	BW	Pamarru	AK5	150	BW
Katuru[1]	J12	8	BW	Iluru[1]	6	28	HP	Pamarru	AK3	200	BW
Kaza[1]	J32	12	BW	Indupalli[1]	J10	43	BW	Pragnam[3]	J35	91	BW
Kothapalem	19	1	BW	Kammanamolu[3]	J25	46	BW	Rajupalem[3]	J6	128	BW
Kothapalu[3]	30	2	BW	Kankipadu	A8	40	BW	Ramapuram[3]	46	70	BW
Kuchipudi[1]	4	10	HP	Kanuru[1]	45	38	BW	Rudravaram	AK6	100	BW
Machhlipattnam-C	J8	0	BW	Katuru[1]	7a	50	TW	Rudravaram	AK7	205	BW
Manchikalapudi	A1	13	BW	Kodali[1]	J16	55	BW	Srikakulam	AK9	80	BW
Movva[2]	J15	29	BW	Machvaram	36	36	BW	Talla Tippa[2]	16	115	BW
Mullapudi[1]	J13	9	BW	Machvaram	AK1	36	BW	Talla Tippa[3]	J4	115	BW
Munjuluru	48a	4	BW	Manikonda[1]	54	50	BW	Tummala[1]	J3	128	BW
Nagavarpadu[1]	50	23	HP	Mudunuru[1]	2	40	HP	Tummala	AG5	140	BW
Nidamanuru[1]	J18	18	BW	Nidamanuru	A9	33	BW	Tummala	AG6	170	BW
Nizampatnam (sea)[3]	26	0	Sea	Pamarru	AK4	50	BW	Uruturu[2]	35	100	BW
Pallipalam River	53	0	Canal	Peda Gottumotu[1]	28	40	BW	Vanukuru[1]	38	60	BW
Patha Majeru[2]	J26	8	BW	Pedana	J28	46	BW				
Pedana[1]	J29	6	BW	Penumatsa[2]	J14	56	BW				
Pedapudi[1]	22	16	BW	Potumarka	AG7	60	BW				
Pedda Kammavari Palem[1]	37	4	BW	Rajupalem	AG8	60	BW				
Pennumarru[1]	J5	10	BW	Rajupalem[3]	J7	58	BW				
Prakasham Barrage[1]	J9	0	BW	Sangameshwaram [2]	33	38	BW				
Prakasham Barrage[1]	J9	0	BW	Tadepalli[1]	1	55	BW				

[1]Fresh water zone; [2]Freshening water zone; [3]Saline water zone; BW, Bore well; HP, Hand pump; AW, Artesian well; DW, Dug well.

available. Samples were also collected from River Krishna and some of its distributaries, from the sea shore (Bay of Bengal) and from the Prakasam Barrage located near Vijayawada. The codes assigned to the various sampling sites are given in Table 1.

The samples collected for stable isotope analyses were analysed at the Isotope Hydrology Laboratory, Bhabha Atomic Research Centre, Mumbai. The samples were analysed for oxygen-18 by CO_2 equilibration method[2] and deuterium by passing through zinc shots[3], using dedicated stable isotope ratio mass spectrometer. The overall analytical error for $\delta^{18}O$ was found to be within ± 0.2‰ and for δD within ± 1.0‰.

Tritium activity was measured in an ultra low level liquid scintillation counter (Quantulus) following electrolytic enrichment. Radiocarbon analyses were carried out using the CO_2 absorption method and Quantulus. The hydrochemical analyses of the samples were carried out at the APGWD Water Quality Lab, Rajahmundry. The hydrochemical analyses were carried out using standard procedures[4]. The overall error of the chemical analyses as determined by replicate measurements and electro-neutrality was found to be less than ± 10%. Information about geohydrological cross-section and groundwater level data was obtained from APGWD.

Results and discussion

Hydrogeological conditions

The hydrogeological cross-sections were prepared for the study area using the data obtained from APGWD. The two-dimensional picture clearly indicates the complex geohydrological settings. The alluvial thickness increases towards the sea coast; typically it is about 20 m thick near Vijaywada and 200 m thick near the sea coast as appeared along cross-section EE′ (Figure 4). The shallow aquifer appears to be more extensive near Vijaywada and found in small patches in southern parts.

The intermediate and deeper aquifers are probably connected to the surface near Prakasam Barrage and at few other places while totally disconnected at other places. The aquifer that may be shallow in the northern part of the delta is deeper in the southern part near the coastal line. The general trend of groundwater at shallow depth is towards sea. However, a reverse trend of groundwater flow exists in the southern part of the delta in Krishna district.

Hydrochemistry

The results of the hydrochemical analyses have been used to classify the water types based on Cl^- concentration, Na^+/Cl^- ratio and major cation–anion concentrations. Based on the above classification procedure, mainly three types of water have been classified as fresh ($Cl^- < 250$ mg/l), freshening ($Cl^- > 250$ mg/l, where the predominant water type is sodium-bicarbonate (Na^+/Cl^- ratio > 1.0)); and saline ($Cl^- > 250$ mg/l), where the water type is sodium-chloride (Na^+/Cl^- ratio < 1.0)). Further, the total dissolved solids (TDS) values have also been used to demarcate the salinity front in the groundwater in different aquifer systems. When the above information corresponding to the shallow aquifer is plotted in the map (Figure 5), the TDS 1.2 g/l appears to form an interface between the saline and freshening zones. From Figure 5, it is also seen that in case of shallow aquifers, the salinity front is confined mainly in the south-east part. It is ~ 19 km in its width along the south-west margin, ~ 35 km wide in the central portion along the River Krishna but narrows on moving from the river to the eastern and western margins. Freshening process is active in the south-west of the delta in areas near the site Garuvupalem (18). This may be due to the recharge by precipitation through the sand bars. Similar process is also active in the southeastern part in a small area near the village Kona (51a). The major cation and anion chemistry, given in Table 2, also shows similar trend as that of TDS.

Freshening water zones of ~ 5 km width are located inland with the margin of saline front that further broadens in the north-east and north-west part of the delta including the area located near the village Kanakvalli (J21), in the eastern part, near the town Kaza (J32) and in the north near the town Indupalli (J11). The fresh water zone of ~ 25 km radius is located in large parts of the delta. This covers the area starting from the downstream of the Prakasam Barrage and most of the area irrigated by the eastern and western Krishna canals. The availability of fresh water in such a large area clearly indicates the recharge to shallow aquifers from the Prakasam Barrage (J9) and the canals of River Krishna. This is reflected by the high tritium values in the shallow groundwater (Figure 6) near the Prakasam Barrage and the village Uruturu (35). The high tritium contour (~ 5 TU) in the central part of the area near the sites Avanigadda (31) and Edlanka (13) indicates the recharge of backwater from River Krishna. The map also indicates a small saline patch of ~ 3 km radius near the city of Vijaywada.

Similar to the shallow aquifers, the salinity front in case of intermediate aquifers lies about 35 km inland from the sea coast (Figure 7). However, the salinity distribution appears to be shifted further inland towards the eastern and western sides. This is apparent from the increase in salinity front by ~ 20 km on its western margins and about 10 km on its eastern margin. Also, a 3–5 km eastern shift of the salinity peak in the central region is visible as compared to the salinity front in the shallow aquifers. The salinity front in the southern parts of the intermediate aquifer is confined by the TDS contour of value 1.2 g/l.

The fresh water zone is located in the northern part of the study area with an increase of ~ 12 km towards the

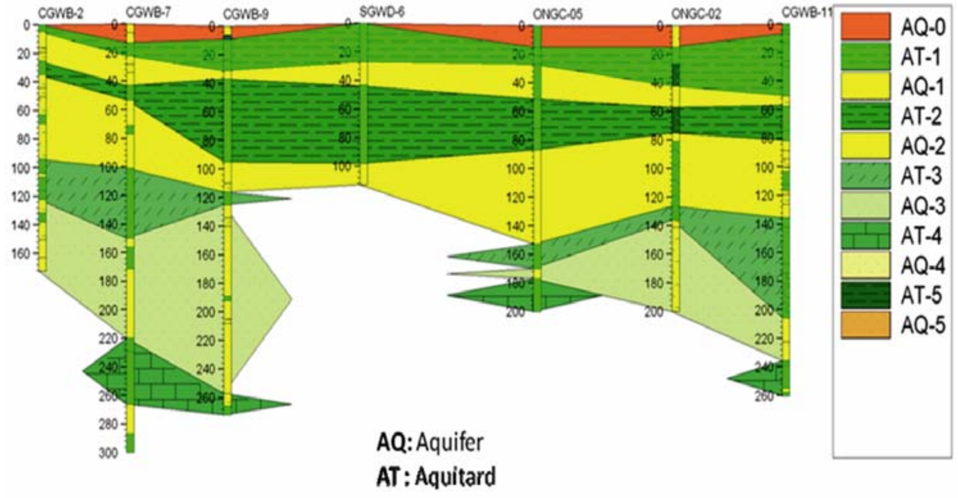

Figure 4. Geological formation along the cross-section EE′ of the study area.

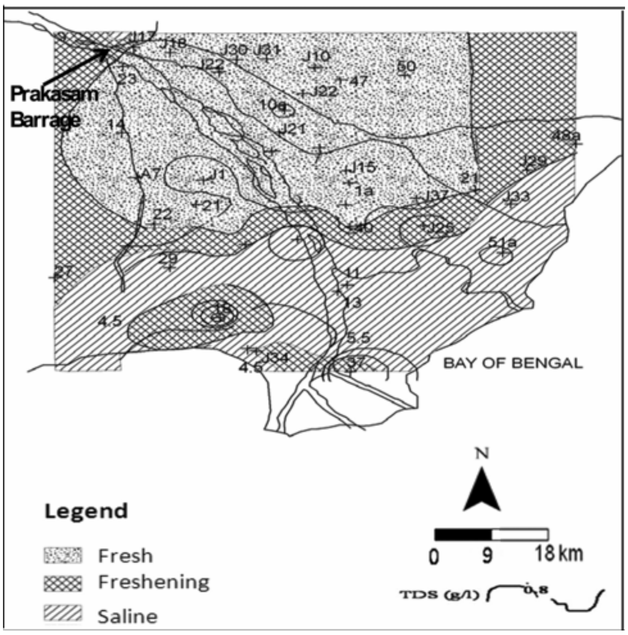

Figure 5. Type of groundwater in aquifers at shallow depths (< 30 m), based on TDS values.

sea coast in the central part. This may be the result of increased recharge from the canal due to its sharp bend near the village Uruturu (35) and the wide flood plain of River Krishna. The tritium values are comparatively higher in area near Prakasam Barrage whereas they are lower near the village Uruturu suggesting the location of recharge zone near the Prakasam Barrage. It further suggests that the intermediate aquifer located near the village Uruturu also receives recharge from the Prakasam Barrage. The groundwater is grossly tritium low (0.3–3) type in the saline part suggesting its non-recent origin, possibly of older origin (discussed in later section). Previous studies[5,6] indicated ingress of sea water, marked by the presence of strand lines of Holocene age in this region. The higher salinity in the intermediate aquifer with respect to the shallow aquifer and the tritium free characteristic of this aquifer suggest its salinity to be due to the influence of palaeo-ingression of the sea. The effective freshening in the intermediate aquifers is visible between the salinity front and the fresh water zone. This is probably due to the existence of a palaeo-channel and the contribution of recharge from canals and River Krishna.

The deeper aquifers located in the area near Prakasam Barrage bear fresh water. The deeper groundwater in the remaining study area is mainly saline type (Figure 8) and compared to the intermediate and shallow aquifers, the salinity front is located closer to the Prakasam Barrage that is surrounded by a freshening water zone in the margins of 10–15 km. A small patch of 5 km radius near the site Tummala (AG 5) also indicates the active freshening process due to the existence of buried channels/artesian conditions in this part of the delta.

The Cl^-/Br^- ratio versus $\delta^{18}O$ cross plot (Figure 9) shows that the deeper aquifers in the southern part of the study area are depleted in Br^- than in the case of typical seawater, which could be due to sorption loss[7] onto the clay, organic debris, etc. Evidences for such increased sorption loss of Br^- with reducing pH conditions are available in literature[8]. The pH values of the groundwater samples with high Cl^-/Br^- ratios (662–835) are less than or about 7.0 indicating a reducing environment[7]. The pH values of groundwater samples with Cl^-/Br^- ratios comparable to that of typical seawater are higher than 7.5. Groundwater samples collected from the same area from where high Cl^-/Br^- ratios are observed also show enrichment in strontium (Table 2). This could be considered as an evidence of longer residence time of groundwater. Hence, the groundwater occurring in the deeper aquifers in the southern most part of the study area and east of the river is isolated and not dynamic.

Table 2. Hydro-chemical data of water samples

Code no.	Depth	EC	CO_3^{2-}	HCO_3^-	SO_4^-	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	Code no.	Depth	CO_3^{2-}	HCO_3^-	SO_4^-	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	CO_3^{2-}
1	55	1406	80	370	153	170	287	5	24	19	26	0	33000	0	160	1538	11100	6400	200	280	607
1a	30	1277	100	330	171	130	270	5	24	15	27	11	1695	0	430	156	280	163	11	96	73
2	40	970	60	190	102	130	178	5	16	15	28	40	1339	0	340	150	200	216	5	32	39
3	75	1500	40	360	107	250	297	4	32	15	29	6	2230	0	490	275	350	288	11	144	44
4	10	1282	0	320	184	170	170	3	64	39	30	2	5460	0	350	359	1601	912	152	136	97
5	30	859	80	170	144	80	185	5	16	5	31	10	2330	40	370	249	470	345	20	48	88
6	28	1285	0	390	84	170	168	47	64	15	32	125	2740	39	194	115	800	523	10	43	44
7a	50	1322	0	255	342	100	192	7	64	29	33	38	1735	0	540	130	230	250	29	48	49
8	50	997	60	250	78	130	208	5	16	5	34	67	1489	39	301	104	290	280	7	32	24
9	65	2050	0	600	155	280	393	12	40	19	35	100	2280	39	427	280	420	463	14	24	44
10	15	1890	0	456	330	180	164	12	144	58	36	36	–	–	–	–	–	–	–	–	–
10a	56	866	0	243	72	120	104	14	32	29	37	4	650	0	155	84	100	60	4	32	34
10b	90	711	0	223	58	80	87	7	32	19	38	60	679	39	184	71	80	49	4	64	24
11	0	660	20	170	81	70	86	8	32	15	39	22	880	0	233	96	120	154	3	32	10
12	0	14380	0	370	233	4800	2381	100	136	404	40	4	1391	0	369	201	170	195	36	32	49
13	10	1675	20	300	70	370	202	30	48	63	41	28	3180	0	291	195	870	514	22	80	78
14	7	1495	0	370	219	200	204	24	40	58	42	35	2140	0	359	149	470	402	14	40	29
15	80	15260	0	370	1596	4500	2090	110	544	549	43	70	4330	0	446	192	1160	767	8	72	83
16	115	2820	0	200	274	776	519	10	144	10	44	11	1163	0	262	117	180	131	4	64	34
17	90	18360	40	420	1460	5300	2500	100	200	802	45	38	596	0	165	70	70	83	4	32	10
18	0	786	40	170	80	108	130	3	24	15	46	70	4870	78	291	188	1440	744	9	152	126
20	0	456	0	160	59	40	40	3	32	19	47	16	974	100	200	136	100	162	7	36	19
21	9	816	0	280	66	90	107	8	48	15	48	65	5300	0	359	455	1400	851	23	112	141
22	16	480	0	160	59	50	47	2	32	19	50	23	1440	0	369	205	150	122	64	40	68
23	8	545	0	180	64	60	45	2	40	24	51	100	8900	0	155	266	3160	931	23	464	399
24	38	966	0	130	216	110	105	16	64	19	53	–	1040	0	270	115	160	90	8	80	39
25	11	4820	0	420	497	1210	386	20	320	219	54	50	850	40	240	56	100	159	2	16	10

(*Contd.*)

Table 2. (*Contd.*)

Code No.	Depth	EC	HCO_3^-	SO_4^-	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	Li^+	Si	Sr^{2+}	Fl^-	I^-
J1	20	1192	380	197	56	232	1	22	33	0	21	0	1.52	0.0128
J2	10	1660	0	165	466	–	–	–	–	–	–	–	1.29	0.0056
J3	128	1080	280	192	78	171	4	59	96	0	9.16	0.95	0.87	0.0105
J4	115	3880	230	174	1113	556	15	86	110	0	9.67	1.4	0.79	0.0317
J5	10	1478	380	152	191	204	2	42	64	0	15.2	0.16	1.71	0.0033
J6	128	3530	270	107	1015	504	15	81	133	0	10.1	1.66	0.79	0.0354
J7	58	35000	280	1272	11306	1377	91	1519	3531	0.15	19.8	12.1	0.63	0.0922
J8	5	37400	144	1274	12233	4370	348	479	2500	0.01	2.58	8.73	1.96	0.0453
J9	18	528	190	58	34	59	2	41	64	0	6.53	0.28	2.28	0.0339
J10	43	676	260	37	62	73	4	28	35	0	11.4	0	2.08	0.0037
J11	24	876	315	65	79	124	5	29	31	0	12.3	0	0.83	0.0044
J12	8	1097	370	61	129	64	47	76	66	0	23	0.15	0.65	0.0339
J13	9	1252	420	88	134	109	5	55	75	0	11.5	0	0.96	0.005
J14	56	1524	460	141	169	286	3	27	23	0	15.6	0	1.1	0.0058
J15	29	1556	600	42	172	304	4	14	24	0	25.2	0	1.83	0.0161
J16	55	1104	480	46	78	237	2	4	7	0	17.9	0	2.46	0.0095
J17	8	1183	380	47	164	92	0	107	73	0	15.2	0.63	1.25	0.0346
J18	18	782	300	58	60	62	0	59	57	0	15.7	0.12	1.31	0.0305
J19	20	911	260	81	112	53	139	24	30	0	18.5	0	1.2	0.0026
J20	9	822	250	34	121	89	3	38	47	0	16.8	0	1.42	0.0035
J21	9	1090	375	84	106	77	3	56	113	0	21.6	0.31	1.45	0.0021
J22	12	1527	390	109	234	192	6	76	56	0	14.1	0.35	1.5	0.002
J23	17	964	400	75	54	68	6	84	67	0	16.7	0.2	1.85	0.016
J24	61	39850	280	1307	12999	4586	214	1013	2785	0.35	38.1	11.3	0.66	0.104
J25	46	40100	250	1311	13102	4208	224	1495	3016	0	22.4	11.7	0.59	0.183
J26	8	1663	430	128	245	194	7	72	116	0	15.1	0.08	1.38	0.0135
J27	7	2510	–	–	–	–	–	–	–	–	–	–	–	–
J28	46	–	0	921	1023	0	0	224	448	0	15.2	3.16	1.22	0.0546
J29	6	1047	0	0	371	53	50	94	68	–	–	–	–	–
J30	9	619	243	57	36	37	8	55	41	0	14	0.02	1.92	0.0342
J31	8	922	320	112	58	50	1	109	73	0	16	0.46	1.59	0.0026
J32	12	1150	360	36	172	91	22	57	95	0	25.6	0.04	1.64	0.0044
J33	3	3600	0	335	1028	–	–	–	–	–	–	–	2.73	0.0935
J34	204	6660	220	0	2233	748	22	345	344	0	14.1	5.9	–	–
J35	91	7410	330	0	2435	1119	20	144	301	0	13.5	2.73	–	–
J36	98	8740	320	0	2912	1288	23	191	416	0	14	3.74	–	–
J37	128	10070	380	0	3349	1375	25	281	535	0	13.2	5.83	–	–

Source: Andhra Pradesh Groundwater Department.

Table 3. Isotopic data of environmental tritium (TU), $\delta^{18}O$ (‰), δD (‰) and C-14 ages (uncorrected in years) of water samples

	TU	$\delta^{18}O$	δD	C–14		TU	$\delta^{18}O$	δD	C–14		TU	$\delta^{18}O$	δD	C–14
Code	Shallow aquifers				Code	Shallow aquifers				Code	Intermediate aquifers			
30	5.7	–	–	–	J23	2.2	–1.6	–	–	J14	–	–0.9	0.7	–
37	5.1	–	–	–	J18	–	–1	–	–	J7	0.5	–1.1	–6.1	–
40	3.8	–0.4	–5	–	J1	0.4	–2.3	–5.3	–					
18	5.1	–	–	–	J19	–	–3.2	–	–		Deep aquifers			
29	4.2	–1.4	–9.7	–	39	5.4	–0.7	–	–					
14	6.3	–0.8	–6.5	–	50	0.4	–3.5	–15.1	–	38	5.3	–0.8	–	–
J17	3.2	–1.4	–4.5	–	J11	0	–0.9	–2.9	–	J24	0	–0.1	–	–
J26	–	0.5	–	–	6	5.3	–	–	–	9	0	–1.9	–5	–
J31	1.2	–1.7	–	–	J15	–	–2	–7.4	–	48	1	–1.7	–13	13,100
J12	2.8	–0.9	–	–	1a	2.6	–1.9	–6.6	–	34	0.8	–1.7	–	–
23	5.6	–	–	–	5	0	–2.3	–5.5	–	43	0.3	–1.5	–	2,580
J13	–	–0.5	1.2	–		Intermediate aquifers				46	0	–3	–17	26,460
J20	0	–1.5	–	–	5	0	–2.3	–5.5	–	3	0.8	–1.8	–4.3	–
21	4.1	–	–	–	42	0.1	–	–	–	15	0.2	–1.8	–3.7	–
J21	–	–1.5	–	–	24	4.4	–0.8	–6	–	10c	0.5	–2.1	–6.4	–
4	7.9	–1.2	–2.1	–	33	0.5	–0.3	–1.3	–	J35	–	–1	–	–
13	6.1	–	–	–	45	3.8	–0.8	–	–	J36	–	–2.3	–	–
31	7.4	–	–	–	2	0	–1.8	–3.2	–	35	0.8	–1.4	–	5,860
J5	3	–0.9	0.6	–	28	0.1	–1.1	–6.5	–	51	–	–1.4	–7.7	–
25	3.7	–	–	–	J10	0	–1.8	–5.7	–	16	1.3	–2	–7.7	21,930
27	4	–	–	–	J25	0	–	–	–	J4	0.5	–2.3	–7.3	–
44	5	–	–	–	7a	4.2	–1.5	–7	–	32	0	–1.8	–9.5	11,770
J22	–	–1	–	–	8	1	–2.2	–5	–	J3	0.9	–1.9	–	–
J32	3.4	–	–	–	J16	0	–2.3	–9.2	–	J6	0.3	–2.3	–8	–
10a	0.2	–1.4	–6.9	–	1	0.7	–2.2	–5.6	–	J37	–	–3.1	–	–
22	4.8	–0.6	–4.8	–	10b	0	–1.8	–3.6	–	J34	–	–1.9	–	–

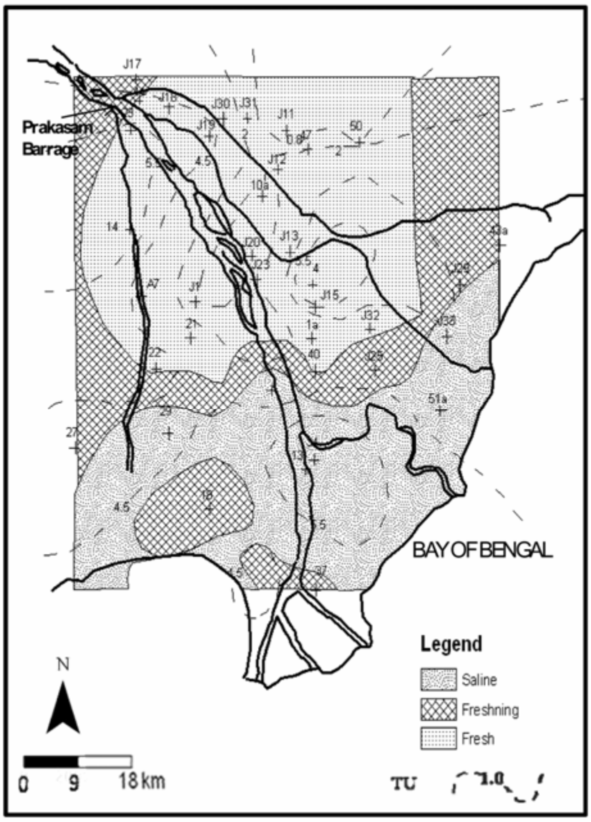

Figure 6. Environmental tritium composition in groundwater at shallow depths (< 30 m).

Environmental tritium

As a thumb rule, the presence of environmental tritium in groundwater indicates replenishment by meteoric water < 50 years old. Therefore, in the present study, this tool has been effectively used to identify the zones influenced by recent precipitation or present day seawater ingress. The distribution of environmental tritium concentration in the shallow aquifer (Figure 6, Table 3) supports the observation made from hydrochemical data that the canal network contributes significantly to the refreshening of the saline groundwater. From the tritium pattern, it is evident that the Prakasam Barrage and the canal network particularly in the area near Kaza in the eastern delta are major sources of recharge to groundwater. The perched shallow aquifers in the saline zone, along the river and its nearby area in the south of the village Avanigadda, show relatively higher tritium contents which indicate modern recharge by surface water sources and rainfall. In the intermediate aquifer (Figure 7, Table 3) also the general tritium distribution pattern is same as in the shallow aquifers, but the maximum tritium values observed are close to 3.0 TU near the Prakasam Barrage (in the area between the villages Kanuru and Katuru). Similarly, in deeper aquifers (Figure 8, Table 3), the tritium is detectable only in the area close to the Prakasam Barrage. High tritium in both intermediate and deeper aquifers near Prakasam Barrage suggests that the barrage is acting as an active recharge source to the groundwater. The absence of tritium in deeper aquifer in general and in the area close to the coast in particular indicates that the deeper aquifers do not have any active connection with the Bay of Bengal or with shallow aquifers.

Radiocarbon

The inferences drawn from hydrochemistry and environmental tritium analyses are of limited use, in a strict sense, until it is verified whether the salinity in the deeper aquifer system is due to the present day sea water intrusion or palaeo-geographical conditions. The radiocarbon dating of groundwater can give decisive clues in this aspect. The radiocarbon dating carried out for tritium free groundwater in the delta region show in general uncorrected ^{14}C ages in the range of 2500–37,000 a BP (Figure 10, Table 3) and these in general show an increasing trend towards the coast. Except for the extreme southern reaches, the radiocarbon ages in the remaining part of the study area increase from north to the coastline from ~ 3000 a BP to 13,000 a BP. In the extreme southern reaches, comparatively higher ages in the range 22,000–37,000 a BP were obtained. The sample that was collected from Ramapuram (46 DA), a site located in the adjacent Budameru River Basin and not connected with the deltaic aquifer systems, also exhibited uncorrected radiocarbon age of 26,452 a BP. Thus, deeper aquifers with ages

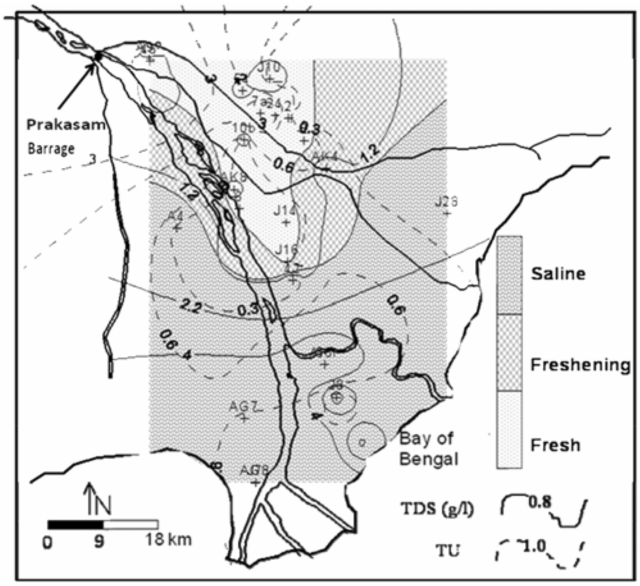

Figure 7. Type of groundwater in aquifers at intermediate depths (30–60 m) based on TDS values. The contours of environmental tritium composition are also shown.

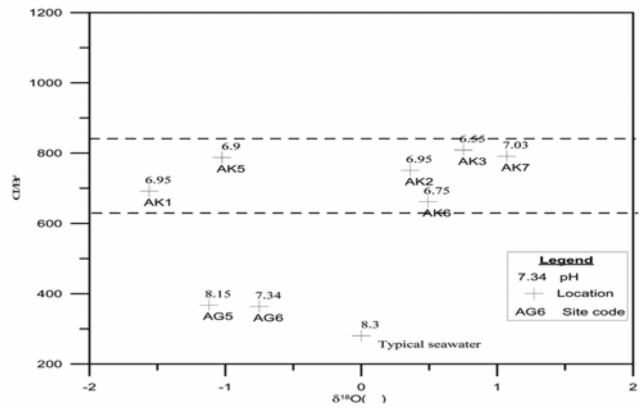

Figure 9. Variations in Cl^{-}/Br^{-} ratios in the groundwater samples from deep aquifers (> 60 m).

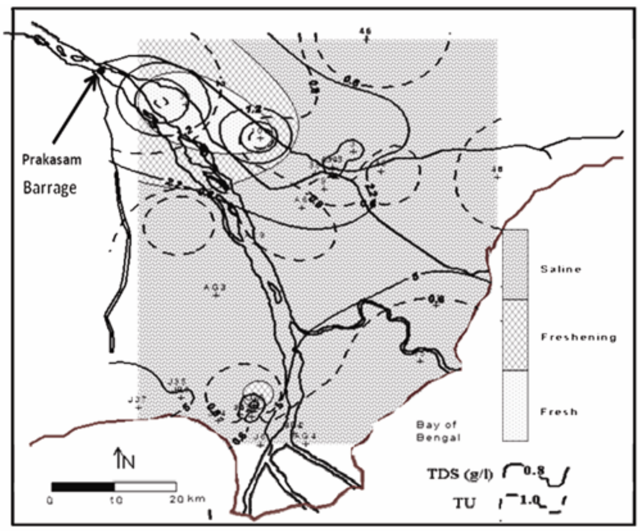

Figure 8. Type of groundwater in aquifers at deeper depths (> 60 m), based on TDS values. The contours of environmental tritium composition are also shown.

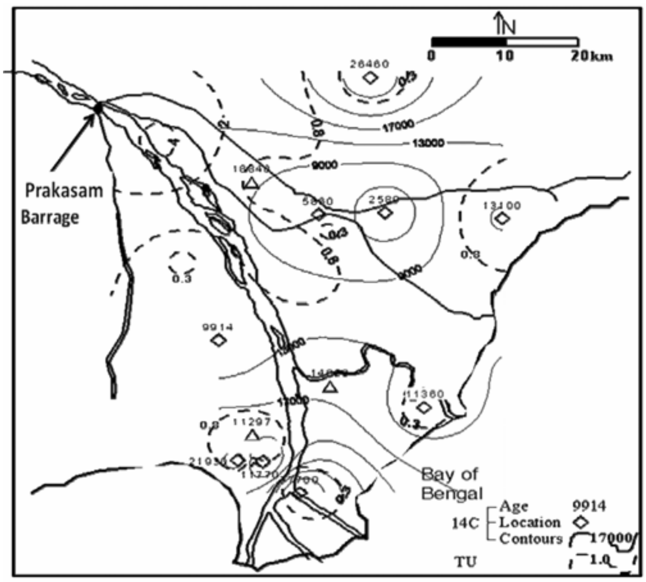

Figure 10. Environmental tritium and radiocarbon ages (uncorrected) contours of groundwater at deeper depth (> 60 m) in the Krishna Delta.

younger than 13,000 a BP years suggest dilution due to mixing with modern water recharged by the canals/ palaeo-channels and the undiluted old groundwater are older than 30,000 a BP.

Stable isotopes

The $\delta^{18}O$–δD cross plot (Figure 11, Table 3) exhibits the complexity of the hydrogeological scenario in the study area. It also includes information on the extent of salinity of each sample.

At least three different groups could be discerned from the plot. They are (i) samples that plot along the Global Meteoric Water Line (GMWL); (ii) samples that plot along the evaporation line with slope of 6, and (iii) samples that exhibit high $\delta^{18}O$ enrichment and do not follow any definite trend.

The samples that plot along the GMWL include low salinity samples (TDS < 1.0 g/l) from shallow and intermediate aquifers in addition to the brackish ones (TDS = 1.0–10 g/l) from deeper aquifers. The water type of these brackish samples is sodium-bicarbonate type except for location no. 15 (Hamsaladevi) that is situated close to a distributary of River Krishna having backwater effect. The brackish water samples from the deep aquifers falling on the GMWL clearly indicate a meteoric origin, and the salinity may be due to leaching of the marine clay. Most of the samples that plot about the evaporation line have low salinity (TDS < 1.2 g/l) and indicate evaporative enrichment during the process of recharge to groundwater as irrigation return flow. The site Pedda Gottumottu (28) located in Krishna Delta bears uncorrected ^{14}C age of 37,700 a BP whereas the site Ramapuram (46) located in the adjacent Budmeru Basin exhibited 26,000 a BP. Therefore, it may be concluded that the deeper aquifers are the trapped palaeo-seawater. The samples collected from the wells Katuru (J12) SA,

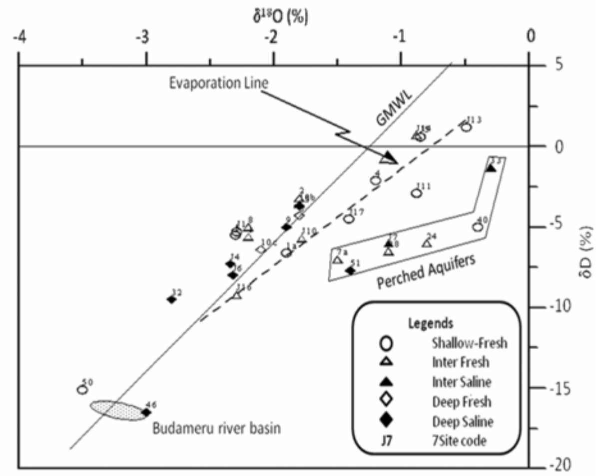

Figure 11. $\delta^{18}O$–δD plot for the groundwater belonging to Krishna Delta. Isotopic values of groundwater from delta in Budameru River Basin are also shown for reference.

Pedda Gottumottu (28) IA, Bollapadu (24) IA and Vakkala Gadda (40) SA exhibit high enrichment of $\delta^{18}O$ but show low salinity. The $\delta^{18}O$ distribution pattern within the shallow aquifers clearly shows that Katuru (J12) SA and Bollapdu (24) IA fall in an isolated patch in the northern part of the study area, whereas Vakkala Gadda (40) SA and Pedda Gottumottu (28) IA fall within the isolated patch in the southern part of the study area. These two aquifers are perched ones and are not associated with the general aquifer systems in the Krishna Delta. One of the most striking features is that the enriched samples from these isolated aquifers described above show a trend with $\delta^{18}O$–δD slope of about 2 that may be because high evaporative enrichment as the recharge takes place at a slow rate through a 6 m thick clay layer. Similarly, site Kona (51a) DA, Rajupalem (J7) IA and Sangameswaram (33) IA exhibit enrichment of $\delta^{18}O$ and high salinity. Rajupalem (J7) IA is located in the southwestern part of the delta near the coast whereas Kona (51a) DA is located in the western part. Sangameswarm (IA 33) is also located in the eastern part of the delta near the coast and Ramapuram (DA 46) is located in the Budameru Basin and is far away from the coast (towards a saline lake side). The radiocarbon ages reflect very old waters in all the four cases. Therefore, in spite of the fact that these four sites if connected will fall on the seawater mixing line, it can be concluded that these sites are isolated geo-hydrologically and their salinity is due to palaeo-geographical conditions that were influenced by the sea in the past. The enrichment in $\delta^{18}O$ values might be the result of evaporative enrichment due to slow recharge through a thick clay layer in the past.

The TDS values, tritium and radiocarbon ages along with stable isotopes (^{18}O and D) composition clearly indicate that the Prakasam Barrage is the major recharge for the aquifers lying close to the marginal alluvium near Vijayawada. The second important area of recharge to groundwater appears to be the north-central portion of the study area and the recharge source is the seepage from the canal network laid on the palaeo-channels.

The information on the aquifer–aquifer interconnection is vital for proper management of groundwater resources in the study area. Similarity in the salinity and tritium pattern indicates that the shallow and intermediate aquifers in the Krishna district have good interconnection and is reflected in the $\delta^{18}O$–δD cross plot. However, in Guntur District, the shallow aquifers are restricted to the northern part only and the thickness of the overlying clay layer increases towards south. Therefore, the deeper aquifers in the south are in fact continuous from north with the recharge area lying near Vijayawada. The $\delta^{18}O$–δD cross plot also shows the presence of perched aquifers both in the northern and southern parts of Krishna district. The groundwater contours indicate a negative pressure head in the southern perched aquifer. The effect of this is also seen as high salinity in the groundwater in this part. This fact proves the absence of connectivity to the sea. Further, the enrichment of $\delta^{18}O$ indicates percolation at a very slow rate through the overlying 6 m thick clay soil. The evapotranspiration index based on Cl^- values in groundwater and rainwater[9,10] indicates that only 5% of annual rainfall reaches the saturated zone.

The salinity distribution in all the three aquifer systems in the study area indicates the salinity is low, implying that the water in general is potable and brackish in certain pockets. The exceptions are the deeper aquifer system at Pammarru (34) (100–200 m bgl) and the area near the river mouth at Etimoga (J24) (60–100 m bgl). The salinity in the groundwater in the study area is most probably due to the palaeo-geographic conditions. The presence of sea appears to have been up to Pamarru in earlier times. This is evidenced by the presence of sand bars that have been mapped by photo-geomorphic interpretations[5,6], radiocarbon dating of fossil shells, peat/wood and calcrete materials recovered from beach ridges[11] and by thermoluminescence dating of beach ridge sands[12] and interpretation of stages in the progradation. The present land-use practices and canal irrigation have lead to freshening of the aquifers; as a result the salinity is receeding. Salinity distribution is related to the strand lines and the salinity is higher in the area south of the fourth strand line in comparison to the area north of it. This establishes that with increased use of fresh water and recharge to groundwater, the salinity in shallow and intermediate depths in different parts of the delta would also reduce.

The effects of anthropogenic activities such as prawn culture involving ponding of highly saline waters in large coastal tracts is not reflected in this study due to want of sampling points. Most of these prawn culture activities are located in the area underlain by very thick clay layer as high as 100 m at some locations, therefore, there are no shallow wells in these areas. However, the long-term effect of this activity has to be studied in detail.

Conclusion

The groundwater condition in the multi-aquifer system of the Krishna River Delta using an integrated approach reveals the following:

- There is no present day seawater intrusion in any of the aquifer systems in the study area. The existing salinity that ranges from slight to moderate brackish quality in shallower and intermediate depths and highly brackish to saline quality in deeper depths in certain locations, is due to palaeo-geographic conditions, when the sea coast was more inland than at present.
- If a TDS value of 1.0 g/l is considered as salinity front, then at depths greater than 60 m bgl, the front is at present about 50 km away from the present day sea coast. The front is about 30–35 km from the coast at intermediate depths (30–60 m bgl) and is about 25–30 km at shallower depths (less than 30 m bgl).
- The major recharge areas lie in the northern part of the study area near the Prakasam Barrage and the area near Kaza (J32; SA) where the canal network systems are intensively used for irrigation.
- The increased canal water irrigation has led to freshening of the groundwater that was saline earlier due to the presence of sea. The canal water irrigation must be intensified and extended to the southernmost part of the study area characterized by isolated aquifers.

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