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Delineation of Saltwater Intrusion into Freshwater Aquifer in Bela Plain, Coastal Area of Pakistan using Analytical Techniques

¹Uzma Mujtaba and ²Muhammad Sajid Latif

¹Independent Researcher, Islamabad, Pakistan

²Researcher, National Center for Water Technology (NCWT), KACST, Riyadh, Saudi Arabia

Corresponding Author: Uzma Mujtaba, Independent Researcher, Islamabad, Pakistan

ABSTRACT

Deterioration of water quality in the coastal zones of Bela plain of Pakistan due to saltwater infiltration into the freshwater aquifer has become a major concern. The present study was conducted to estimate the depth of the fresh water-salt water interface using appropriate analytical techniques to data obtained from test boreholes. The theoretical values were not valid for the study area especially where the sedimentary deposits are not homogeneous or isotropic, commonly assumed for such solutions. Zones of fresh and salt water are stratified and a maximum chloride value occurred near to the surface indicating salt water intrusion in the upper layers. The lower layers due to their low permeability appear to be resisting the inland encroachment of sea water. The extent of intrusion was related to the rate of ground water outflow from the aquifer to the sea. The numerical and analytical results were compared and showed good agreement.

Key words: Sea water intrusion phenomenon, water quality, groundwater

INTRODUCTION

Sea intrusion into coastal aquifers has become a major concern (Batayneh, 2006) due to the changes in quantity and quality of fresh groundwater discharged to coastal salt water systems. Therefore, understanding of saline water intrusion is essential for the management of coastal water resources (Ginzburg and Levanon, 1976). The location of fresh water-sea water interface in a coastal aquifer is highly significant for use and management of available water resources. The flow of freshwater in the aquifer towards sea is necessary to avoid salt water from encroaching farther into the aquifer (Cooper *et al.*, 1964). When a fresh water aquifer is connected to a surface body of salt water, such as the sea or a salt lake, the denser salt water will tend to penetrate some distance into the aquifer until a state of balance with fresh water is established which is called as equilibrium state of sea water intrusion.

Previously, salt water intrusion into coastal aquifers has been the focus of many researchers. A number of researchers have been engaged in the area of seawater intrusion. Bear and Dagan (1964) and Shamir and Dagan (1971), among others, published solutions based on a sharp interface assumption. Mualem and Bear (1974) considered the effect of discontinuous stratifications

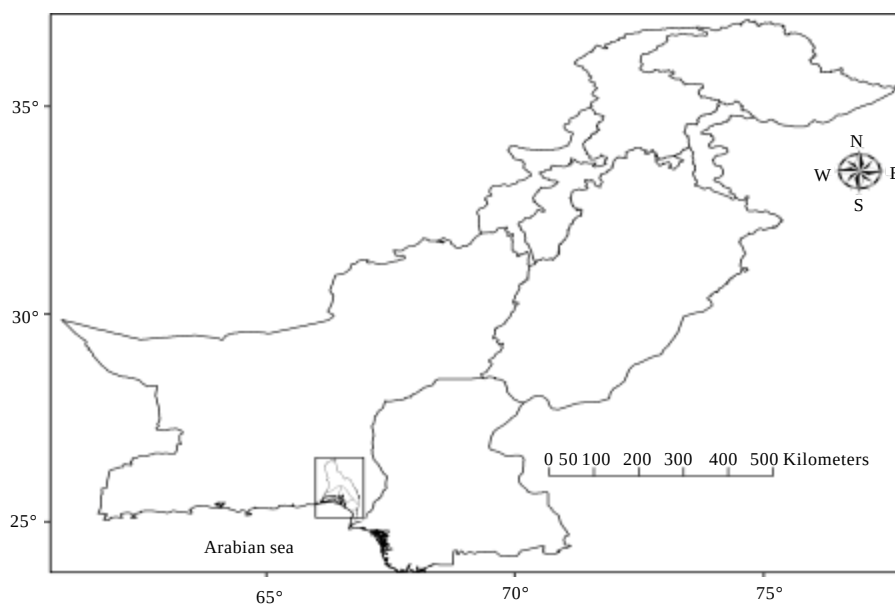


Fig. 1: Location map of Bela plain

on the shape of the interface. Henry developed the first analytical solution that includes the effect of dispersion. Pinder and Cooper Jr. (1970) used the method of characteristics to solve the convective-dispersive transport equation with a constant dispersion coefficient. Lee and Cheng (1974) used stream functions to obtain a steady-state solution of the same equation. In working with confined coastal aquifers, most researchers considered the existence of an exit face that connects the aquifer directly to the sea.

The study of this problem arose from the increasing demand of subsurface water supplies, especially in the arid areas, due to domestic and irrigation projects adjacent to the coastal regions around the world. To manage the water resources amicably in coastal areas, it is pertinent to predict the changes in groundwater quality with special emphasis on water salinity within the aquifer due to any future abstraction plans. Proper future planning and regular monitoring of water quality changes in coastal areas is a pre-requisite to implement feasible correction measures (Mercado, 1985).

Location of study area: Beta Plain of Lasbela district covers an area of about 3100 km². It is located in the southern part of Baluchistan between the latitude 25°15'-26°25' North and longitude 66°0'-66°55' East (Fig. 1). The area is surrounded by mountains in the east, west and north Miani Harbor, a bay of Arabian Sea, is the southern boundary. It lies in an arid zone with mean annual rainfall between 75-125 mm, potential evaporation is very high thus resulting in very low recharge to the ground water.

Agriculture is the principle economic source in the area which depends on rainfall, stream flow and open wells. The streams in the area are mostly intermittent and Porali River is the only

perennial one, located on the southern side. It is bounded by sedimentary rocks on the east, west and north while in the south, it extends to the Arabian sea. The floor of the plain constitutes the unconsolidated deposits of quaternary age. The topography of the area has been formed by erosion.

Bela Plain consists of five main physiographic units i.e. Mountains, piedmont area, flood plain, Porali plain and rolling sand plain (Fig. 2). The main mountains are: Mor Range (north-eastern side), Par Range (south-eastern side), Halar Range (north-western side) and Haro Range (south-western side). These mountains are composed mainly of dense, indurated, sedimentary and igneous rocks.

Hydrology: In the piedmont and foothill areas of Bela Plain, water is derived directly from precipitation and the stream flow originates from the mountains (Fig. 3). In the area underneath and adjacent to Porali River and other streams, the ground water is recharged by stream runoff through permeable beds. Whereas, in the remaining part of the area, ground water is recharged mainly from percolation of precipitation.

Porali River is the main stream of the region. Its main sources of water are in Mor and Par Ranges in the north, with drainage area of 4040 km² at Sinchi Bent gauging station. The discharge measurements of streams and rivers are done by Surface Water Hydrology, WASID (WAPDA, 1973). The average annual flow was 120 million m³ from 1962-1971 and is mostly used for irrigation. The Kud River flows into the Porali about 13-16 km downstream from the Sinchi Bent gauging station. The average annual flow was 102 million m³ recorded at Mai Gondrani from 1962-1971. Windar Nai is a major non-perennial stream with a drainage area of 1735 km² and flows directly into the sea. Another prominent non-perennial stream is Khantra Nai.

Test drilling revealed that the most permeable and extensive aquifer in the unconsolidated deposits is gravel that underlies the alluvial fans and piedmont areas. The groundwater in major part of Bela Plain is generally unconfined except in the south-western part where it is confined beneath with semi-permeable beds of silt and clay. The depth to water table varies from 11 m (near the sea) to 260 m (near the mountains).

In south western and almost all the middle portion of the study area, the water table depth zones are concave in shape along Khantra Nai and Porali River (Fig. 3). The conditions of recharge depend on the seasonal surface water discharge into the existing ground water. Almost all over the Bela Plain, the direction of ground water movement is in conformity with surface water flow (Fig. 4). In the south-eastern part of the plain, the flow lines are converging into a narrow strip which is indicative of very low hydraulic conductivity of this area.

Chemical quality of water: Water samples were collected from 25 shallow wells from the whole study area. The distribution of total water salinity (TDS mg L⁻¹) into different zones is presented (Fig. 5). The TDS values of groundwater ranged from 280 to 9080 mg L⁻¹. Out of 25 total samples, the TDS values of only 12 water samples were less than 1500 mg L⁻¹ and is useable. The remaining 13 water samples were highly saline and unfit for irrigation (WAPDA, 1973). In general, the shallow water in eastern part of Bela Plain, beginning from Naka Khari to area north of Bela town, is fresh with low salt concentration.

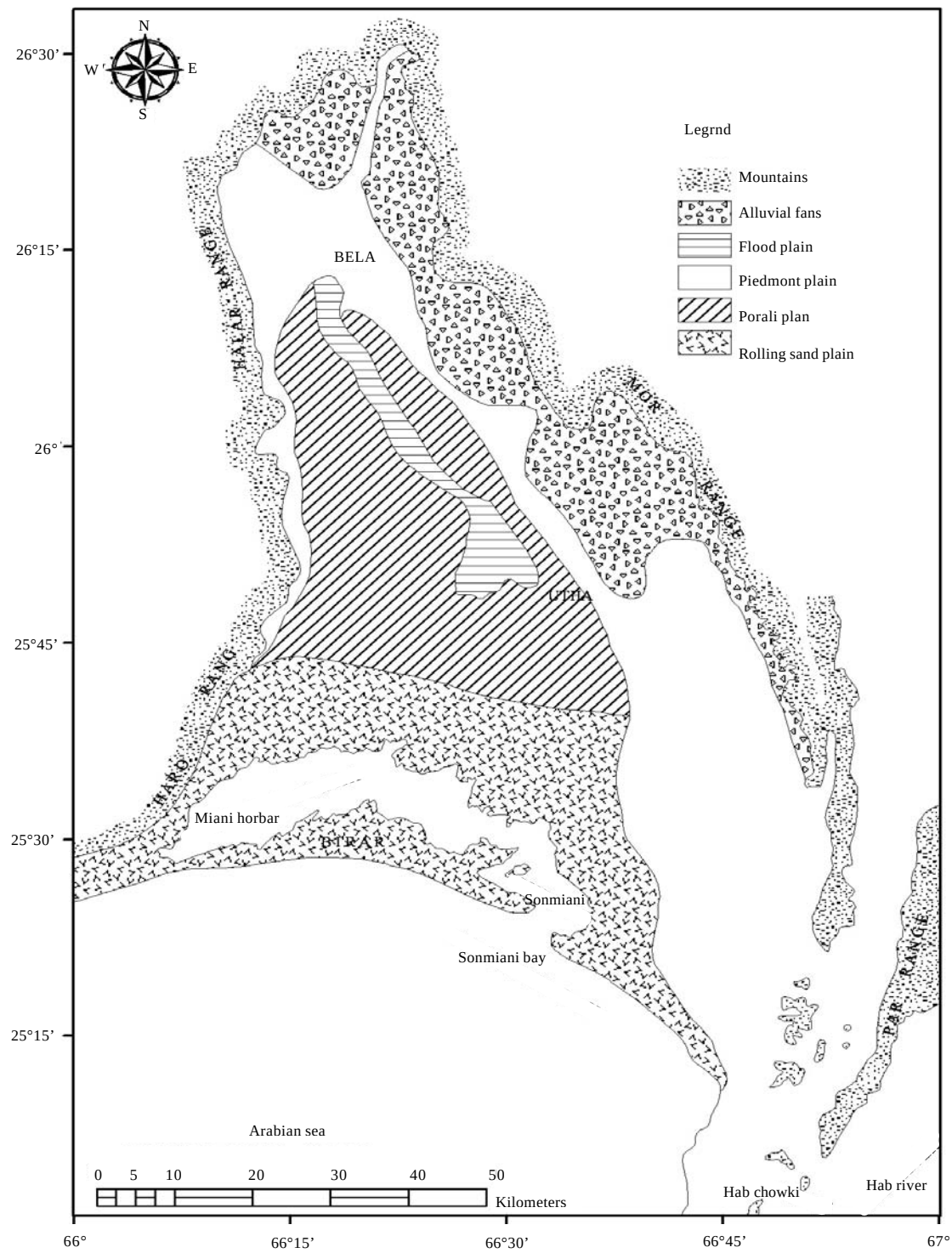


Fig. 2: Physiographic features of Bela plain

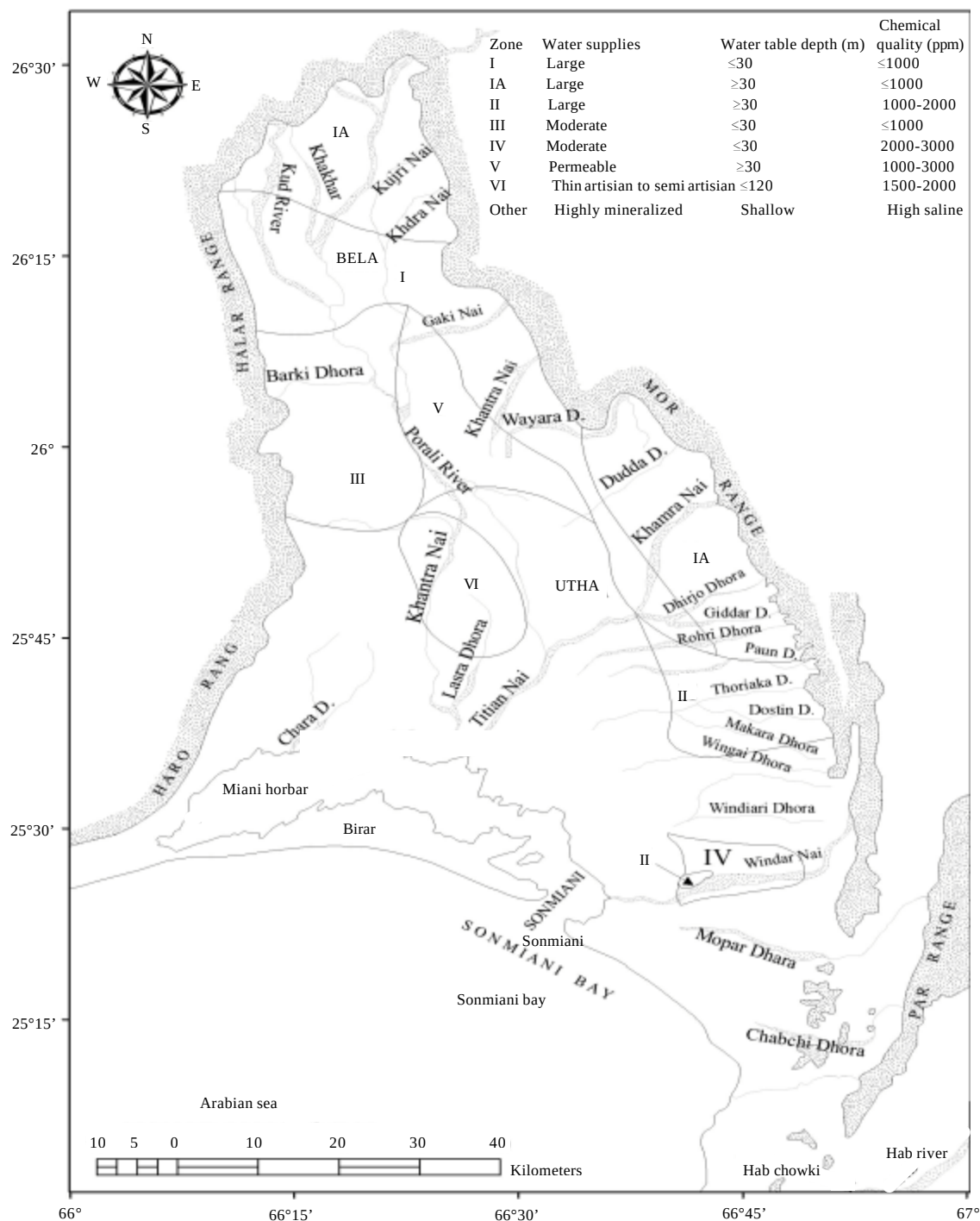


Fig. 3: Map of water channels and water table depth zones

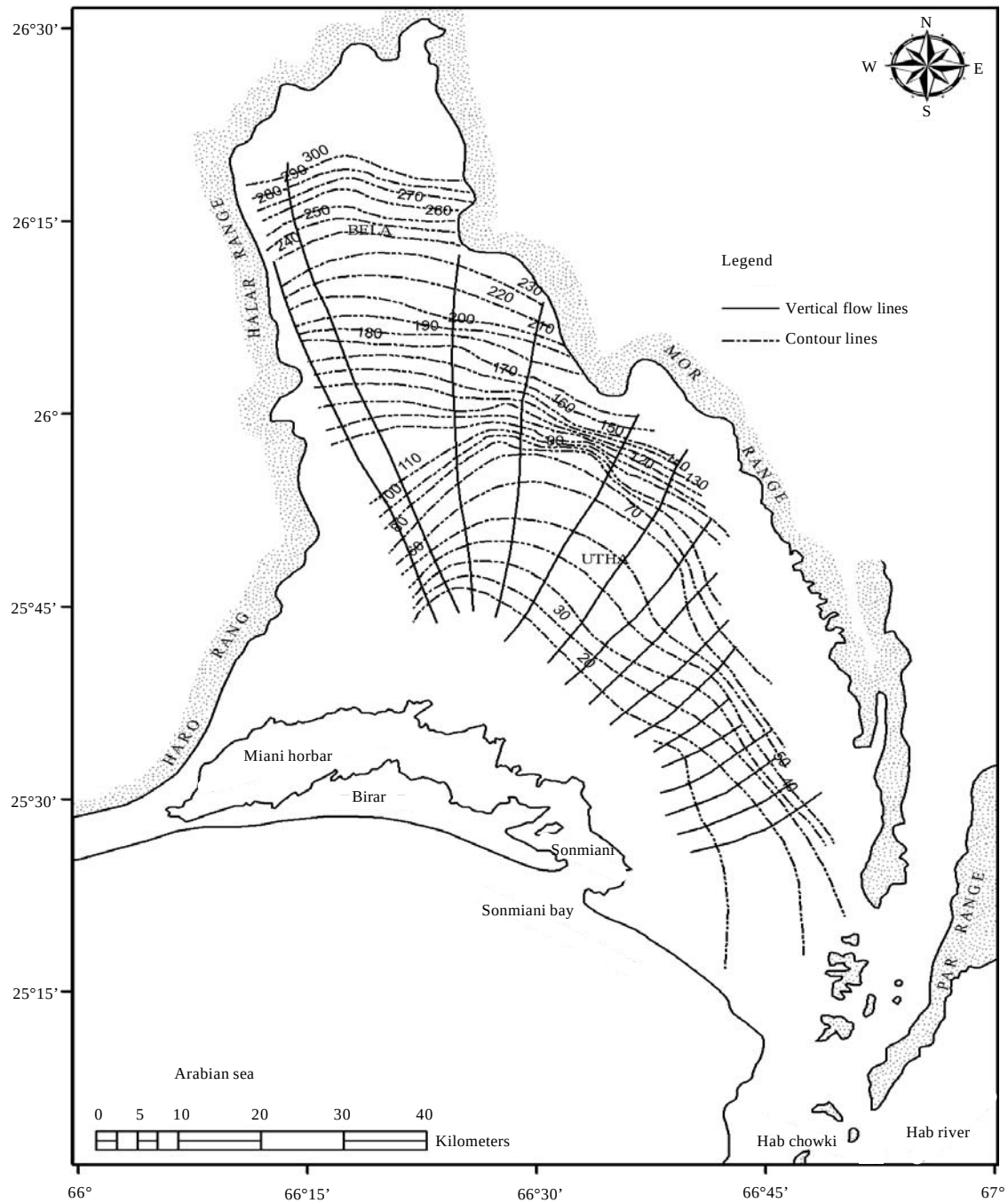


Fig. 4: Flow net of Bela plain

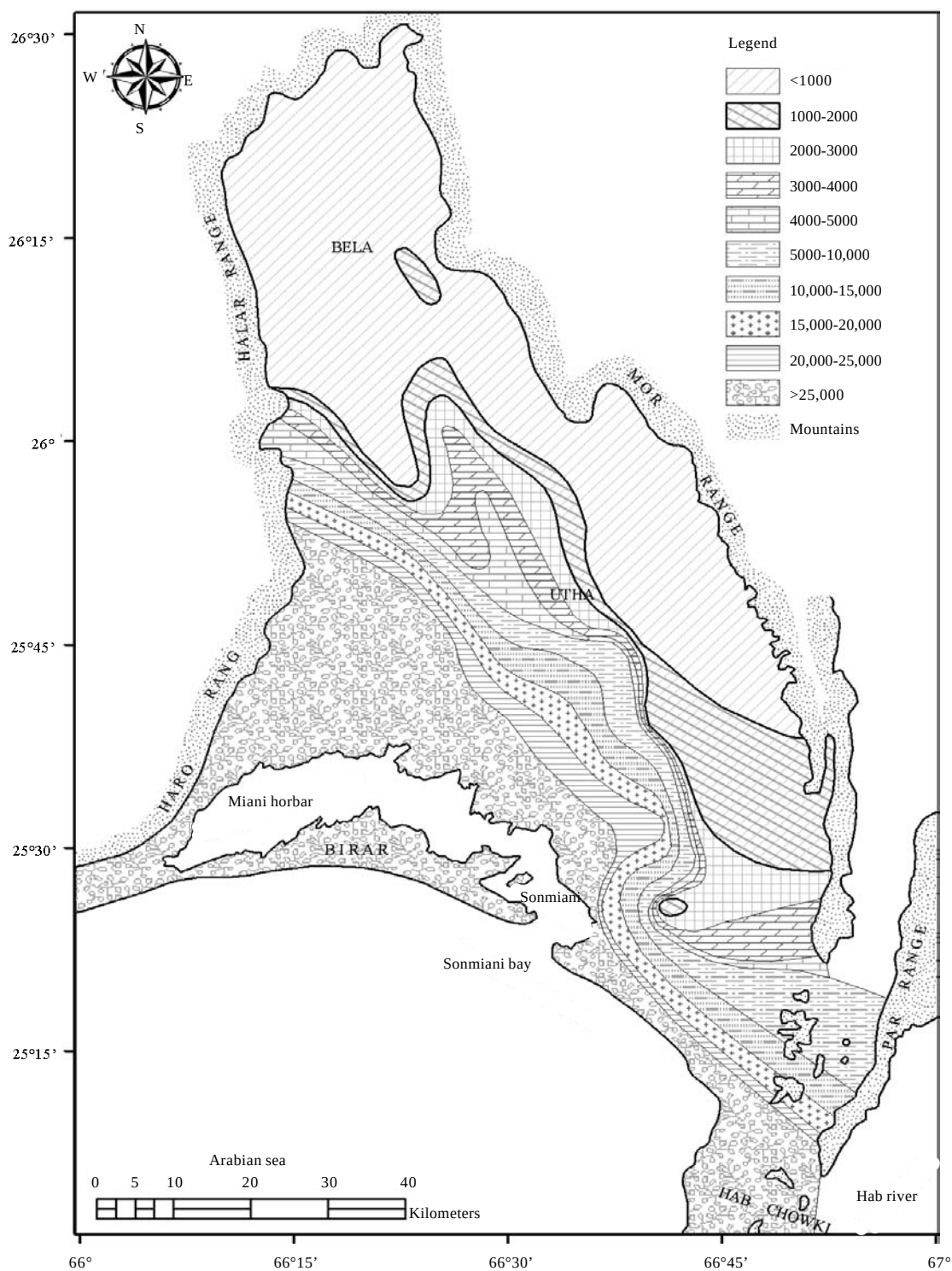


Fig. 5: Map of chemical quality of ground water in test holes wells

MATERIALS AND METHODS

Two approaches were followed for the study. First dealt with the salt water-fresh water interface in homogeneous and isotropic aquifers and the second dealt with the layered aquifers.

Interface in homogeneous and isotropic aquifers: Several analytical methods were reviewed to locate the fresh water and saline water interface in homogeneous and isotropic aquifers (Table 1). Based on the data available and the simplicity of the methods, three methods were selected for use in the study. In order to apply the analytical methods, the study area was divided into three zones based on the topography and aquifer thickness (Fig. 6). Due to the non-availability of the bed rock data, the aquifer thicknesses was assumed based upon the lithological data.

Zone 1: It is the western portion. Its left boundary is Haro Range and right boundary crosses Lasra Dhora while running parallel to Khantra Nai

Zone 3: It is the eastern portion which is in fact the Windar Valley, with Windar Nai flowing in it, Pab Range and a small portion of Mor Range is bordering it on the right side

Zone 2: It is lying in between Zone 1 and Zone 3. The outlet of all the three zones is in Miani Horbar as shown Fig. 6

Groundwater discharge was calculated in the three zones by applying Darcy's Law:

$$Q = K \cdot I \cdot A$$

where, Q is the discharge ($\text{m}^3 \text{sec}^{-1}$), I is the hydraulic gradient of the ground water (%) and A is the area of the aquifer (m^2):

$$A = K \cdot H = (\text{Length} \cdot \text{Thickness})$$

where, H is the thickness of the aquifer in m, L is the length of the aquifer in m:

Table 1: Classification of methods for determining the interface location

Interface	Analytical	Numerical
Sharp interface		
Homogeneous and isotropic medium	Herzberg (1901) Hubbert (1940) Van Der Veer (1977) Urish (1980) Kashef (1983) Gupta and Gaikwad (1987)	Chidley and Lloyd (1977) Gupta (1983) Reilly <i>et al.</i> (1987)
Layered medium	Rumer and Shiau (1968) Collins and Gelhar (1971) Fetter Jr. (1972), Mualem and Bear (1974)	
Moving interface	Bear and Dagan (1964) Isaacs (1985) Isaacs and Hunt (1986)	Shamir and Dagan (1971) Vappicha and Nagaraja (1976) Gupta (1985) Inouchi <i>et al.</i> (1985) Ledoux <i>et al.</i> (1990)
Zone of diffusion		Andrews (1981)
Homogeneous and isotropic medium		Volker and Rushton (1982) Bond and Bredehoeft (1987)
Layerd medium	Rumer and Harleman (1963)	

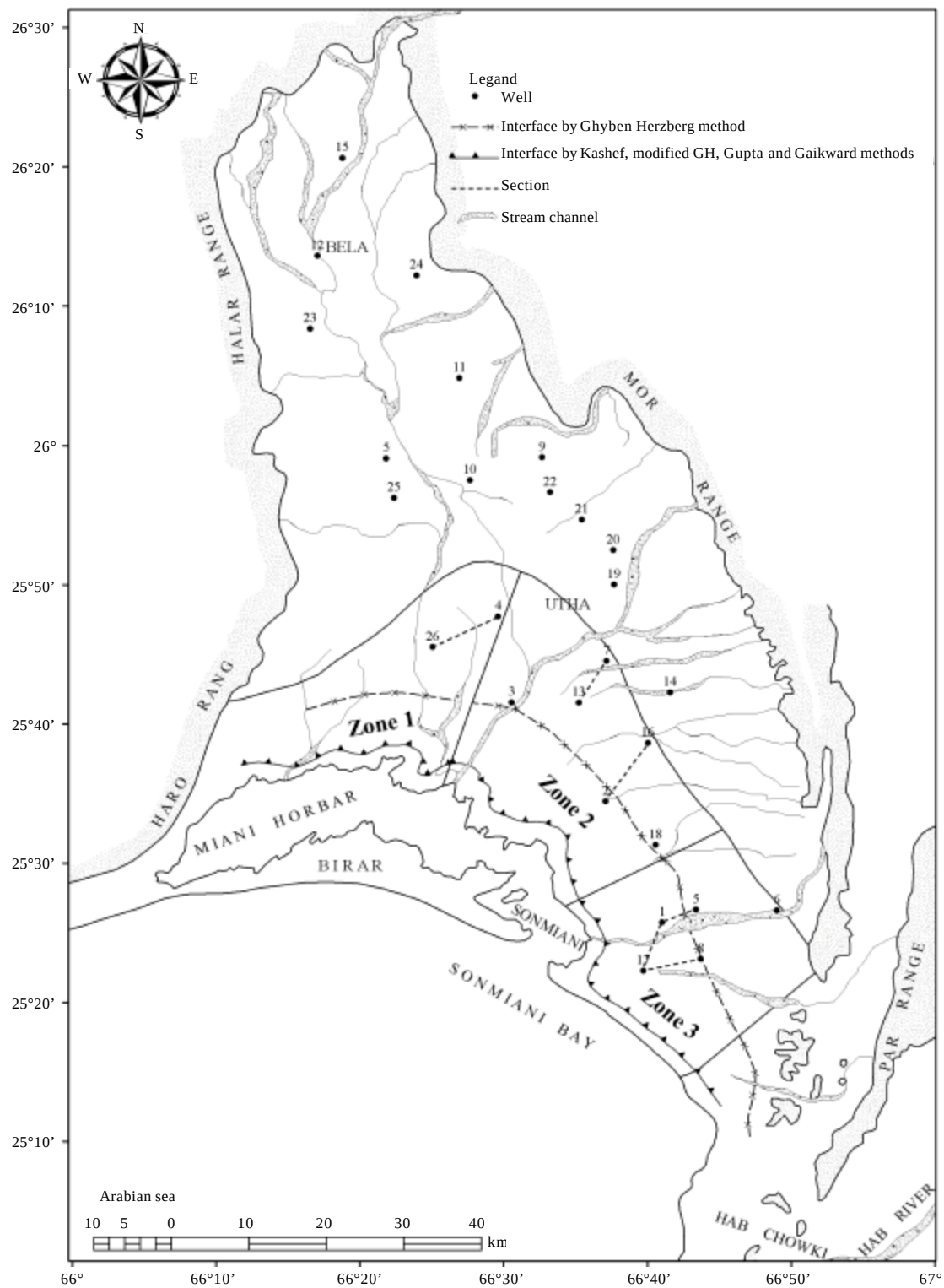


Fig. 6: Map of saline water classification zones

Table 2: Hydrologic characteristics of aquifer in the three zones

Zones	I	H (m)	K 10^{-4} (m sce $^{-1}$)	q* (cumec/m)
1	0.00157	213.36	0.56	0.000014
2	0.00157	274.32	1.09	0.000037
3	0.00138	213.36	13.53	0.003362

*Discharge per unit length of the aquifer

$$Q = K \cdot I \cdot L \cdot H$$

So, the discharge per unit length of the aquifer becomes:

$$q = Q/L = K \cdot I \cdot H$$

Groundwater discharge to the sea calculated by Darcy's Law, total thickness of the aquifer, hydraulic conductivity and the hydraulic gradient of each zone is given in Table 2. Hydraulic gradient was estimated with the help of water table elevation contours.

In the present study, the following analytical methods were used and the results obtained by these methods were represented in graphical form Herzberg (1901) equation.

The study assumed a static equilibrium between aquifer fresh water and sea water and a sharp interface around the middle of the mixed region. Considering the equilibrium between pressures from either side on the interface at point P gives:

$$\rho_f g(h+D) = \rho_s gD$$

$$\text{As } \gamma = \rho \cdot g$$

Therefore:

$$\gamma_f h + \gamma_f D = \gamma_s D$$

$$D(\gamma_s - \gamma_f) = \gamma_f h$$

$$D = \left(\frac{\gamma_f}{\gamma_s - \gamma_f} \right) h$$

where, D is depth of interface below the mean sea level, λ_f is fresh water specific weight, taken as 1 g cm^{-3} , γ_s is salt water specific weight, taken as 1.025 g cm^{-3} , h is water table altitude.

This leads to:

$$D = 40 h$$

This relation is valid only under the following conditions:

- Salt water must be stagnant, so that the head of the salty ground water below the interface is equal to that of sea

- Flow in the fresh ground water is horizontal
- Water table or piezometric surface lies above the sea level and slopes downward toward the sea

Where the groundwater flow is nearly horizontal, the G-H relation gives satisfactory results. Only near the seashore, where vertical components of water flow become pronounced, causes significant errors in the position of the interface occur (Todd, 1980).

For applying G-H method, water table profile up to the sea was needed which is not available for the study area. In order to apply the above method, Dupuit equation was applied to estimate water table profiles in the three zones. Dupuit equation requires the head difference in ground water and the respective distance which was solved by the following equation:

$$h(x) = -\frac{(H^2 - h^2) \cdot x}{L} + H^2$$

where, $h(x)$ is the required water table elevation at any point x , H and h are the upstream and downstream head of ground water respectively, L is the horizontal distance existing between these heads.

Kashef method (Kashef, 1983): To determine the configuration of the salt water-fresh water interface in the coastal unconfined aquifers, some selected rigorous mathematical solutions were adopted according to Kashef (1983). For the zones very close to the sea shore, two simple equations were derived on the basis of rigorous solutions according to Charmonman (1965) and Kashef and Csallany (1977).

In the case of horizontal fresh water outflow to the sea, the solution was deduced from the solution of Charmonman (1965) and for vertical outflow face, the solution was deduced from the author's own solution (Kashef and Csallany, 1977). He also provided a solution for interface location by modifying the G-H equation.

Procedure:

- First of all discharge per unit length is determined by applying Darcy's Law
- Then M is determined by applying the equation:

$$M = \frac{\alpha}{2I} = \frac{L}{H}$$

where, α is the excess specific gravity:

$$\alpha = \frac{\gamma_s - \gamma_f}{\gamma_f}$$

where, γ_f is Fresh water specific weight, as 1 g cm^{-3} , γ_s is Salt water specific weight, as 1.025 g cm^{-3} , α is 0.025, L is the total length; the sea has intruded into the aquifer. With the value of N calculated, L can be found out. x is taken as horizontal distance inland from the sea shore. Then following equations are used for locating the interface.

- When the fresh water outflow to the sea is vertical, the solution was deduced from the solution of Kashef and Csallany (1977) as given by the following equation:

$$\frac{D_v}{H} = \sqrt{\bar{X} + \frac{0.1375(1 - \bar{X})}{M^2}}$$

where, D is depth to interface (outflow face being vertical):

$$\bar{X} = \frac{X}{H}$$

- In the case of horizontal outflow, the solution was derived from the solution of Charmonman (1965) and was:

$$\frac{D_v}{H} = \sqrt{\bar{X} + \frac{1}{4M^2}}$$

D_H is depth to interface (outflow face being horizontal).

- Solution derived, by using G-H approximation:

$$\frac{D_v}{H} = \sqrt{\bar{X}}$$

Hence, it gives the modified G-H interface.

The values of D_v and those of D_H are always larger than D (Kashef, 1983).

Gupta and Gaikwad (1987) developed a model to predict the equilibrium location of upconed interface due to a horizontal well in an unconfined coastal aquifer of finite thickness. In the present study only that portion of the model was considered which accounted for a specified natural flow condition i.e., the interface profile and length of intrusion are determined.

In this model an unconfined coastal aquifer of uniform thickness was considered. The following assumptions were considered:

- Ground water flow is steady
- Aquifer is homogeneous and isotropic
- Tidal and barometric fluctuations of the water level are neglected
- No infiltration to the aquifer
- Interface is sharp

The following procedure was adopted to predict the equilibrium location of upconed interface.

Procedure: The length of the domain where the interface intersects the base of the aquifer is determined from the equation:

$$Y = \frac{q}{\alpha(1 + \alpha)KH}$$

$$\frac{L}{H} = \frac{1 - Y^2}{2Y}$$

$$\alpha = \frac{\gamma_s - \gamma_f}{\gamma_f}$$

where, q is the fresh water discharge to the sea per unit length of the aquifer, γ_f is fresh water specific weight, as 1 g cm^{-3} , γ_s is salt water specific weight, as 1.025 g cm^{-3} , α is 0.025.

This equation is then used to find the interface profile for the natural flow condition:

$$\frac{D}{H} = 1 - \frac{2M}{\beta \left(\sqrt{1 + \frac{\beta}{M^2}} - 1 \right)} \sqrt{1 - \bar{X}}$$

Where:

β = 1, for horizontal outflow face

β = 0.55, vertical outflow face

D = depth to the interface

$\bar{X}$ = X/L

M = L/H

RESULTS AND DISCUSSION

G-H method (Herzberg, 1901): Data in Table 3 show some selected points in the three zones and the depth of salt water-fresh water interface calculated by G-H method at these points. These points were selected for comparison with the other methods used in the analyses.

In zones 1 and 3, the head difference of 6 m was considered. The difference between the two heads cannot be taken more than 6 m because G-H relation simply multiplies the water table elevation with 12.2 m, i.e., $6.1 \times 12.2 \text{ m} = 243.84 \text{ m}$, whereas, thickness of the aquifer in these zones is assumed to 215 m only. Similarly the head difference in zone 2 is taken as 10 m.

Water table profiles and the respective depths to the interface in the three zones are shown in Fig. 6. The largest sea water extent of 13.7 km was observed in zone 3 due to the existence of flat hydraulic gradient as compared to the other zones. Because, flat gradients resulted from high hydraulic conductivities allow greater sea water intrusion.

Table 3: Calculation of fresh water and sea water interface position by Ghyben-Herzberg method at some selected points

Zones	Distance from sea (km)	Water table altitude (m)	Depth to interface (m)
1	0.805	1.372	54.529
	1.609	1.920	77.108
	12.070*	5.273	211.165
2	0.951	2.042	81.778
	1.902	2.896	115.672
	2.853	3.536	141.671
	10.462*	6.782	271.242
3	0.914	1.372	54.529
	1.828	1.920	77.084
	13.711*	5.273	211.165

*Total length of intrusion

Table 4: Calculation of fresh water-sea water interface position by Kashef's method at selected points

Zone	L (km)	Displacement of nearest well to the sea (km)	X (km)	D _H (m)	D _V (m)	D _{AVR} (m)
1	1.759	16.093	1.6764	212.4	211.8	212.1
2	2.184	9.656	2.1641	273.6	273.1	273.3
3	1.933	6.437	1.9202	213.0	211.8	212.4

Table 5: Calculation of freshwater-seawater interface position by modified ghyben-herzberg method at some selected points

Zones	Distance from sea (km)	Depth to interface (m)
1	1.737	213.0
2	2.225	274.0
3	1.951	211.8

Table 6: Calculation of freshwater-seawater interface position by Gupta and Gaikwad method at some selected points

Zone	L (km)	Displacement of nearest well to the sea (km)	X (km)	D _H (m)	D _V (m)	D _{AVR} (m)
1	1.7430	16.093	1.7374	213.0	212.7	212.8
2	2.2305	9.656	2.2250	274.0	273.7	273.9
3	1.9786	6.437	1.9507	211.8	211.7	212.1

The least sea water extent of 10.5 km was observed in zone 2. Sharp hydraulic gradients were observed here due to low hydraulic conductivity. This property of aquifer here is resistant to sea water intrusion. However, the sea water extent of 12.1 km was found in zone 1 which is between the two other zones due to the existence of intermediate hydraulic gradient.

Kashef method (Kashef, 1983): Figure 8 shows the interfaces for the three zones with the outflow face being horizontal and vertical, respectively according to Kashef Method (1983). In the graphical presentation, the two interfaces are nearly identical. But the calculated values were greater for D_H than D_V values, but the difference increased as the sea is approached (Table 4).

A comparison of three graphs showed that zone 2 has the deepest interface and the largest extent due to the depth and thickness of aquifer (275 m). It was reported that the extent of intrusion increases with an increase in the thickness and hydraulic conductivities of aquifer (Bear, 1979). The results obtained by Kashef method are given in Table 4. The sea water interface calculated with modified Ghyben-Herzberg formula by Kashef (1983) for some selected points are given in Table 5 (Gupta and Gaikwad, 1987).

Data in Fig. 9 show the interfaces for three zones with the outflow face being horizontal and vertical, respectively according to Gupta and Gaikwad (1987). The results were almost identical to those obtained by Kashef (1983). The results of some selected points is Table 6 indicated that the modified G-H formula by Kashef (1983) shows the interfaces at shallow depths as compared to those found by Kashef (1983) and Gupta and Gaikwad (1987) including also the G-H method (Herzberg, 1901). Although the calculated values by this method are far greater than those by the other method, the depths to interfaces in three zones are:

$$D_{G-H} < D_{G-HMOD} < D_{GUP} < D_{KAS}$$

where, D_{G-H} is depth to interface by G-H method (Herzberg, 1901), D_{G-HMOD} is depth to interface by Modified G-H method by Kashef (1983), D_{GUP} is depth to interface by Gupta and Gaikwad (1987), D_{KAS} is depth to interface by Kashef (1983) method.

A comparison of the interface locations as calculated by three methods is presented in Fig. 7-9 (Modified G-H, Kashef and Gupta). Data in Fig. 6 shows the areal extent (zones) of saline water intrusion as calculated by the analytical methods.

The G-H Method (Herzberg, 1901) showed the largest area for sea water intrusion, whereas, Kashef (1983) and Gupta and Gupta (1987) methods showed the identical areas on this scale i.e., 2.5 cm and 10 mL. But the study of results obtained by Kashef (1983) showed less extent of sea water intrusion than that determined by Gupta and Gupta (1987). The estimated extent of saline water intrusion applying G-H method for homogeneous conditions is presented in Table 7. It was assumed that the permeable layers of zone 1 and zone 2 are 150 m thick and that of zone 3 is 180 m thick.

Chemical analyses helped to set some criteria in order to check the variability and extent in aquifer water quality due to sea water intrusion. An increase in chloride (Cl) content indicated sea water intrusion. However, the variations in the concentration of other ions were frequently ignored due to their modification resulting from the interaction with aquifer minerals (Mercado, 1985).

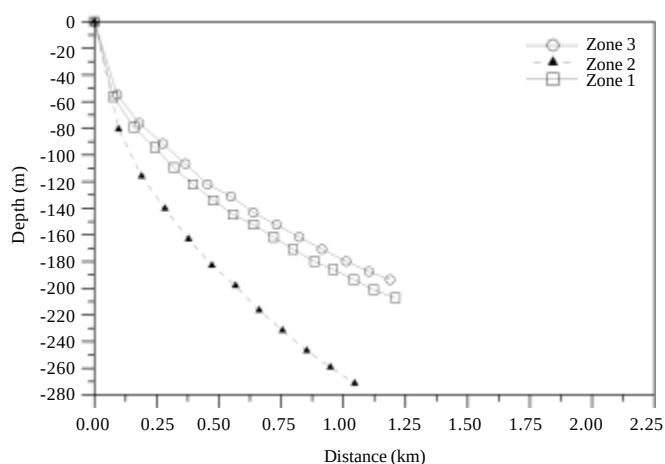


Fig. 7: Profiles of Ghyben-Herzberg (G-H) interface in classified saline zones

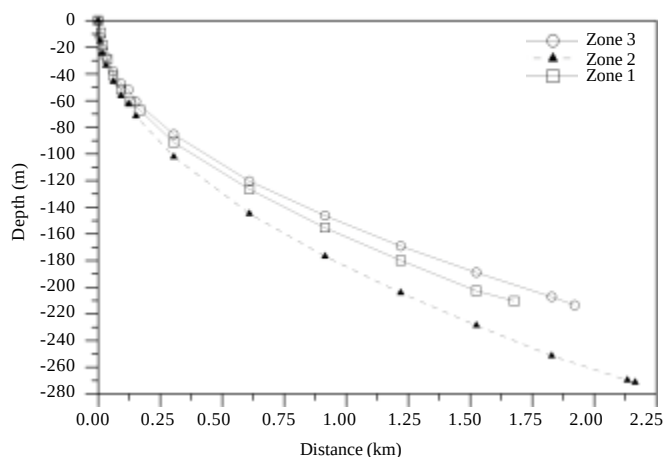


Fig. 8: Profiles of Kashef interface in classified saline zones

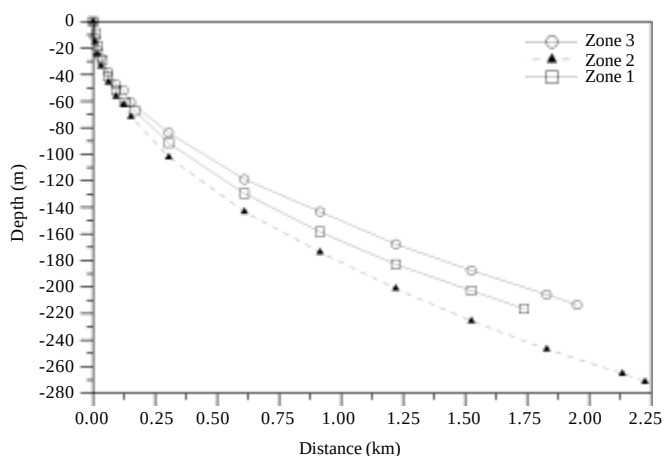


Fig. 9: Profiles of Gupta-Gaikwad interface in classified saline zones

Table 7: Calculation of freshwater-seawater interface position by Ghyben-Herzberg method at some selected points assuming two layered aquifer

Zones	Distance from sea (km)	Water table altitude (m)	Depth to interface (m)
1	0.805	1.4	54.5
	1.609	1.9	77.1
	5.633	3.6	144.3
2	0.951	2.0	81.8
	1.902	2.9	115.7
	2.853	3.5	141.7
3	0.914	1.4	54.5
	1.828	1.9	77.1
	4.756	4.6	182.9

Table 8: Mean values of Anion (WAPDA)

Well	Cl	SO ₄	HCO ₃	Cl/HCO ₃
3	10985.3	968.4	48.2	227.90
13	4959.2	813.5	59.2	83.77
17	3842.2	1004.9	59.2	64.90
18	10156.6	636.3	72.7	139.70
26	8992.4	1450.5	69.8	128.80

The average anion values are taken for each well in ppm

Harris (1967) stated that Cl contents in water in excess of 50 mg L⁻¹ indicate salt water contamination. Similar results were reported by Studies in stratified aquifer of Barrier Island by Chow (1964) who suggested Cl content in average sea water to be 18,930 mg L⁻¹ as stated by Reilly and Goodman (1985).

WAPDA (1973) analyzed the chemical quality of all the wells of Bela Plain. They selected 5 wells which were found to be contaminated by the sea water intrusion on the basis of the order of abundance of the following anions (Table 8):

- Chlorides (Cl)
- Sulphates (SO₄)
- Bicarbonates (HCO₃)

It was pointed out that while considering the sea water contamination, the Cl to HCO_3 ratio is important to diagnose sea water intrusion. Because sea water is low in HCO_3 so an increase in this ratio might be due to an increase in Cl contents resulting from sea water. But no criteria was set up for this ratio, these ratios are shown in Table 8.

According to Termblay *et al.* (1973), the ratio of Cl contents to TDS in the sea water remains almost constant when the sea water is mixed with fresh water. They considered Cl content of 20 mg L^{-1} as belonging to uncontaminated ground water, Cl content greater than 40 mg L^{-1} indicates salt water contamination and Cl content in excess of 100 mg L^{-1} was considered to be a part of the zone of diffusion.

According to Todd (1980), the Cl concentration in natural water is commonly less than 10 mg L^{-1} (milligram per liter) in humid regions but up to 1000 mg L^{-1} in more arid regions; about $19,300 \text{ mg L}^{-1}$ in sea water and as much as $200,000 \text{ mg L}^{-1}$ in brines.

Based upon the above discussion, the groundwater or freshwater having Cl content of $10,000 \text{ mg L}^{-1}$ or more will be considered as being contaminated by sea after intrusion and the water with Cl content equal to or less than 1000 mg L^{-1} fresh water.

Considering the chemical quality of ground water in well No. 26 and 4 (Fig. 10), the transition (in horizontal as well as in vertical direction) from fresh to saline water is observed as sea is approached. In the case of well no 26, both the Cl and TDS values concentration decreased with depth. The values near the surface were 16873 and 35800 mg L^{-1} for Cl and TDS, respectively which were very close to sea water quality. Whereas, the values of Cl and TDS were 1180 and 2540 mg L^{-1} , respectively at a depth of 185 m .

The distribution of Cl contents with depth in the groundwater in test well No. 26 is shown in Fig. 10. A zone of transition existed from fresh water (chloride content of 1000 ppm) to saline water (chloride content of $10,000 \text{ ppm}$).

A similar pattern of water quality deterioration except the value of Cl shows that well 4 lies almost in the fresh water zone. The Cl contents rose to 3445.9 mg L^{-1} at a depth of $55\text{-}60 \text{ m}$. As the location of well No. 4 is far away from the sea and near to Porali River, the decrease in Cl values might be due to the flushing of this zone by the fresh water from Porali River. However, Price (1996) reported that in arid areas, the potential evapotranspiration generally exceeds the rainfall for most of the year; the aquifer outcrop may be a zone of concentration rather than dissolution of salts. In this way high salinity level in ground water can be formed at or near the surface.

Well No. 13 showed a decrease in Cl contents with depth which might be attributed to the movement of high saline water to aquifer due to high permeability of aquifer layers in this zone. Well No. 7 located along the Titian Nai showed low concentration of Cl (Fig. 10) ranging from $308\text{-}1212 \text{ mg L}^{-1}$ which lies almost in the fresh water zone. Well No. 16 located far inland shows low Cl contents ranging from $524.6\text{-}861.4 \text{ mg L}^{-1}$ which lies in the fresh water zone. Also, Thoriako Dhora, originating from the Mor Range, might be responsible for improving the chemical quality of this well.

Well No. 14 is located above well No. 16 (Fig. 10). might have caused contamination in the latter well due to abstraction of water. But it seems that the area here is being excessively recharged by the numerous streams from the Mor Range which checks the contamination.

At the location of well No.18, the ground water is confined below thick shale layer. There was found a zig zag pattern of Cl concentration from a depth of $30\text{-}80 \text{ m}$ below the sea level. This pattern is due to the permeability of the formations encountered in this well i.e., a permeable layer

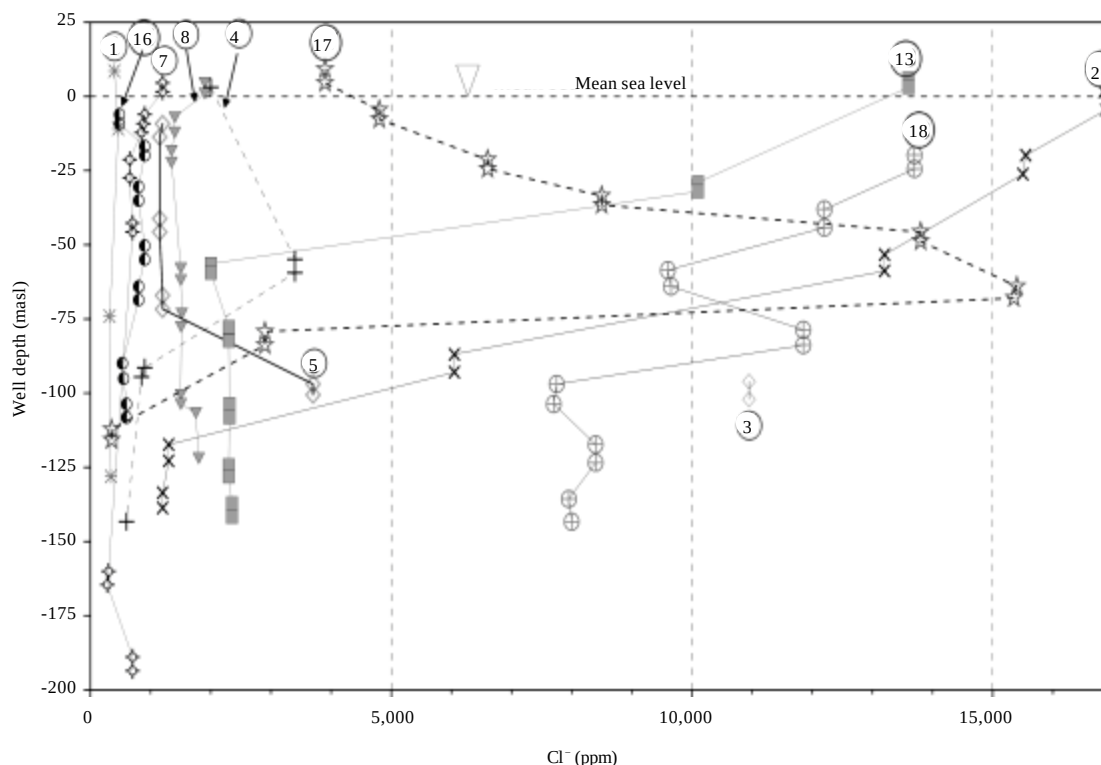


Fig. 10: Chloride distribution in different wells

is present at 75 m depth which abruptly increased the Cl value to more than 12000 mg L⁻¹. However, based on the criteria for groundwater contaminated with sea water, it can safely be concluded that the water of this well is being affected by sea water intrusion through the permeable formations. Because, low chlorides contents were found in less permeable clay layers due to increased resistance of the clay layers.

Well No. 17 is located at a distance of 3.5 km from sea and is 1.5 km south of Windar Hal. The depth to water table is 14.5 m and high evapo-transpiration may be responsible for high salinities at shallow depth.

Now consider that the Cl content is attaining the maximum value of 15395 mg L⁻¹ in the layer of coarse to medium sand with gravels at a depth of 67-70 m below mean sea level. The high Cl content (15395 mg L⁻¹) might be indicating the presence of interface penetrating the pervious layer. Furthermore, operation of well No.1 might have extended the zone of dispersion in well No. 17 or the tidal fluctuations, that are more pronounced near the shore, also directly contribute to variations in chloride content (Termblay *et al.*, 1973).

Well No. 8 is located about 6.4 km inland of well No. 17, 2.6 km north of Mobar Dhora and 3.8 km south of Windar Nai. The well water is not affected by sea water intrusion which might be attributed to its greater distance from the sea and flushing of permeable zones by the surface sources or fresh ground water (Table 9).

The convex shape of the water table contours along Windar Nai indicated that this stream is recharging the ground water (Fig. 4). This is clearly shown from the good quality of ground water at shallow depths in this area.

Table 9: Comparison between G-H interface and the available data

Zone	Well No.	Distance from the sea (km)	(G-H) Depth to interface (m)	Average depth (m) to max. Cl.>10,000 ppm
2	3	12.875	207.26	209.70
	2	9.656	219.46	Fresh water
	18	14.162	158.50	15.24
3	1	9.656	109.73	Fresh water
	17	6.437	97.54	93.57
	8	12.875	115.82	Fresh water

The zonal interpretation of water quality data in the three important aspects of the pattern of saline water intrusion in the area is given below:

- Water quality deterioration towards the sea is common to all zones which is an apparent indication of saline water intrusion
- The extent of sea water intrusion in zone 1 and zone 2 is more than twice as compared to zone 3 which shows greater outflow from the aquifer in zone 3 compared to the others
- Pattern of distribution of Cl contents does not agree to the theoretical or analytical approach due to the heterogeneity and configuration of the strata

CONCLUSION

Application of Ghyben-Herzberg method showed the largest extent of sea water intrusion as compared to other three methods. Because, it assumed zero outflows from the aquifer. According to this method, sea water intrusion was observed up to 6 km inland. The data of well No. 3 and 17 indicated that the depth to water contamination is occurring at about depths where Ghyben-Herzberg interface was located.

The high Cl contents found in the water of shallow well No. 26, 13 and 18 might have been transported from the chloride rich soils of the sea shore. In conclusion, in the non-homogeneous sediments of the study area, the depth to the fresh water-sea water interface responded to the differential flushing of stratified sediments of different permeability. Also, no regular pattern of chlorides is found in the ground water. In the presence of surface fresh water sources, high quality ground water was found in the subsurface permeable formations and relatively saline water in the impermeable formations. In those areas, where the recharge is less or absent, sea water seems to be intruded through the permeable layers, but the impermeable layers were least affected by the sea water.

REFERENCES

- Andrews, R.W., 1981. Salt-water intrusion in the Costa de Hermosillo, Mexico: A numerical analysis of water management proposals. *Groundwater*, 19: 635-647.
- Batayneh, A.T., 2006. Use of electrical resistivity methods for detecting subsurface fresh and saline water and delineating their interfacial configuration: A case study of the Eastern Dead Sea coastal aquifers, Jordan. *Hydrogeol. J.*, 14: 1277-1283.
- Bear, J. and G. Dagan, 1964. Moving interface in coastal aquifers. *J. Hydraul. Div. Am. Soc. Civ. Eng.*, 90: 193-215.
- Bear, J., 1979. *Hydraulics of Ground Water*. McGraw Hill Book Co., New York, ISBN-13: 9780070041707, pp: 379-435.

- Bond, L.D. and J.D. Bredehoeft, 1987. Origins of seawater intrusion in a coastal aquifer-A case study of the Pajaro Valley, California. *J. Hydrol.*, 92: 363-388.
- Charmonman, S., 1965. A solution of the pattern of fresh-water flow in an unconfined coastal aquifer. *J. Geophy. Res.*, 70: 2813-2819.
- Chidley, T.R.E. and J.W. Lloyd, 1977. A mathematical model study of fresh-water lenses. *Groundwater*, 15: 215-222.
- Chow, V.T., 1964. Salt-Water Intrusion of Coastal Aquifers: Handbook of Applied Hydrology. McGraw-Hill Book Co., New York, pp: 13-52.
- Collins, M.A. and L.W. Gelhar, 1971. Seawater intrusion in layered aquifers. *Water Resour. Res.*, 7: 971-979.
- Cooper, H.H., F.A. Kohout, H.R. Henry and R.E. Glover, 1964. Sea water in coastal aquifers. U.S. Geological Survey Water Supply Paper No. 1613-C. <http://pubs.usgs.gov/wsp/1613c/report.pdf>.
- Fetter Jr., C.W., 1972. Position of the saline water interface beneath oceanic islands. *Water Resour. Res.*, 8: 1307-1315.
- Ginzburg, A. and A. Levanon, 1976. Determination of a salt-water interface by electric resistivity depth soundings. *Hydrogeol. Sci. Bull.*, 21: 561-568.
- Gupta, A.D. and V.P. Gaikwad, 1987. Interface upconing due to a horizontal well in an unconfined aquifer. *Groundwater*, 25: 466-474.
- Gupta, A.D., 1983. Steady interface upconing beneath a coastal infiltration gallery. *Groundwater*, 21: 465-474.
- Gupta, A.D., 1985. Approximation of salt water interface fluctuations in an unconfined coastal aquifer. *Groundwater*, 23: 783-794.
- Gupta, S.K. and I.C. Gupta, 1987. Management of Saline Soils and Water. Oxford and IBH Publ. Co., New Delhi, India, Pages: 399.
- Harris, W.H., 1967. Stratification of fresh and salt water on barrier islands as a result of differences in sediment permeability. *J. Water Resour. Res.*, 3: 89-97.
- Herzberg, A., 1901. Die Wasserversorgung einiger Nordseebader. *J. Gasbeleucht Wasserversorg*, 44: 815-819.
- Hubbert, M.K., 1940. The theory of ground-water motion. *J. Geol.*, 48: 785-944.
- Inouchi, K., Y. Kishi and T. Kakinuma, 1985. The regional unsteady interface between fresh water and salt water in a confined coastal aquifer. *J. Hydrol.*, 77: 307-331.
- Isaacs, L.T., 1985. Estimating interface advance due to abrupt changes in replenishment in unconfined coastal aquifers. *J. Hydrol.*, 78: 279-289.
- Isaacs, L.T. and B. Hunt, 1986. A simple approximation for a moving interface in a coastal aquifer. *J. Hydrol.*, 83: 29-43.
- Kashef, A.A.I. and S.C. Csallany, 1977. Management and control of salt-water intrusion in coastal aquifers. *Crit. Rev. Environ. Sci. Technol.*, 7: 217-275.
- Kashef, A.A.I., 1983. Harmonizing ghyben-Herzberg interface with rigorous solutions. *Ground Water*, 21: 153-159.
- Ledoux, E., S. Sauvagnac and A. Rivera, 1990. A compatible single-phase/two-phase numerical model: 1. Modeling the transient salt-water/fresh-water interface motion. *GroundWater*, 28: 79-87.
- Lee, C.H. and R.T.S. Cheng, 1974. On seawater encroachment in coastal aquifers. *Water Resour. Res.*, 10: 1039-1043.

- Mercado, A., 1985. The use of hydrogeochemical pattern in carbonate sand and sandstone aquifer to identify intrusion and flushing of saline water. *Groundwater*, 23: 635-645.
- Muallem, Y. and J. Bear, 1974. The shape of the interface in steady flow in a stratified aquifer. *Water Resour. Res.*, 10: 1207-1215.
- Pinder, G.F. and H.H. Cooper Jr., 1970. A numerical technique for calculating the transient position of the saltwater front. *Water Resour. Res.*, 6: 875-882.
- Price, M., 1996. *Introducing Ground Water*. 2nd Edn., Chapman and Hall, London, ISBN: 9780748743711, pp: 156-168.
- Reilly, T.E. and A.S. Goodman, 1985. Quantitative analysis of saltwater-freshwater relationships in groundwater systems-A historical perspective. *J. Hydrol.*, 80: 125-160.
- Reilly, T.E., M.H. Frimpter, D.R. LeBlanc and A.S. Goodman, 1987. Analysis of steady-state salt-water upconing with application at Truro well field, Cape Cod, Massachusetts. *Groundwater*, 25: 194-206.
- Rumer Jr., R.R. and D.R.F. Harleman, 1963. Intruded salt water wedge in porous media. *J. Am. Soc. Civil Eng.*, 89: 193-220.
- Rumer Jr., R.R. and J.C. Shiau, 1968. Salt water interface in a layered coastal aquifer. *Water Resour. Res.*, 4: 1235-1247.
- Shamir, U. and G. Dagan, 1971. Motion of the seawater interface in coastal aquifers: A numerical solution. *Water Resour. Res.*, 7: 644-657.
- Termblay, J.J., J. D'Cruz and H. Anger, 1973. Salt water intrusion in the summerside area, P.E.I. *Groundwater*, 11: 21-27.
- Todd, D.K., 1980. *Ground Water Hydrology*. 2nd Edn., John Wiley and Sons, New York, USA., ISBN-13: 9780471876168, pp: 494-520.
- Urish, D.W., 1980. Asymmetric variation of Ghyben-Herzberg lens. *J. Hydraulics Division*, 106: 1149-1158.
- Van Der Veer, P., 1977. Analytical solution for steady interface flow in a coastal aquifer involving a phreatic surface with precipitation. *J. Hydrol.*, 34: 1-11.
- Vappicha, V.N. and S.H. Nagaraja, 1976. An approximate solution for the transient interface in a coastal aquifer. *J. Hydrol.*, 31: 161-173.
- Volker, R.E. and K.R. Rushton, 1982. An assessment of the importance of some parameters for seawater intrusion in aquifers and a comparison of dispersive and sharp-interface modeling approaches. *J. Hydrol.*, 56: 239-250.
- WAPDA, 1973. Annual report of river and climatological data of Pakistan, river discharge, sediment and quality data: Prepared by surface water hydrology project. WASID, WAPDA, Lahore, Pakistan.