Evaluation of seawater intrusions in left bank sediments of coastal district Thatta, Sindh, Pakistan.

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Abstract Due to insufficient fresh water flow downstream the Kotri barrage built on river Indus and very meager rainfall in the area, seawater from Arabian sea has penetrated into coastal sediments of southern Sindh, Pakistan. And due to large mixing of seawater into groundwater, the coastal aquifer system has been polluted at alarming level and environment & ecosystem have been damaged in the region.

To evaluate the extent of seawater intrusions in the area, three techniques isotopic, chemical analysis and geophysical survey were applied. The water sampling network based on installation of six piezometers, two each at Sujawal, Jati and Shah Bundar area was established. Water samples were collected upto the depth of eighty feet from the ground surface through piezometers to perform isotopic analysis for determination of Oxygen 18 & Deuterium isotopes (18O & 2H) and chemical analysis for determination of Chloride & Bicarbonate ions ratio. In addition to this drill log of all piezometers and surface geophysical resistivity method were also used to compare and correlate the results of seawater intrusions and their variations during Dry and Wet seasons of the years 2002 2003 & 2003 2004.

Permeability values of sand samples collected while drilling and installing piezometers at different depths were measured in the laboratory by various methods. Permeability values of sand (aquifer) can be classified as Low. The isotopic and geochemical evaluation in groundwater samples supplemented by geophysical method reveals the presence of a significant contribution of seawater intrusions into groundwater system during Dry & Wet seasons.

During the year 2002 2003 the contribution of seawater into groundwater has been measured through isotopes of oxygen & hydrogen was upto the extent of minimum (18%) at Sujawal which is about 75 km away from the coast and maximum (92%) at Shah Bundar which is on the coast. During the year 2003 2004 the contribution of seawater into groundwater was lowered upto the extent of minimum (17%) at Sujawal and maximum (77%) at Shah Bundar, due to release of substantial amount (about 20 MAF) freshwater downstream below the Kotri barrage.

Index Terms **Key words: Intrusion of seawater, Pakistan, Thatta**

I. Introduction

Indus river is a lifeline of Pakistan. During the 18th century, one of the largest irrigation system of the world was developed to utilize the water of the river Indus. Subsequently, construction of dams, barrages, channels upstream areas of Pakistan has reduced water flow downstream into delta region. Further scanty rainfall and negligible discharge of Indus river water below the Kotri barrage, which is about 175 km from the coast, has worsened the eco system & environment of the region due to seawater intrusions in coastal district Thatta of Pakistan.

The Ghijben-Herzberg relationship of Fresh-Saltwater equilibrium [1] requires that the water table or the piezometric surface lies above the sea level and slopes downward towards the sea. Without these conditions, seawater will advance directly inland. In coastal areas of district Thatta, the water table gradient has reversed its slope, which is towards the land now. Hence seawater has intruded into the coastal sediments and has polluted the aquifer system of the area.

To detect and to investigate the seasonal changes in seawater intrusions on the left bank of river Indus, six piezometers were installed in three different towns of district Thatta, two each at Sujawal (Latitude:24º 36′, Longitude:68º 05′, Elevation:7m), Jati (Latitude:24º 20′, Longitude:68º 16′, Elevation:5m) and at Shah Bundar (Latitude:24º 10′ , Longitude:47º 54′, Elevation:2m) to conduct chemical and isotope analysis of groundwater samples obtained from different depths. As the electrical conductivity increases with the salt content, so it was also determined for all groundwater samples obtained from all six piezometers

II. Methods of detection of seawater intrusions

In the present study the chemical, isotopic and geophysical electrical resistivity methods were applied to detect seawater intrusions. Porosity & Permeability of the sand recovered while installing the piezometers were also determined. Geo-electric data obtained in field have been correlated and compared to borehole logs to identify aquifer(s) at different piezometers sites

A. Chemical method

Chloride (Cl) is a dominant ion of seawater and Bicarbonate (HCO_3) is usually the most abundant ion in groundwater. There is such a large difference between the proportions of Chloride-Bicarbonate ions ratio in groundwater and in seawater, that the ratio between these two ions is a useful index of the presence of the seawater into groundwater. If this ratio of Chloride & Bicarbonate ions (Cl / HCO_3) exceeds by 2/3 then it is indicative of seawater intrusions [2]. Tables I-IV present a view of EC, TDS, Chloride, Bicarbonate and the ions ratio (Cl/HCO3) in groundwater samples in coastal aquifer system during Wet and Dry seasons.

TABLE I-CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES COLLECTED IN DECEMBER 2002.
WET SEASON (PHASE-I).

Sample Code	EC μS/cm	TDS (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	Cl/HCO_3 (Milliequivalent)
SL N 04+	25600	16384	8000	312	21.1
SL N 12	16740	10714	4424	374	9.7
SL N 21	27300	17472	8269	312	21.8
SL S 04	3020	1933	102	280	0.29
SL S 12	1247	7891	3871	312	10.2
SL S 21	13970	8941	4166	374	9.1
JI N 06	65700	42048	25428	249	83.7
JI N 11	56600	36224	19738	249	65.0
JI N 23	64700	41408	23345	312	29.4
JI S 06	40100	25664	12660	249	41.7
JI S 12	55800	35712	20130	280	58.9
JI S 14	53400	34176	18445	218	69.4
SB S 05	70600	45184	28241	249	92.9
SB S 14	70900	45376	28978	249	95.4

Table II
Chemical Analysis of groundwater samples collected in June 2003.
Dry season (Phase-II)

Sample Code	EC μS/cm	TDS (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	Cl/HCO_3 (Milliequivalent)
SL-N-04+	8300	5312	1985	271	6.0
SL-N-12	16750	10720	3970	283	11.5
SL-N-21	38200	24448	10067	215	38.5
SL-S-04	28600	18304	18224	243	61.5
SL-S-12	35600	22784	10209	300	27.9
SL-S-21	34200	21888	9713	283	28.2
JI-N-06	63700	40768	14747	161	75.2
JI-N-11	64200	41088	15739	164	78.9
JI-N-23	63800	70832	18575	164	93.2
JI-S-06	54100	34624	14463	187	63.6
JI-S-12	54000	34560	14605	158	75.78
JI-S-14	54300	34752	14889	186	65.5
SB-S-05	65000	41600	20419	164	102.5
SB-S-14	64600	41344	282	170	94.0

SL = Sujawal JI = Jati SB = Shah Bandar N = North S=South

TABLE III
CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES COLLECTED IN NOVEMBER 2003. WET SEASON (PHASE-III).

Sample Code	EC μS/cm	TDS (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	Cl/HCO_3 (milliequivalent)
SL-N-04+	23200	14848	7797	354	18.0
SL-N-12	21400	13696	6381	240	21.8
SL-N-21	30200	19328	9855	288	28.0
SL-S-04	13860	8870	4697	264	14.5
SL-S-12	14700	9408	5104	329	12.7
SL-S-21	21600	13824	7444	180	33.9
JI-N-06	23800	15232	8644	259	27.3
JI-N-11	51100	32704	19639	247	65.2
JI-N-23	60100	38464	23893	269	72.9
JI-S-06	48200	30848	17157	240	58.7
JI-S-12	33800	21632	11627	219	43.5
JI-S-14	37300	23872	12903	305	34.7
SB-S-05	78200	50048	33748	328	84 3

TABLE IV
CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES COLLECTED IN MAY 2004.
DRY SEASON (PHASE-IV)

Sample Code	EC µS/cm	TDS (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	Cl/HCO_3 (milliequivalent)
SL-N-04+	13060	8358	3332	351	7.8
SL-N-12	15600	9984	4199	343	10.0
SL-N-21	42500	27200	13895	252	45.2
SL-S-04	11870	7597	3466	210	13.5
SL-S-12	9820	6285	2766	203	11.1
SL-S-21	15250	9760	4765	217	17.9
JI-N-06	37700	24128	12563	259	39.7
JI-S-06	47300	30272	14795	247	49.1
JI-S-12	41500	26560	12829	238	7.9
JI-S-14	45000	28800	15162	217	57.2
SB-S-05	69100	44224	26658	228	96.0
SB-S-14	68700	43968	25311	210	98.7

TABLE V
ISOTOPIC ANALYSIS OF GROUNDWATER SAMPLES COLLECTED IN DECEMBER 2002. WET SEASON (PHASE-I).

Sample Code / Depth	δ^2H ‰ (V-SMOW)	$\delta^{18}O$ ‰ (V-SMOW)	Percent Contribution from Arabian Seawater (Based on Hydrogen Isotope ^2H)	Percent Contribution from Arabian Seawater (Based on Oxygen Isotope ^{18}O)
SL-N-04+	-47.90	-6.47	25.17	27.19
SL-N-12	-46.17	-6.31	27.32	28.46
SL-N-21	-45.21	-5.91	28.51	31.66
SL-S-04	-58.50	-7.52	12.01	18.81
SL-S-12	-56.29	-7.24	14.75	21.05
SL-S-21	-54.24	-6.92	17.30	23.60
JI-N-06	-37.47	-4.43	38.04	44.25
JI-N-11	-37.17	-4.00	38.49	46.88
JI-N-23	-36.91	-4.30	38.81	44.49
JI-S-06	-30.59	-3.74	46.66	48.96
JI-S-12	-40.56	-4.84	34.28	43.06
JI-S-14	-37.72	-4.64	37.81	41.78
SB-S-05	1.67	1.75	86.7	92.7
SB-S-14	-4.05	0.53	79.6	83

TABLE VI
ISOTOPIC ANALYSIS OF GROUNDWATER SAMPLES COLLECTED IN JUNE 2003.DRY SEASON (PHASE-II).

Sample Code / Depth	δ^2H ‰ (V-SMOW)	$\delta^{18}O$ ‰ (V-SMOW)	Percent Contribution from Arabian Seawater (Based on Hydrogen Isotope ^2H)	Percent Contribution from Arabian Seawater (Based on Oxygen Isotope ^{18}O)
SL-N-4+	-47.17	-6.19	26.07	29.42
SL-N-12	-51.07	-6.40	21.23	27.75
SL-N-21	-43.95	-5.74	30.07	33.01
SL-S-04	-45.86	-5.94	27.70	31.41
SL-S-12	-47.30	-5.93	25.91	31.49
SL-S-21	-43.16	-5.85	31.05	32.13
JI-N-06	-38.21	-4.06	37.20	46.41
JI-N-11	-31.22	-4.02	45.87	46.73
JI-N-23	-39.39	-4.29	35.73	44.57
JI-S-06	-35.71	-4.42	40.30	43.54
JI-S-12	-43.46	-4.87	30.63	38.43
JI-S-14	-43.82	-4.89	30.23	39.79
SB-S-05	4.42	0.24	90.11	80.7
SB S 14	5 79	0 25	77 44	76 79

TABLE VII
ISOTOPIC ANALYSIS OF GROUNDWATER SAMPLES COLLECTED IN NOVEMBER 2003.
WET SEASON (PHASE-III

Sample Code / Depth	*δ^2H ‰ (V-SMOW)*	*$\delta^{18}O$ ‰ (V-SMOW)*	*Percent Contribution from Arabian Seawater (Based on Hydrogen Isotope ^2H)*	*Percent Contribution from Arabian Seawater (Based on Oxygen Isotope ^{18}O)*
SL-N-4+	**-41.41**	**-5.98**	**27.01**	**29.39**
SL-N-12	**-47.45**	**-6.02**	**19.19**	**29.05**
SL-N-21	**-38.18**	**-5.73**	**48.85**	**31.51**
SL-S-04	**-53.20**	**-7.37**	**11.75**	**17.61**
SL-S-12	**-54.16**	**-7.42**	**10.50**	**17.19**
SL-S-21	**-50.57**	**-6.82**	**15.15**	**22.30**
JI-N-06	**-23.61**	**-2.56**	**50.04**	**58.39**
JI-N-11	**-35.26**	**-3.98**	**34.97**	**46.36**
JI-N-23	**-28.56**	**-4.0**	**43.64**	**46.19**
JI-S-06	**-27.42**	**-4.26**	**45.11**	**43.98**
JI-S-12	**-24.12**	**-3.55**	**49.38**	**50.0**
JI-S-14	**-21.92**	**-3.4**	**52.23**	**51.27**
SB-S-05	**-8.68**	**-0.52**	**69.37**	**75.67**
SB-S-14	**-8.52**	**-0.34**	**69.57**	**77.19**

TABLE VIII
ISOTOPIC ANALYSIS OF GROUNDWATER SAMPLES COLLECTED IN MAY 2004.
DRY SEASON (PHASE-IV).

Sample Code / Depth	*δ^2H ‰ (V-SMOW)*	*$\delta^{18}O$ ‰ (V-SMOW)*	*Percent Contribution from Arabian Seawater (Based on Hydrogen Isotope ^2H)*	*Percent Contribution from Arabian Seawater (Based on Oxygen Isotope ^{18}O)*
SL-N-4+	**-46.04**	**-5.98**	**21.01**	**29.4**
SL-N-12	**-45.75**	**-6.38**	**21.39**	**26.04**
SL-N-21	**-45.78**	**-5.88**	**21.35**	**30.25**
SL-S-04	**-52.40**	**-6.96**	**12.78**	**21.11**
SL-S-12	**-44.82**	**-6.34**	**22.59**	**26.36**
SL-S-21	**-50.16**	**-6.72**	**15.68**	**23.14**
JI-N-06	**-33.68**	**-3.59**	**73.01**	**49.65**
JI-S-06	**-39.57**	**-4.43**	**29.39**	**42.53**
JI-S-12	**-34.49**	**-4.05**	**35.96**	**45.75**
JI-S-14	**-28.47**	**-3.91**	**43.75**	**46.94**
SB-S-05	**2.00**	**-0.53**	**83.19**	**75.56**
SB-S-14	**8.83**	**-0.27**	**92.03**	**77.76**

SL Sujawal, JI Jati, SB Shah Bundar, N North, S South + Numeric value after location code indicates the depth of groundwater sample in meters

A. Isotopic method

Among the nuclear techniques, the stable isotopes of oxygen and hydrogen viz. Deuterium (^{2}H) and Oxygen-18 (^{18}O) have strong potential for study of hydrological problems such as identification of the sources of recharge, mixing characteristics of water of different sources in the hydrological system, seawater intrusions in coastal aquifers, etc. These isotopes are present naturally in the water molecule and its dissolved compounds, dissolved gases, waste matter, and geological materials. Due to fractionation effects, their abundance varies in different sources [3]. The heavier isotope of Oxygen (^{18}O) and Hydrogen (^{2}H) are natural and typical tracers of seawater intrusions and are used to detect relative mixing of seawater into groundwater in coastal sediments of the studied area.

In order to evaluate the relative contribution of various sources of recharge to groundwater such as Indus river and/or seawater, it is necessary to know the stable isotopic composition of oxygen ($\delta^{18}O$ ‰ V – SMOW) and hydrogen ($\delta^{2}H$ ‰ V – SMOW)in various possible sources of water. The isotopic input functions (or isotopic indices) for the Indus river at Jamshoro and seawater at Shah Bundar are given in the Table-IX.

Since the rainfall intensity in the study area is very low (average annual rainfall is upto 160mm), it appears that contribution to groundwater recharge from the rainwater component is very low or negligible. Thus rainfall is not a potential source of recharge to groundwater. This leaves the Indus river as the main source of recharge to groundwater in district Thatta and the Arabian seawater as the secondary source of recharge to groundwater in the main coastal zone of the area. The following two component isotope balance equation based on $\boldsymbol{\delta^{18}O_{water}}$ may be used to evaluate the mixing fraction of Arabian seawater (f_{sea}) in shallow groundwater of mainly Indus river origin in the studied area:

$$\delta^{18}O_{mix\ groundwater} = \mathbf{f_{sea}}\ \delta^{18}O_{seawater} + (1- \mathbf{f_{sea}})\ \delta^{18}O_{Indus\ River\ Water} \quad (I)$$

where $\boldsymbol{\delta^{18}O_{mix\ groundwater}}$ designates stable oxygen isotope compositions of actual groundwater sample from boreholes / piezometers, $\boldsymbol{\delta^{18}O_{Indus\ River\ Water}}$ designates the stable oxygen isotope compositions of Indus river water; and $\boldsymbol{\delta^{18}O_{seawater}}$ designates the stable oxygen isotope compositions of Arabian seawater at Shah Bundar area of district Thatta. For practical purposes, we can rearrange equation (I) to deduce the percent mixing fraction of Arabian seawater (f_{sea}) intruded in shallow groundwater of mainly Indus river origin in the studied area by the following two equations for the oxygen and hydrogen isotopes respectively

$$f_{sea}\ (\%) = [\ (\delta^{18}O_{mix\ groundwater} - \delta^{18}O_{Indus\ River\ Water}) / (\delta^{18}O_{seawater} - \delta^{18}O_{Indus\ River\ Water})]\ x100 \quad (II)$$

$$f_{sea}\ (\%) = [\ (\delta\ ^{2}H_{mix\ groundwater} - \delta\ ^{2}H_{Indus\ River\ Water}) / (\delta\ ^{2}H_{seawater} - \delta\ ^{2}H_{Indus\ River\ Water})]\ x100 \quad (III)$$

Tables V-VIII present a view of the stable isotope composition of oxygen and hydrogen in groundwater samples and the percent mixing fraction "f_{sea}" of seawater (percent contributions of seawater) into coastal aquifer system during Wet and Dry seasons.

B. Geophysical resistivity method

A great variety of electrode arrangements are available to measure earth electrical resistivities. The present study has been limited to the Wenner array. The ABEM Terrameter was used for all the resistivity surveys in the present study. Apparent resistivity of different layers in the subsurface was obtained by Vertical Electric Sounding (VES) is interpreted by the use of the computer software Resixplus produced by Interpex (USA) Ltd. Geophysical survey (electrical resistivity method) was conducted on ground surface at varying distances from each and every borehole/piezometer sites to determine the resistivities & thicknesses of different layers in the subsurface. The Geoelectric section at every piezometer site was constructed by measuring five Vertical Electric Soundings (VES) including one at piezometer site and two in north and two in south of piezometer at a fifty meter distance from eachother. Thirty VES were measured in every Dry season (June/July) and Wet season (November/December). In all 120 VES have been measured during the two years period on six piezometer sites. Electrical resistivities of the different aquifer materials measured through geophysical resistivity survey have been correlated with boring log data, isotopic & chemical tests on the groundwater samples.

Figures of Geoelectric sections at Sujawal North are drawn using interpreted results of five Vertical Electric Soundings during Dry & Wet seasons. From the comparison / correlation of Geoelectric sections of Dry & Wet seasons (Fig.1) it can be seen that during Dry season (June 2003) aquifer resistivities ranged from 0.27 Ωm to 0.66 Ωm. About 20 MAF water was released downstream below the Kotri barrage during the Wet season. Due to infiltration of fresh Indus river water in adjoining areas on left bank of river Indus, the salinity of the aquifer was decreased and the electrical resistivities values of the same aquifer were increased and raised to 4.2 Ωm to 5.2 Ωm in the Wet season (December 2003).

TABLE IX
STABLE ISOTOPE COMPOSITION OF OXYGEN AND HYDROGEN IN WATER MOLECULE REPRESENTING SOURCE OF RECHARGE TO GROUNDWATER IN SOUTHERN SINDH, PAKISTAN

Source of Recharge	*$\delta^{18}O$ ‰ (V-SMOW)*	*$\delta^{2}H$ ‰ (V-SMOW)*
Indus river water at Jamshoro	**-9.88**	**- 68.18**
Arabian seawater at Shah Bundar	**+2.66**	**+12.38**

V-SMOW Vienna Standard Mean Ocean Water

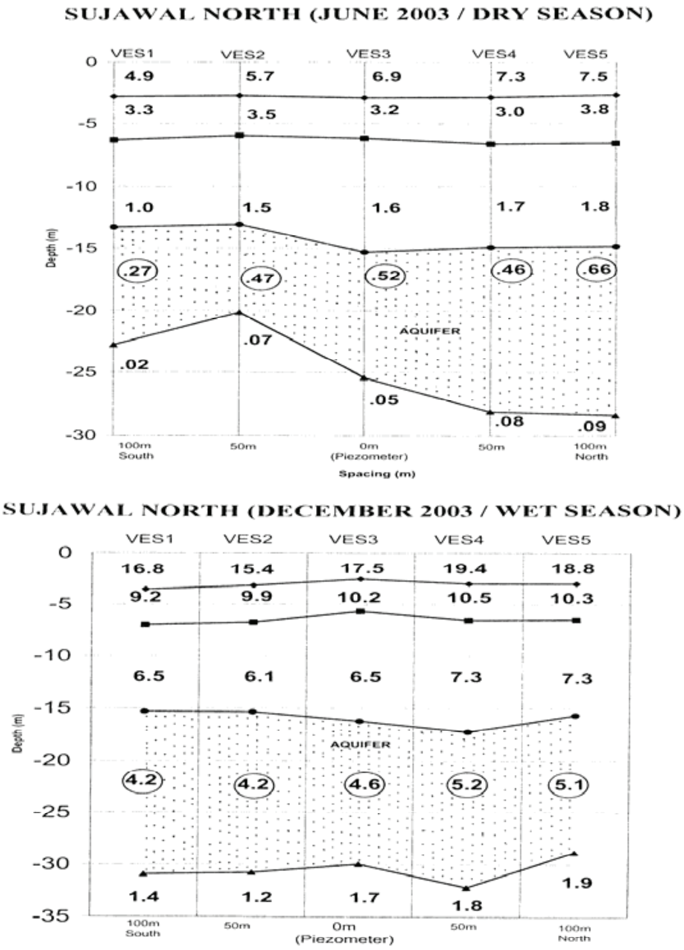

Figure 1: Geoelectric sections of Dry and Wet seasons at Sujawal North based on interpreted results of Vertical Electric Soundings (VES) from 1-5 with piezometer site (VES3) at the center. Numerical values encircled show apparent value of resistivity of the aquifer in ohm.m. Apparent values of resistivity of the same aquifer were increased after wet season due to infiltration of fresh river water and rain recharge.

TABLE X

PERMEABILITY AND POROSITY VALUES OF SAND EXCAVATED AT VARIOUS SIX PIEZOMETER SITES, MEASURED IN THE LABORATORY.

Piezometer site / Location of sand sample	*Depth of sand sample (m)*	*Permeability (K) of sand sample (m/s)*
Sujawal North	**21**	**4.4×10^{5}**
Sujawal South	**21**	**5.4×10^{6}**
Sujawal South	**24**	**1.6×10^{5}**
Jati North	**18**	**2.16×10^{5}**
Jati North	**24**	**5.4×10^{5}**
Jati South	**12**	**1.2×10^{5}**
Jati South	**24**	**3.84×10^{5}**
Shah Bundar North	**06**	**2.16×10^{5}**
Shah Bundar North	**15**	**2.94×10^{5}**
Shah Bundar South	**06**	**3.81×10^{5}**
Shah Bundar South	**12**	**2.16×10^{5}**

Permeability ranges from 5.4 x 10-6 m/s to 1 2 x 10-5 m/s.
Porosity ranges from 22 % to 39 %.

C. Porosity & Permeability

The porosity determined in the laboratory on the actual sediments range from 22% to 39%. Permeability (K) values of sand (Table X) measured using Hazen's formula [4] $K = C\ (d_{10})^2$ cm/s for all sand samples obtained from six piezometers are mean average values and they range from 5.4 x 10^{-6} m/s to 1.2 x 10^{-5} m/s. The permeability values prove to be Low. Water bearing sediment with such permeability values could be classed in a category, which minimizes the rate of the seawater intrusions.

III. Results & Discussions

A. Seawater intrusions in Sujawal area

The Sujawal area is quite far from the coast (about 75 km distance from the coast) but it is quite close to the Indus river on the left bank. Lithologically, the shallow aquifer system in the Sujawal area has quite variable thickness. The Cl- / HCO-3 ratios of sampled groundwater are well above 2/3 and are indicative of the presence of seawater intrusions (Tables I-IV). Tables V-VIII present the oxygen and hydrogen isotope based comparison of the extent of seawater intrusions in the Sujawal zone during Wet & Dry seasons. It appears that there is more tendency of seawater intrusions in this area during the Dry season as compared to the Wet season. In both regimes (piezometers at north & south of the town), the deeper groundwater contains relatively more proportions of seawater as compared to the shallow groundwater in the southern as well as the northern zone. The contribution of seawater into groundwater ranges from 18%–31% in the Wet season (Phase-I) and 27%–33% in the Dry season (Phase-II) during year 2002-2003. The contribution of seawater into groundwater ranges from 17%–31% in the Wet season (Phase-III) and 21%–30% in the Dry season (Phase-IV) during year 2000-2004.

B. Seawater intrusions in Jati area

The Jati area is not too far from the coast (about 45 km distance from the coast) and lies in between Sujawal and Shah Bundar areas. Unlike Sujawal and Shah Bundar areas, the Jati is not so close to the Indus river. Lithologically, the shallow aquifer system in the Jati area has quite variable thickness. In all groundwater samples, the Cl- / HCO-3 ratios is well above a value of 2/3 and are clear indicative of the presence of seawater intrusions (Tables I-IV). Tables V-VIII present the hydrogen and oxygen isotope based comparison of the extent of seawater intrusions in the Jati zone during the Wet & Dry seasons. The contribution of seawater into groundwater ranges from 41%–49% in the Wet season (Phase-I) and 38%–46% in the Dry season (Phase-II) during year 2002-2003. The contribution of seawater into groundwater ranges from 43%–58% in the Wet season (Phase-III) and 42%–49% in the Dry season (Phase-IV) during year 2000-2004. The relative proportions of seawater intrusions are more as compared to the Sujawal area because it is nearer to Arabian sea.

C. Seawater intrusions in Shah Bundar area

The Shah Bundar area is quite close to the coast. Lithologically, the sands are at the top up to 15m, followed by clay in the bottom. The Cl- / HCO-3 ions ratios of sampled groundwater are well above a value of 0.66 or (2/3) from the southern side of Shah Bundar and are clear indicative of the presence of seawater intrusions in groundwater system (Table I-IV). Tables V-VIII present the oxygen and hydrogen isotope based comparison of the extent of seawater intrusions in the Shah Bundar zone during the Wet & Dry seasons. It appears that there is much higher tendency of seawater intrusions in the Shah Bundar area due to nearness of Arabian sea. The contribution of seawater into groundwater ranges from 83%-92% in Wet season (phase-I) and 76%-80 % in Dry season (phase-II) during year 2002-2003. The contribution of seawater into groundwater ranges from 75%–77% in the Wet season (Phase-III) and 75%–77% in the Dry season (Phase-IV) during year 2003-2004. TDS has reached around 41000 mg/l, whereas WHO's upper limit for drinking water is TDS 1000 mg/l. It indicates that almost all the groundwater system has been polluted by the seawater intrusions in Shah Bundar area even up to the shallow depth.

D. Conclusions

1. Permeabilities measured in the laboratory on the samples of sand collected while drilling and installing the six piezometers, can be classified as Low.

2. The groundwater up to Sujawal, which is about 75 km from the coast, seems very much affected due to the seawater intrusions and has reached its 14 feet depth level. The Chloride is one of the indicator of seawater intrusion is about 8000 mg/l (SL-N-14 in December 2002), whereas WHO's upper limit for drinking water is 250 mg/l.

3. During December 2002 the contribution of seawater into groundwater measured through isotope of oxygen-18 ranges from 18%-31% at Sujawal, which is about 75km from the coast. The contribution of seawater into groundwater ranges from 41%-49% at Jati, which is about 45km from the coast. The contribution of seawater into groundwater ranges from 83%-92% at Shah Bundar, which is nearest to the coast.

4. During November 2003 (Wet season) the contribution of seawater into groundwater was lowered upto the extent of minimum 17 % at Sujawal and maximum 77 % at Shah Bundar due to release of about 20 MAF fresh river water downstream below the Kotri barrage.

5. Results finally support that adequate fresh (river) water, which is required to prevent present/existing seawater intrusions, should be released downstream below the Kotri barrage to reduce seawater intrusions. It is further suggested that the flow of water shall be regularized and spread throughout the year so that fresh water from Indus river

should infiltrate subsurface and adjoining areas for whole year round and consequently reduce the severity of seawater intrusions

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