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European Journal of Experimental Biology, 2013, 3(3):80-94

ISSN: 2248 –9215
CODEN (USA): EJEBAU

Seawater intrusion and groundwater resources management in coastal aquifers

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ABSTRACT

As result of density difference between seawater and fresh water in coastal aquifers, a transition zone between two fluids is formed. A wedge of saltwater can be entered in coastal areas to the aquifer. Seawater intrusion rate and extent of transition zone depends on several factors including: changes in sea level, aquifer characteristics, hydrologic conditions of upstream, discharging from the aquifer, tidal and seasonal fluctuations of sea water. In this paper height of interface between seawater and freshwater in Mazandaran coastal aquifers is calculated by relationships that have been used in previous researches. According to available information, x_{max} *(maximum seawater intrusion) in sections of Mazandaran coastal aquifers and allowable development of exploitation of this area have been calculated. Results show that development of exploitation is not possible for section A, B and O among total sections of Mazandaran coastal aquifers.*

Keywords: length of seawater intrusion, coastal water resources management**,** groundwater, saline, height of interface line from sea level.

INTRODUCTION

Ground water aquifers are an important resource in coastal regions because these serve as major sources for freshwater supply in many countries around the world, especially in arid and semi-arid zones. In many coastal areas, high rates of urbanization and increased agriculture have arises the demand for groundwater [1]. Several wells have been drilled to supply increasing water demand .The increase in water withdrawals from the wells have caused unacceptable drawdowns and deterioration of the quality of water pumped by some of the wells. Fresh groundwater in the coastal aquifer is drained seas or lakes under natural conditions and the interface line between fresh and salt water occurs. Heavy exploitation of coastal aquifers has effect on the hydraulic gradient. Changes of hydraulic gradient in groundwater aquifer are caused advance of salt water far away the sea at the coast. This phenomenon is called seawater intrusion. Two researchers named Ghybn and Herzberg separately studied fresh underground water flow to the oceans along the coasts of Europe**.** They found that anywhere from a coastal aquifer, If depth of interface between fresh and saltwater is measured from sea level, (h_s), then level of fresh ground water from sea level, (h_f), will be 1/40 (h_s) in that point [15]. Since these studies were started by two scientists this phenomenon is mentioned with regard to "Ghyben - Herzberg" that will be explained. Many reviews on the types of groundwater management models and their applications are made by [14], and [25]. The management models applications in saltwater intrusion, is relatively recent, (Cummings and McFarland, 1974 [4]), (Shamir et al., 1984 [8]), (Willis and Finney, 1988 [23]), (Emch and Yeh, 1998 [11]), (El Harrouni et al., 1998 [10]), (Das and Datta, 1999a & b [8]), (Cheng et al, 1999 [3]), (Fatemi and Ataie-Ashtiani, 2008 [12]), (Bear and Cheng, 1999 [1]), (Cheng and et al., 1999 [2]), (Cheng and Ouazar,1999 [3]), (Cummings, 1971 [4]), (Cummings and McFarland, 1974 [5]), (Dagan and Bear, 1968 [6]), (Das Gupta and et al., 1996 [7]), (Finney and et al., 1992 [13]), (Naji and et al., 1999 [19]), (Kwanyuen and Fontane, 1998 [17]), (Shamir and et al., 1984 [20]), (Strack, 1974 [21]), (Willis and Liu, 1984 [22]), (Willis and

Yeh, 1987 [24]) and (Loaiciga and Leipnik, 2000 [18]). Most of these problems have been investigated in a more complex setting involving various management objectives. Concerning saltwater intrusion into wells, it is often addressed in an indirect manner such as constraining drawdown at control points, or minimizing the intruded saltwater volume. These studies were conducted to maintain aquifer levels and prevent the saltwater intrusion so that undesirable economic consequences and legal violations are prevented.

MATERIALS AND METHODS

Perpendicular section is considered on the seaside in an aquifer (Fig. 1). Hydrostatic pressure at point A is:

$$P_A = \rho_s g h_s \tag{1}$$

That ρ_s is density of salt water, h_s is height of point A from sea level, and g is acceleration of gravity. Similarly, the hydrostatic pressure at point B that has the same depth to point A equals:

$$P_B = \rho_f g h_f + \rho_f g h_s \tag{2}$$

ρ_f is density of fresh water, h_f is freshwater height above sea level in the aquifer layer. Now, if the above two equations equal then Ghybn–Herzberg relationship would obtain as follows (see Fig (1), (2) and (3)):

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f \tag{3}$$

If in equation (3) the density of the salt water is 1.025 $\frac{g}{m^3}$ and fresh water density is 1 $\frac{g}{m^3}$ then equation (4) is calculated as follows:

$$h_s = 40 h_f \tag{4}$$

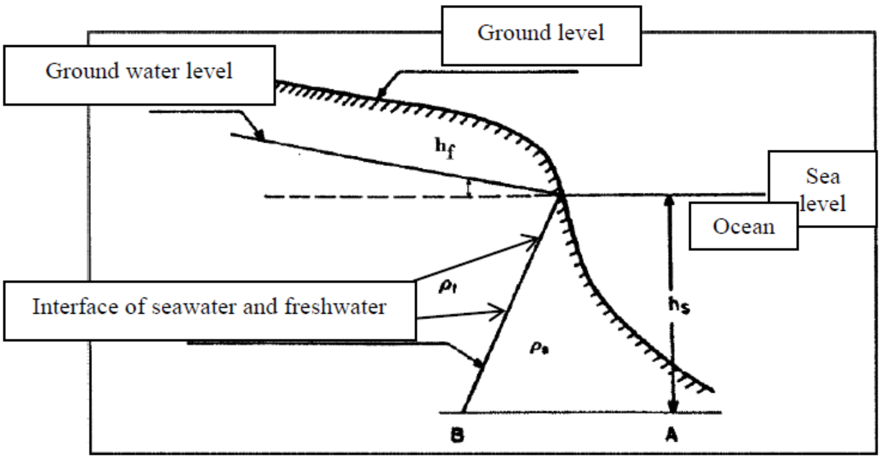


Figure 1. Ghyben – Herzberg relationship parameters

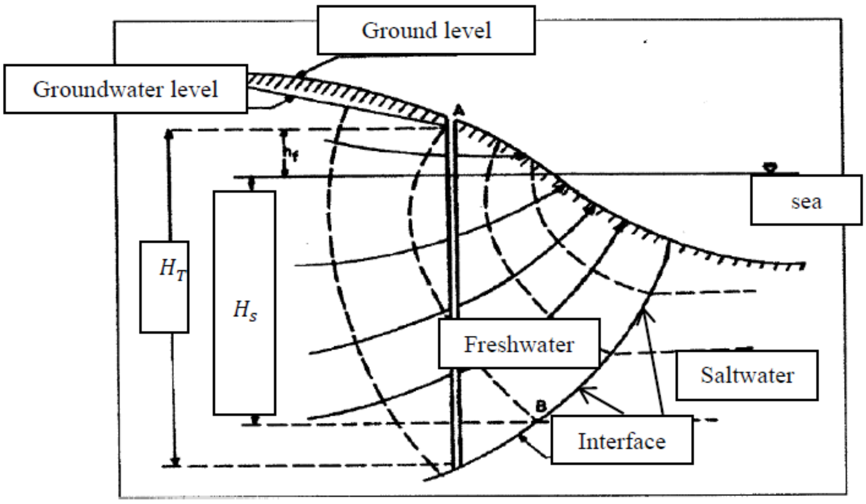


Figure 2: Ghyben – Herzberg relationship parameters

H_T is exact depth of interface and H_s is depth of interface based on Ghyben- Herzberg relationship that is lesser than H_T.

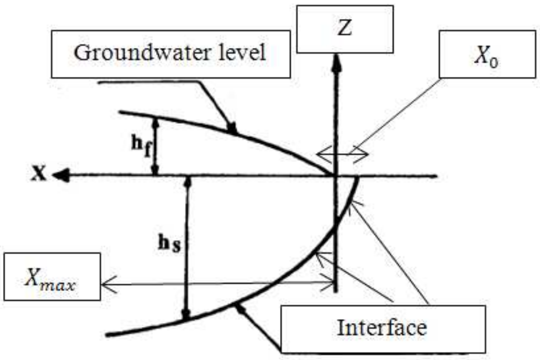
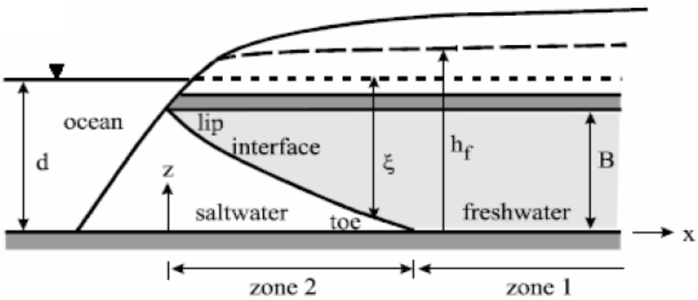


Figure 3: Ghyben – Herzberg relationship parameters

Thus it is seen that the influence of saline water into coastal freshwater aquifer depends on h_f the height of ground water level above the sea level. True picture of the quality of sea water intrusion are shown in Figure 2 by using flow lines and potential lines. [21] derived a single potential theory such that a single governing equation could be applies to both the saltwater and the freshwater zones. Figures 4(a) and (b) give a definition sketch in the vertical cross-section of a confined and an unconfined aquifer, respectively. Distinction has been made between two zones -a freshwater only zone (zone 1), and a freshwater-saltwater coexisting zone (zone 2). [21] demonstrated that for a homogeneous aquifer of constant thickness, a potential Φ which is continuous across the two zones, can be defined:

(a)



(b)

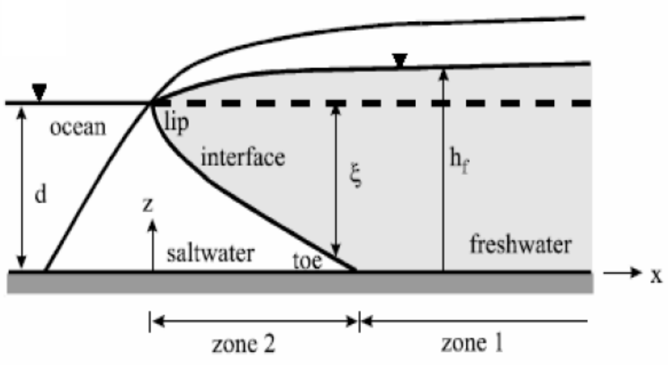


Figure 4: Definition sketch of saltwater intrusion in (a) a confined aquifer, and (b) an unconfined aquifer

For confined aquifer:

$$\Phi = \frac{1}{2}\left(h_f - sd^2\right) \quad \text{for zone1,} \quad \Phi = \frac{s}{2(s-1)}\left(h_f - d^2\right) \quad \text{for zone2} \tag{5}$$

For unconfined aquifer:

$$\Phi = Bh_f + \frac{(s-1)B^2}{2} - sBd^2 \quad \text{for zone1,} \; \Phi = \frac{s}{2(s-1)}\left(h_f + (s-1)B - sd^2\right) \text{ for zone2} \tag{6}$$

In the above h_f is the freshwater piezometric head, *d* is the elevation of mean sea level above the datum, *B* is the confined aquifer thickness, see Fig 4. We also note that

$$s = \frac{\rho_s}{\rho_f} \tag{7}$$

is the saltwater and freshwater density ratio, and ρ_s and ρ_f are respectively the saltwater and freshwater density. We note these functions and their first derivatives are continuous across the zonal interface. The potential defined in (5} and (6) satisfies the Laplace equation in the horizontal (*xy*) plane.

$$\Delta\Phi=0 \tag{8}$$

The problem is solved as a one-zone problem with appropriate boundary conditions. Once the problem is solved by analytical or numerical means, the interface location ζ (see Figure fig4) is evaluated as:

$$\zeta = \sqrt{\frac{2\Phi}{s(s-1)}} \text{ For unconfined aquifer, } \zeta = \sqrt{\frac{2\Phi}{s-1}} + d - B \text{ for confined aquifer} \tag{9}$$

The toe of saltwater wedge (see Figure fig1) is located at ξ = d. From (4), this means that the toe is located at where Φ takes these values:

$$\Phi_{toe} = \frac{s(s-1)}{2}d^2 \text{ For unconfined aquifer, } \Phi_{toe} = \frac{(s-1)}{2}B^2 \text{ for confined aquifer} \tag{10}$$

For both the confined and unconfined aquifer, once the solution is found, the location of the toe can be tracked using the above equations. In our problem, we consider a two– dimensional geometry of infinite coastal plain bounded by a straight coastline fig 4:

A pumping well with discharge Q_w is located at a distance x_w from the coast. There are also exists a uniform freshwater outflow of rate *q*. the aquifer can be either confined or unconfined .Solution of this problem can be found by the method of images for multiples pumping wells and is given by (Strack, 1976):

$$\Phi = \frac{q}{k}x + \sum_{i=1}^{n} \frac{Q_{w(i)}}{4\pi k} \ln[\frac{(x-x_{w(i)})^2+(y-y_{w(i)})^2}{(x+x_{w(i)})^2+(y-y_{w(i)})^2}] \quad (11)$$

where (x_w, y_w) are well coordinates, Q_w is the pumping rate of well i., and *k* is the hydraulic conductivity. The toe location x_{toe}can be solved from:

$$\Phi_{toe} = \frac{q}{k}x_{toe} + \sum_{i=1}^{n} \frac{Q_{w(i)}}{4\pi k} \ln[\frac{(x_{toe}-x_{w(i)})^2+(y_{toe}-y_{w(i)})^2}{(x_{toe}+x_{w(i)})^2+(y_{toe}-y_{w(i)})^2}] \quad (12)$$

When freshwater is located above the saltwater in underground aquifers, pumping water from a well in the aquifer, causing the boundary level between saltwater and freshwater rise below the well. This reaction is the reduction in pressure on the boundary between two fluids below the well because of reduction of the groundwater level in sides of the well. The form of rising boundary level between two fluids is similar to cone. And it is known to upconing. Maximum height of upconing is located below the well, where the maximum reduction of water level has occurred. If the pumping rate is relatively high, and if the bottom of the well is near to the surface of the boundary between saltwater and freshwater then upconing of seawater may reach into the well. If you stop pumping water, saltwater is heavier than fresh water moves down into position before starting of pumping. Under steady flow of freshwater into horizontal wells, saltwater moves in the vertical direction, and the specific exact interface between the two fluids, height of upconing in the below well axis (z) by using of the Ghyben - Herzberg equation wrote as follows [15] and [16]:

$$z = \frac{\rho_f}{\rho_s-\rho_f} S_w \quad (13)$$

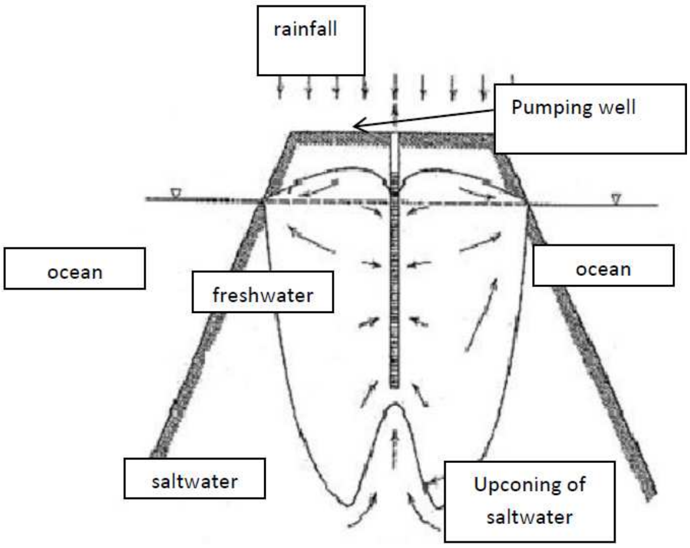


Figure 5: freshwater lens on an oceanic island in natural conditions

Where S_w is drawdown of groundwater level in well, ρ_f is density of freshwater and ρ_s is density of saltwater. [6] determined by below exact equation the height of upconing of the saltwater below well axis:

$$z = \frac{Q\rho_f}{2\pi(\rho_s-\rho_f)\, d\, K_x} \quad (14)$$

Where z is final elevation or balanced height of saltwater upconing below the well, K_x is aquifer hydraulic conductivity and d is depth of interface of between saltwater and freshwater from below the well before start of pumping (sea Figure 5 and 6). Field and laboratory measurements have shown that equation (14) for values of z/d from 0.3 to 0.5 is true; so if the bottom limit 0.3 is the criterion, the pumping rate is the maximum allowed without a wedge of saltwater into the wells to be as follows:

$$Q_{max} = 0.6\pi d^2 K_x \frac{\rho_s-\rho_f}{\rho_f} \quad (15)$$

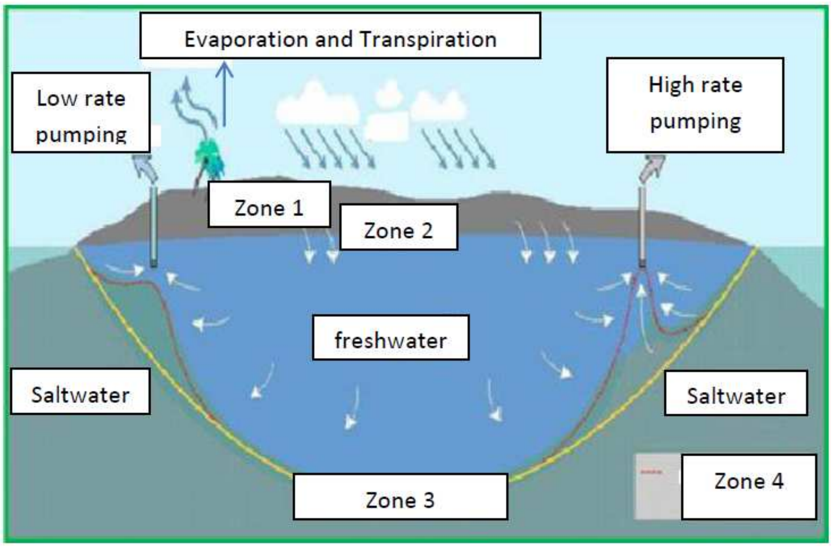


Figure 6: freshwater lenses on a small oceanic island with pumping wells, zone1 is recharge zone, zone 2 is underground water, zone 3 is boundary of freshwater and saltwater in steady state (yellow line), zone 4 is boundary of freshwater and saltwater in unsteady state (red line)

Last assumed ignoring the thickness of the transitional boundary between salt and fresh water As a result of this boundary is considered to be one page. Relation to the boundaries of saltwater and freshwater depends on the size of the island, aquifer hydraulic conductivity and recharge rates as follows:

$$z = [\frac{w}{0.05125k}(R^2 - r^2)]^{\frac{1}{2}} \qquad (16)$$

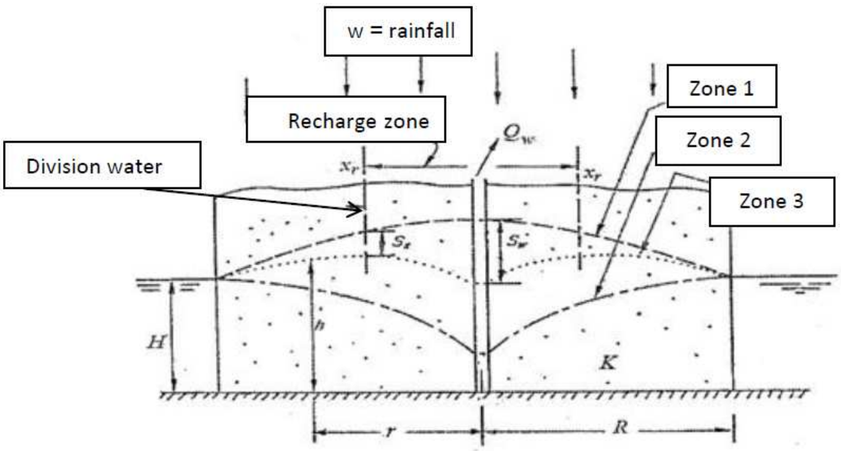


Figure 7: a circular island with a central well in the center of the aquifer and rainfall, zone1 is underground water surface with rainfall and no pumping, zone2 is underground water surface with no rainfall and pumping, zone3 is underground water surface with rainfall and pumping

Where z is the depth of the interface below sea level at radius r, R the radius of the circular-shaped island, w is effective recharge rate as result of rainfall and k is aquifer hydraulic conductivity. Figure (7) a well has been drilled completely to the bottom impervious layer of the aquifer in the island. The island form is almost a circle that R is the radius of it. The rain is fall with w rate on the island and recharges the aquifer. Wells drilled in the middle of the island and the water is pumped at a rate of Q_w in stable condition. Extraction of underground water level equation during pumping is as follows:

$$H^2 - h^2 = \frac{Q_w}{\pi K}\ln\frac{R}{r} - \frac{w}{2K}(R^2 - r^2) \qquad (17)$$

2. Thickness of fresh and seawater interface

The thickness of the fresh and seawater interface depends on a few factors such as the freshwater flows, tidal fluctuations and exploitation of groundwater aquifers. Interface can be measured with samples from various depths in a well drilled near the beach and chemical analysis of them. Electrical conductivity in depth and the depth of the water are plotted on the coordinate system. If electrical conductivity changes in depth then interface depth will specify. Verruijt showed surface groundwater and surface interface between fresh and seawater in homogeneous aquifer are parabolic.

Height of groundwater level to sea level is h_f (see fig (1) and (2)).

$$h_f = \sqrt{\frac{2\beta q x}{k(1+\beta)}} \tag{18}$$

Height of surface interface between fresh and seawater to sea level is $\mathbf{h_s}$ (see fig (1), (2) and (3)).

$$\mathbf{h_s} = -\sqrt{\frac{2qx}{\beta k(1+\beta)} + \frac{1-\beta}{1+\beta} \quad \frac{q^2}{\beta^2 k^2}} \tag{19}$$

$$x_0 = \frac{Q}{2\beta K} \tag{20}$$

Where x is the distance from the point to the seaside and the land direction is positive. $\mathbf{h_s}$ is height of interface surface from the sea level that is positive upward. h_f is height of groundwater surface to sea level. q is amount of freshwater discharge per length unit to the sea. β equals $\frac{\rho_s-\rho_f}{\rho_f}$ and K is permeability coefficient.

Hydraulic Gradient in Coastal Aquifer

Hydraulic gradient in coastal aquifer is calculated using groundwater levels Measurement in observation wells and nivellement of wells relative to sea level. Hydraulic gradient is calculated at some sections that have not the annual statistics of observation wells by using of hydraulic gradient curves obtained for the 7-years average of the other sections.

Hydrodynamic coefficients of the coastal aquifer

For determination of hydrodynamic coefficients in the five kilometers strip of seaside are used from the pumping wells data in the area and calculated hydrodynamic coefficients of them. Transmissivity coefficients from pumping tests are presented in Table 1.

Density of freshwater and seawater

Coastal aquifer water density has considered equal to 1$(\frac{g}{cm^3})$ in all prepared reports. Density of seawater is considered equal to 1.0185 $(\frac{g}{cm^3})$ in Mazandaran Sea.

RESULTS AND DISCUSSION

Table1: Hydrodynamic coefficients of the sections A-Q in Mazandaran coastal aquifers

Density of salt water $(\frac{g}{cm^3})$	Density of fresh water $(\frac{g}{cm^3})$	Distance of two sections along the seaside (m)	T $(\frac{m^2}{day})$	freshwater Thickness (m)	Slope of water table (%)	UTM y	UTM x	Position Name	Section number
1.0185	1	3324	200	28	0.6	4082118	477717	Mian Haleh	A
1.0185	1	3110	160	50	0.87	4080317	480663	Noroddin Mahaleh	B
1.0185	1	8922	150	24	0.45	4079127	482755	Shiroud	C
1.0185	1	12258	540	52	0.45	4070943	495574	Mirshamseddin	D
1.0185	1	11035	400	67	0.3	4067130	503880	Nashtaroud	E
1.0185	1	9832	250	41	0.521	4063485	516263	Tazeh Abad	F
1.0185	1	12737	310	25	0.82	4062373	523062	Kelar Abad	G
1.0185	1	15523	270	35	0.45	4058747	541203	Majid Abad	H
1.0185	1	13513	200	63	0.23	4053424	552814	Tejardeh	I
1.0185	1	11902	200	28	1.1	4049915	566685	Androud	J
1.0185	1	8453	220	28.5	1.13	4048571	576268	Salaheddin Kala	K
1.0185	1	10727	200	47.5	0.9	4048255	583265	Galandroud	L
1.0185	1	12389	150	19	0.11	4050787	597915	Rostam Kala	M
1.0185	1	12591	150	23.75	0.173	4053920	607351	Kheshtsar	N
1.0185	1	11898	180	47.5	0.11	4058272	621227	West of Haraz river	O
1.0185	1	10028	180	23.75	0.083	4061092	630079	Haraz river	P
1.0185	1	10826	150	28.5	0.249	4062604	640601	Darya kenar	Q

Interaction of seawater and freshwater in Mazandaran Aquifers

Variation of transmissivity coefficients is 540 to 150 (m^2/day) from Ramsar (section A) to Daryakenar (section Q). Changes in aquifer thickness are from 67 to 24 meters, and changes in hydraulic gradient of groundwater are between 1.13 to 0.23 percent. Maximum seawater intrusion into coastal aquifers (x_{max}) is variable 254 meters at the section I to 15.8 meters at the section J. Latitudinal permeability of freshwater (x_0) from coastline to the sea is variable between 12.16 m at section L and 2.9 m at section C. Groundwater discharge per unit length of coastline is variable between 2.5 to 0.5 (m^3/day) from Ramsar area (section A) to Galandroud (section L). Maximum discharge is at east of Kojoor and Kelarabad and minimum discharge is at section I that is located in east of Noshahr. Variation of transmissivity coefficients is 180 to 150 (m^2/day) from Rostamroud (section M) to west of Babolsar (section Q). Changes in aquifer thickness are from 50 to 20 meters, and changes in hydraulic gradient of groundwater are 0.25 to 0.08 percent. Maximum seawater intrusion into coastal aquifers (x_{max}) is variable 426.8 meters at the section O to 15.8 meters at the section Q. Latitudinal permeability of freshwater (x_0) from coastline to the sea is variable between 2.02 m at section Q and 0.56 m at section P. Groundwater discharge per unit length of coastline is variable between 0.4 to 0.2 (m^3/day) from Rostamroud area (section M) to west of Babolsar (section Q). Maximum discharge is at west of Babolsar (section Q) and minimum discharge is at section M, O and P. The average discharge rate calculated 0.26 (m^3/day) per unit length of coastline which is about 6 times smaller than the average discharge rate at the Ramsar – Galandroud zone (1.575 m^3/day per unit length of coastline), see Table 2 and fig 8.a, 8.b and 8.c.

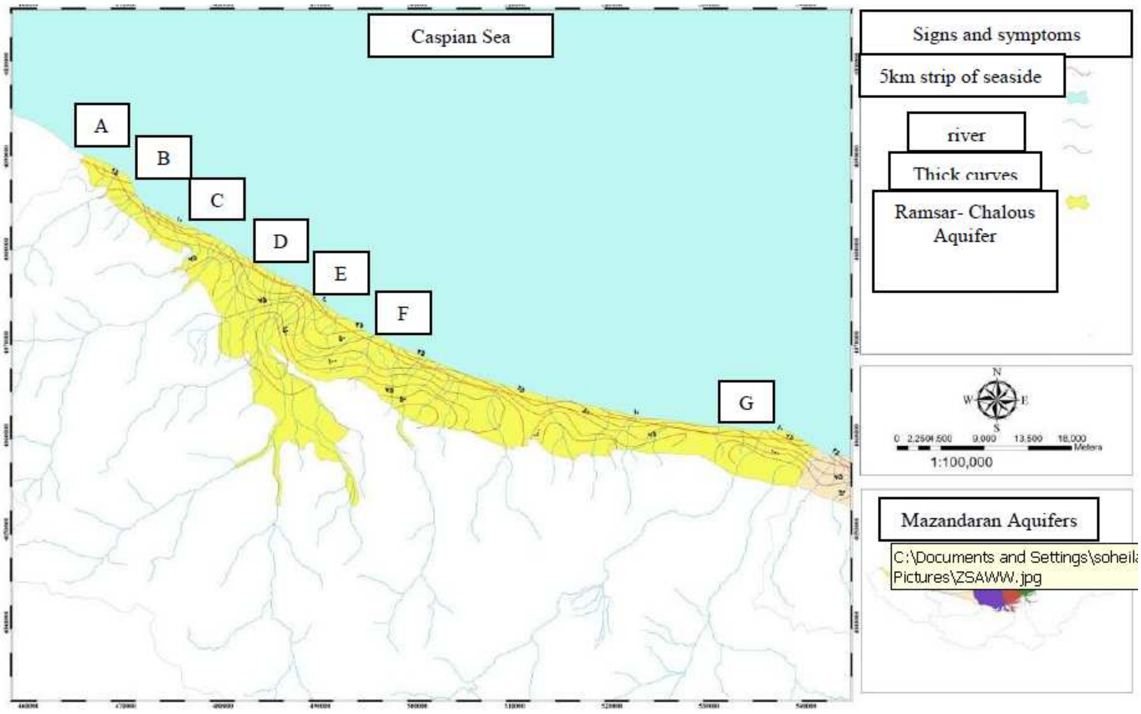


Figure 8: a. sections (A- G) in Ramsar- Chalous Aquifer

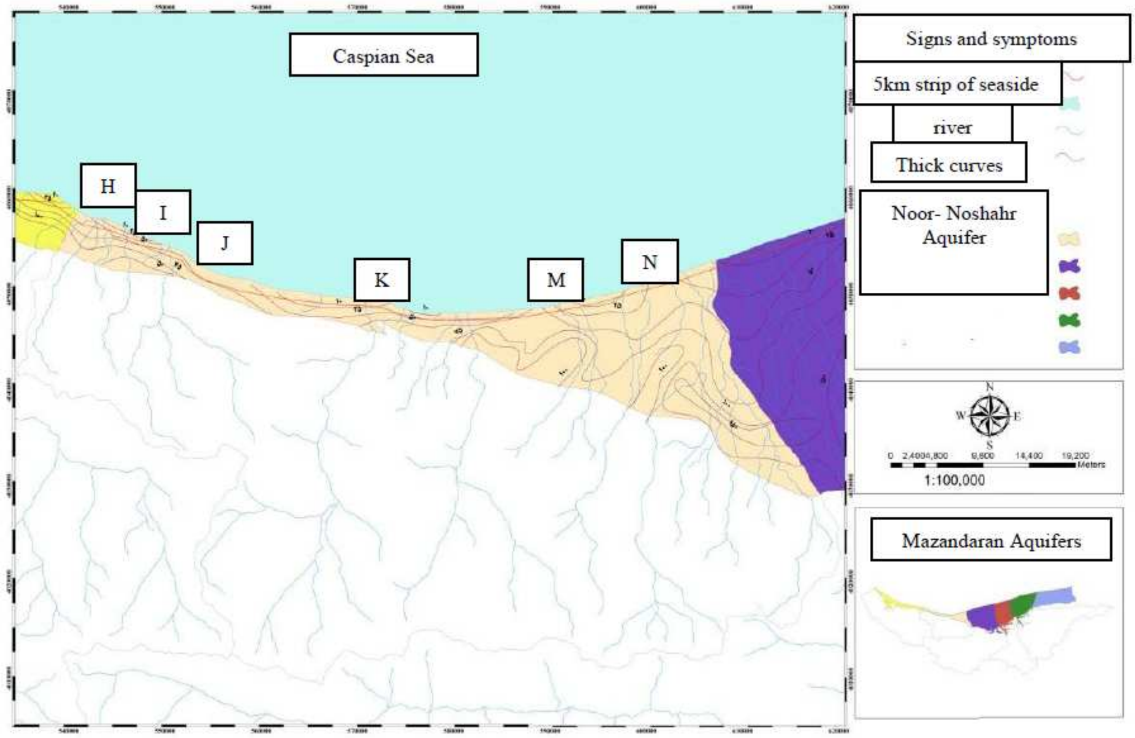


Figure 8: b. sections (H- N) in Noor- Noshahr Aquifer

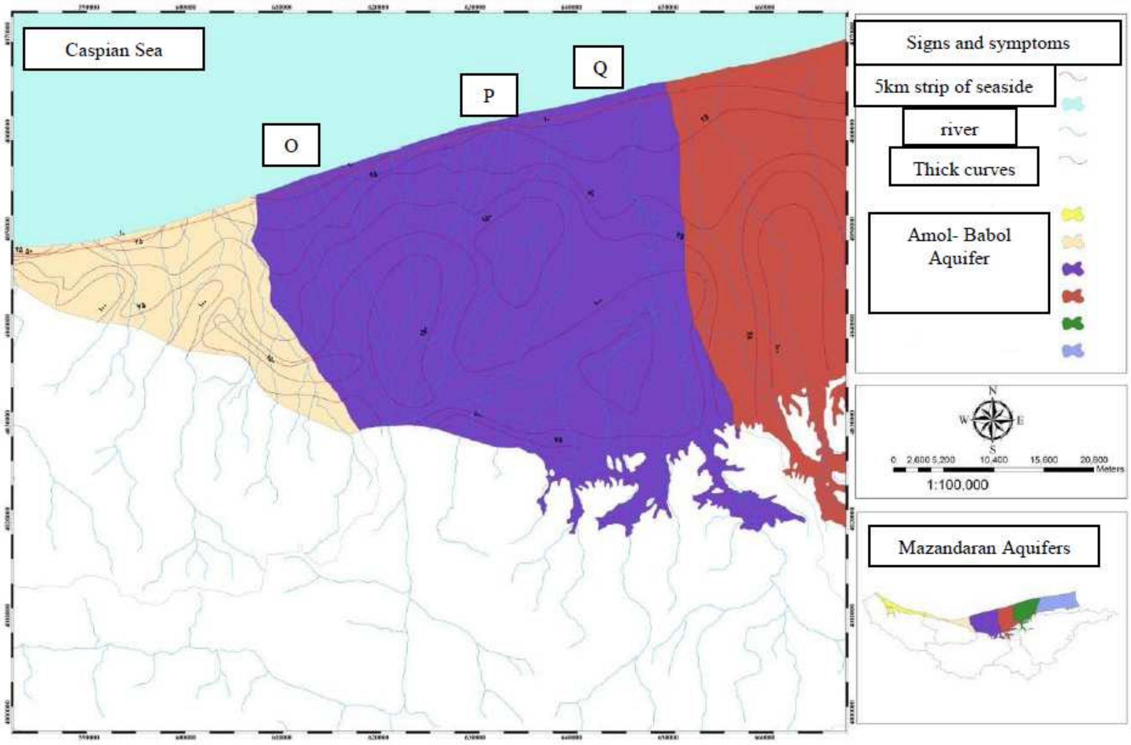


Figure 8: c. sections (O- Q) in Amol- Babol Aquifer

Table 2.a Characteristics of interface between sea and freshwater at sections

$H_w(m)$	Z(m)	X(m)	Q_{all} $\frac{m^3}{day.m}$	x_0 (m)	x_{max} (m)	Q $\frac{m^3}{day.m}$	K $\frac{m}{day}$	position	section
0	2.85	-4	1.2	4.54	39.51	1.2	7.14	Mian Haleh	A
0	8.91	0							
0.25	16.06	10							
0.37	21.72	22							
0.43	24.79	30							
0.49	28	39.51							
0	23.08	0	1.39	11.76	42.61	1.39	3.2	Noroddin Mahaleh	B
0.36	30.04	8							
0.49	35.01	15							
0.63	41.07	25							
0.74	46.36	35							
0.82	50	42.61							
0	5.73	0	0.67	2.92	47.38	0.68	6.25	Shiroud	C
0.2	12.14	10							
0.24	14.31	15							
0.31	17.87	25							
0.37	20.83	35							
0.43	24	47.38							
0	12.42	0	2.43	6.32	102.7	2.43	10.4	Mirshamseddin	D
0.29	20.06	10							
0.41	25.51	20							
0.58	33.88	40							
0.71	40.55	60							
0.82	46.27	80							
0	10.67	0	1.2	5.43	205.1	1.2	5.97	Nashtaroud	E
0.54	31.1	40							
0.76	42.67	80							
0.94	51.71	120							
1.08	59.39	160							
1.22	67	205.07							
0	11.33	0	1.3	5.77	68.47	1.3	6.1	Tazeh Abad	F
0.34	21.65	15							
0.44	26.37	25							
0.52	30.37	35							
0.59	33.89	45							
0.73	41	68.47							

Table 2.b Characteristics of interface between sea and freshwater at sections

$H_w(m)$	Z(m)	X(m)	Q_{all} $\frac{m^3}{day.m}$	x_0 (m)	x_{max} (m)	Q $\frac{m^3}{day.m}$	K $\frac{m}{day}$	position	section
0	8.65	-2	2.54	5.54	23.28	2.54	12.4	Kelar Abad	G
0.12	12.72	0							
0.17	14.33	4							
0.24	17.1	8							
0.35	21.6	16							
0.42	25	23.28							
0	8.36	0	1.22	4.26	69.1	1.22	7.71	Majid Abad	H
0.2	13.67	7							
0.29	17.91	15							
0.34	20.1	20							
0.45	25.59	35							
0.53	30.1	50							
0	7.69	0	0.46	3.92	254.2	0.46	3.17	Tejardeh	I
0.51	28.78	50							
0.73	39.96	100							
0.89	48.64	150							
1.03	55.99	200							
1.16	63	254.21							
0	16.34	0	2.2	8.32	15.81	2.2	7.14	Androud	J
0.21	19.95	4							
0.26	21.52	6							
0.32	23.69	9							
0.37	25.68	12							
0.42	28	15.81							
0	17.99	0	2.49	9.16	16.02	2.49	7.33	Salaheddin Kala	K
0.22	21.62	4							
0.29	23.99	7							
0.35	26.14	10							
0.4	28.13	13							
0.44	30	16.02							
0	23.88	0	1.8	12.16	40.4	1.8	4	Galandroud	L
0.36	30.86	8							
0.48	35.2	14							
0.57	39.06	20							
0.7	44.76	30							
0.81	50	40.4							

Table 2.c Characteristics of interface between sea and freshwater at sections

$H_w(m)$	Z(m)	X(m)	Q_{all} $\frac{m^3}{day.m}$	x_0 (m)	x_{max} (m)	Q $\frac{m^3}{day.m}$	K $\frac{m}{day}$	position	section
0	1.17	0	0.17	0.59	170.07	0.17	7.5	Rostam Kala	M
0.17	9.12	35							
0.24	12.84	70							
0.28	15.33	100							
0.33	18.12	140							
0.37	20	170.71							
0	2.29	0	0.26	1.17	135	0.26	6	Kheshtsar	N
0.14	10.96	13							
0.25	13.74	40							
0.31	16.75	60							
0.38	20.46	90							
0.46	25	135							
0	2.92	0	0.2	1.49	426.8	0.2	3.6	West of Haraz river	O
0.4	21.81	80							
0.63	34.29	200							
0.75	40.54	280							
0.84	45.3	350							
0.92	50	426.77							
0	1.1	0	0.15	0.56	283.2	0.15	7.2	Haraz river	P
0.21	11.55	60							
0.27	14.88	100							
0.34	18.21	150							
0.39	21.02	200							
0.46	25	283.22							
0	3.96	0	0.37	2.02	111.5	0.37	5	Darya kenar	Q
0.16	9.75	10							
0.31	17.12	35							
0.37	20.3	50							
0.45	24.71	75							
0.55	30	111.53							

Determination Limitation for seawater intrusion to the coastal aquifer

Depth of wells in coastal aquifer is a function of water required and aquifer thickness. The average depth of wells in each of these sections is half of the aquifer thickness. It is assumed that 10 percent of the thickness of below the aquifer is contaminated with saltwater. Thickness of the aquifers and hydraulic gradients change. Based on these new data, the maximum advance of saltwater into the aquifer (x_{max}) is calculated that is given in Table 3. In Table (4) allowable limit of seawater intrusion into coastal aquifers in available condition and hypothetical condition (contaminated 10% of below the aquifer thickness) are presented. These data show that the maximum advancing seawater in coastal aquifers in existing condition is 426.8 meters at O section that appears in hypothetical condition to 470 meters. Analysis of the data related to interface in Table 4 show that maximum advancing saltwater in aquifer from M to Q section is more than the other sections and groundwater output discharge in M to Q section is less than the other sections, thus possibility of development is not for exploitation of these sections.

Determination of allowable exploitation from Mazandaran coastal aquifer

Given the maximum extent of seawater intrusion to the coastal aquifer, (x_{max}), at any section you can use the following formula to calculate the amount of allowable discharge. Also in Table 4 are presented (x_{max}) and annual output volume of groundwater discharge in hypothetical condition (contaminated 10% of below the aquifer thickness). Subtracting annual output volume of groundwater discharge in Hypothetical condition from available condition gives development rate of exploitation at every section. In Table 5 evaluation figures show that the development rate of operation in A, B, O and P sections are less than the other sections.

$$Q^2\left(\frac{1-\beta}{\beta K}\right) + 2Qx_{max} - Z^2\beta K(1+\beta) = 0 \qquad (21)$$

Table 3. Hydrodynamic coefficients of the sections A-Q in Mazandaran coastal aquifers in hypothetical condition (contaminated 10% of below the aquifer thickness)

Density of salt water ($\frac{g}{cm^3}$)	Density of fresh water ($\frac{g}{cm^3}$)	Distance of two sections along the seaside (m)	T ($\frac{m^2}{day}$)	freshwater Thickness (m)	Slope of water table (%)	UTM y	UTM x	Position Name	Section number
1.0185	1	3324	200	25.2	0.49	4082118	477717	Mian Haleh	A
1.0185	1	3110	160	45	0.73	4080317	480663	Noroddin Mahaleh	B
1.0185	1	8922	150	21.6	0.37	4079127	482755	Shiroud	C
1.0185	1	12258	540	46.8	0.37	4070943	495574	Mirshamseddin	D
1.0185	1	11035	400	60.3	0.24	4067130	503880	Nashtaroud	E
1.0185	1	9832	250	36.9	0.43	4063485	516263	Tazeh Abad	F
1.0185	1	12737	310	22.5	0.69	4062373	523062	Kelar Abad	G
1.0185	1	15523	270	31.5	0.37	4058747	541203	Majid Abad	H
1.0185	1	13513	200	56.7	0.19	4053424	552814	Tejardeh	I
1.0185	1	11902	200	25.2	0.94	4049915	566685	Androud	J
1.0185	1	8453	220	27	0.97	4048571	576268	Salaheddin Kala	K
1.0185	1	10727	200	45	0.76	4048255	583265	Galandroud	L
1.0185	1	12389	150	18	0.09	4050787	597915	Rostam Kala	M
1.0185	1	12591	150	22.5	0.14	4053920	607351	Kheshtsar	N
1.0185	1	11898	180	45	0.09	4058272	621227	West of Haraz river	O
1.0185	1	10028	180	22.5	0.07	4061092	630079	Haraz river	P
1.0185	1	10826	150	27	0.2	4062604	640601	Darya kenar	Q

Table 4. Comparison of seawater intrusion in available condition and hypothetical condition (contaminated 10% of below the aquifer thickness)

10% Aquifer thickness has been Polluted from below				Available condition				Distance of two sections along seaside (m)	Section number
V_{out} MCM/Year	Q_{out} $m^3/day/$m	x_{max} (m)	Aquifer thickness (m)	V_{out} MCM/Year	Q_{out} $m^3/day/$m	x_{max}(m)	Aquifer thickness (m)		
1.189	0.98	45.2	25.2	1.456	1.2	39.5	28	3324	A
1.328	1.17	49.4	45	1.589	1.4	42.6	50	3110	B
1.791	0.55	52.9	21.6	2.279	0.7	47.4	24	8922	C
8.948	2	114.6	46.8	10.74	2.4	103	52	12258	D
3.866	0.96	233	60.3	4.833	1.2	205	67	11035	E
3.875	1.08	76.6	36.9	4.665	1.3	68.5	41	9832	F
9.948	2.14	26.6	22.5	11.62	2.5	23.3	25	12737	G
5.665	1	77	31.5	6.8	1.2	69	35	15523	H
1.874	0.38	278	56.7	2.466	0.5	254	63	13513	I
8.167	1.88	19	25.2	9.557	2.2	15.8	28	11902	J
6.571	2.13	19.3	27	7.713	2.5	16	30	8453	K
5.951	1.52	46.7	45	7.047	1.8	40.4	50	10727	L
0.633	0.14	188	18	0.904	0.2	170	20	12389	M
0.965	0.21	150.6	22.5	1.378	0.3	135	25	12591	N
0.694	0.16	470	45	0.868	0.2	427	50	11898	O
0.475	0.13	302	22.5	0.732	0.2	283	25	10028	P
1.185	0.3	126	27	1.58	0.4	111	30	10826	Q

Sensitivity Analysis

As results of pumping tests on 60 operated wells in every section (A to Q) of Mazandaran aquifers obtained Transmissivity coefficient 150 to 540 m^2/day, freshwater thickness 19 to 67 (m). Hydraulic conductivity coefficient is T/b that is limited between 3 m/day to 12.4 m/day. We obtained that maximum seawater intrusion in section O is because of hydraulic conductivity, hydraulic gradient and output groundwater discharge less than other sections and freshwater thickness more than its near sections.

Table 5. Development of exploitation of groundwater resources in Mazandaran coastal aquifers in two conditions

Development of using water resources in coastal aquifers	10% Aquifer thickness from below has been Polluted		Available condition		Distance of two sections along seaside (m)	Section number
$V_{operation}$ MCM/Year	V_{out} MCM/Year	x_{max} (m)	V_{out} MCM/Year	x_{max}(m)		
1.456 - 1.189= 0.267	1.189	45.2	1.456	39.5	3324	A
1.589-1.328= 0.261	1.328	49.4	1.589	42.6	3110	B
0.448	1.791	52.9	2.279	47.4	8922	C
1.79	8.948	114.6	10.74	103	12258	D
0.967	3.866	233	4.833	205	11035	E
0.79	3.875	76.6	4.665	68.5	9832	F
1.674	9.948	26.6	11.62	23.3	12737	G
1.135	5.665	77	6.8	69	15523	H
0.592	1.874	278	2.466	254	13513	I
1.39	8.167	19	9.557	15.8	11902	J
1.142	6.571	19.3	7.713	16	8453	K
1.096	5.951	46.7	7.047	40.4	10727	L
0.271	0.633	188	0.904	170	12389	M
0.413	0.965	150.6	1.378	135	12591	N
0.174	0.694	470	0.868	427	11898	O
0.257	0.475	302	0.732	283	10028	P
0.395	1.185	126	1.58	111	10826	Q

CONCLUSION

Changes of hydraulic gradient in groundwater aquifer are caused advance of saltwater far away the sea at the coast. This phenomenon is called seawater intrusion. x_{max} (Maximum seawater intrusion) in sections of Mazandaran coastal aquifers and allowable development of exploitation of this area have been calculated. These data show that the maximum advancing seawater in coastal aquifers in existing condition is 426.8 meters at O section that appears in hypothetical condition (contaminated 10% of below the aquifer thickness) to 470 meters. Analysis of the data related to interface in Table 4 show that maximum advancing saltwater in aquifer from M to Q section is more than the other sections**.** Results show that development of exploitation is not possible for section A, B and O among total sections of Mazandaran coastal aquifers.

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