Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env. Pharmacol. Life Sci., Vol 2 (11) October 2013: 30-38

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com

ORIGINAL ARTICLE

Possibility of Groundwater Operation in Coastal Aquifers for Prevention of Seawater Intrusion

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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 Azarshahr coastal aquifer is calculated by relationships that have been used in previous researches. According to available information,x_{max} (maximum seawater intrusion) in sections of Azarshahr coastal aquifers and allowable development of exploitation of this area have been calculated. Results show that development of exploitation is not possible fora distance of less than 1,000 meters from the sea.
Keywords: length of seawater intrusion, coastal water resources management, *groundwater, saline, height of interface from sea level.*

Received 19/08/2013 Accepted 27/09/2013

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 salt water 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[2, 3].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 [4] and [5]. The management models applications in saltwater intrusion, is relatively recent, [6], [7], [8], [9], [10], [11], [12], [13], [14], [6], [1], [11], [19[20], [21], [8], [22], [23] 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.

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

$P_A = \rho_s g h_s$(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:

$P_B = \rho_f g h_f + \rho_f g h_s$ (2)

ρ_f isdensity 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 relationshipwould obtain as follows (see Fig (1), (2) and (3)):

$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f$ (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:

$h_s = 40 h_f$ (4)

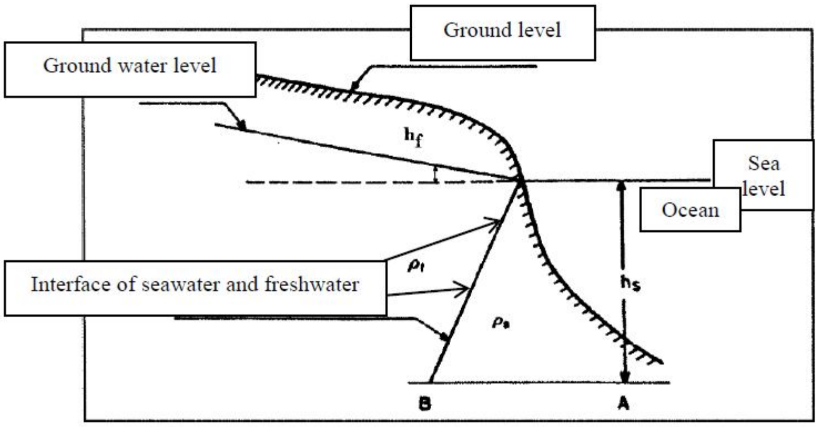


Figure1:Ghyben – Herzberg relationship parameters [25]

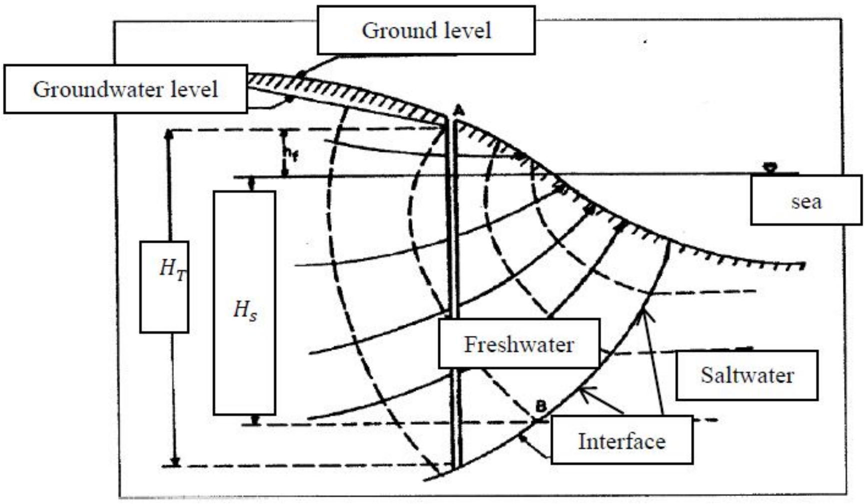


Figure 2: Ghyben – Herzberg relationship parameters.
H_T is exact depth of interface and
H_s is depth of interface based on Ghyben- Herzberg relationship that is lesser than H_T [23].

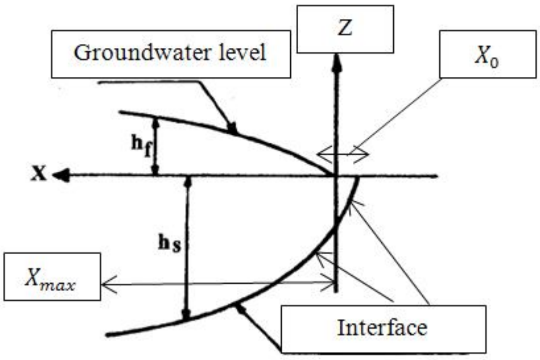
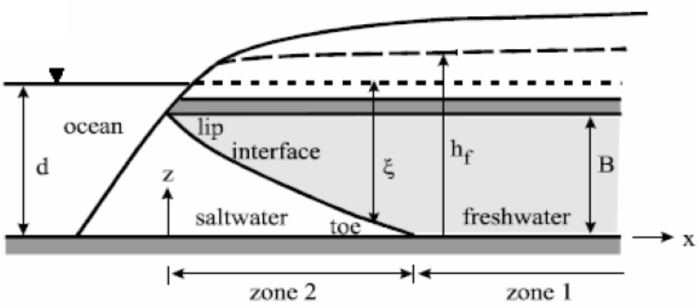


Figure 3: Ghyben – Herzberg relationship parameters[25].

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.[26] 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). Strack, 1976[24] that for a homogeneous aquifer of constant thickness, a potential Φ which is continuous across the two zones, can be defined:

(a)



(b)

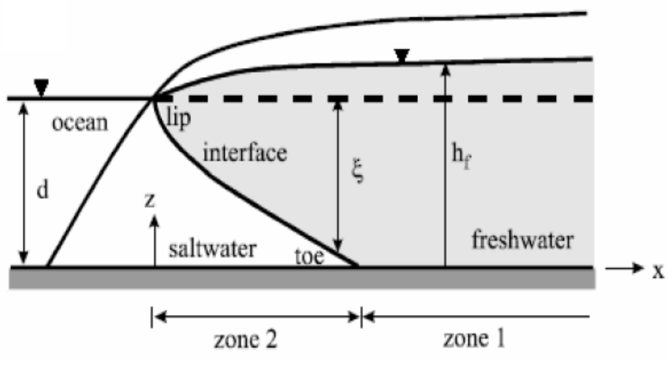


Figure 4: Definition sketch of saltwater intrusion in (a) a confined aquifer, and (b) anunconfined aquifer [26].

For confined aquifer:

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

For unconfined aquifer:

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

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

$$s = \frac{\rho_s}{\rho_f} \quad (7)$$

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.

$\Delta\Phi=0$(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:

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

$\Phi_{toe} = \frac{s(s-1)}{2} d^2$ For unconfined aquifer, $\Phi_{toe} = \frac{(s-1)}{2} B^2$ for confined aquifer (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 [24].

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

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:

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

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 [2] and [3]:

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

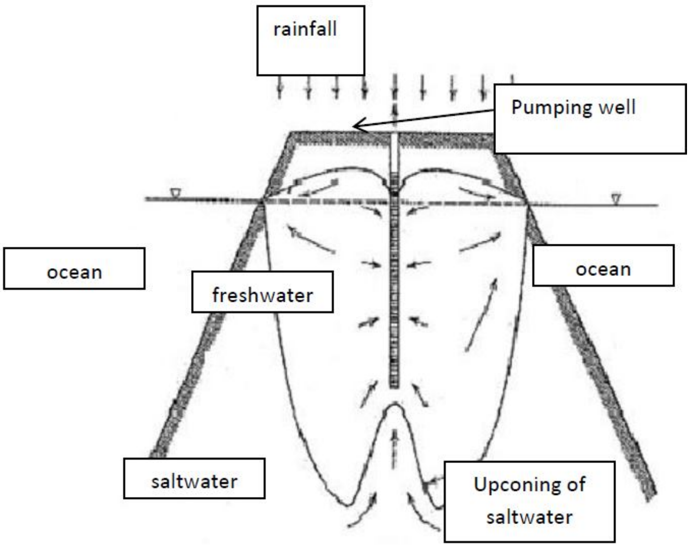


Figure5: fresh water lens on an oceanic is land in natural conditions [25]

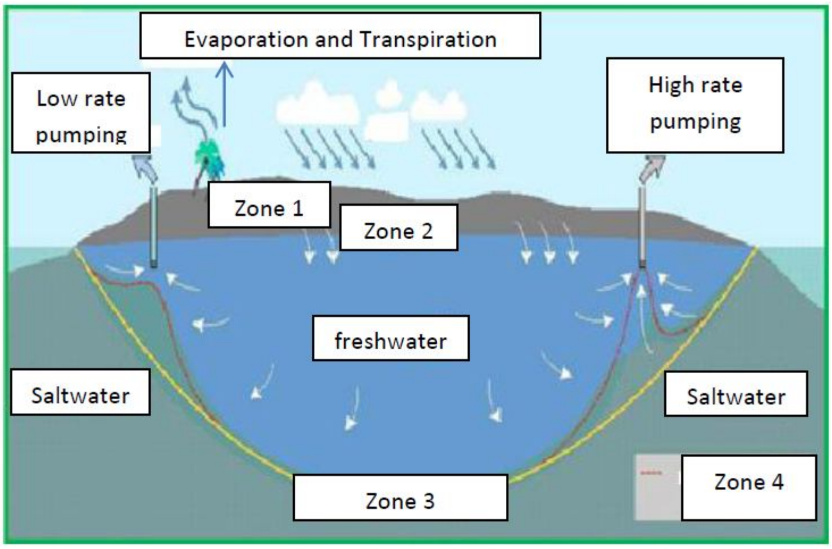


Figure 6:freshwaterlensesona small oceanic island with pumping wells, zone1 is recharge zone, zone 2 is underground water, zone 3 is boundary of freshwater and saltwater in steady state (yellow line), zone 4 is boundary of freshwater and saltwater in unsteady state (red line)[23].

Where S_w isdrawdown of groundwater level in well, $\rho_f$is density of freshwaterand ρ_s is density of saltwater. [17] determined by below exactequationtheheightof upconing of the saltwaterbelow wellaxis:

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

Where z is final elevation or balanced height of saltwater upconing below the well, $K_x$is aquiferhydraulic 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 from0.3to0.5is true; so if the bottom limit0.3 is the criterion, the pumping rate is the maximum allowed without a wedge of salt water into the wells to be as follows:

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

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

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

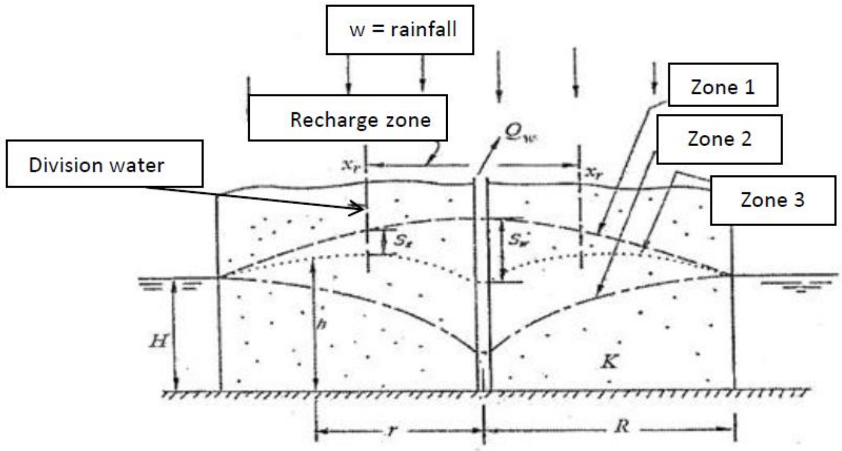


Figure 7:a circular island with a central well in the center of the aquifer and rainfall, zone1 is underground water surface with rainfall and no pumping, zone2 is underground water surface with no rainfall and pumping, zone3 is underground water surface with rainfall and pumping[23].

Where z is the depth of the interface below sea level atradiusr, R the radius of the circular-shaped island, w is effective recharge rateas result of rain fall 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$Q_w$instable condition. Extraction of underground water level equation during pumping is as follows:

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

MATERIALS AND METHODS

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)).

$$h_f = \sqrt{\frac{2\beta qx}{k(1+\beta)}} \quad (18)$$

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

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

$$x_0 = \frac{Q}{2\beta K} \quad (20)$$

Where x is the distance from the point to the seaside and the land direction is positive. $h_s$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.

Calculation interface between freshwater and saltwater to sea surface in coastal aquifers of Azarshahr plain:
In 1998, hydraulic gradient is 0.022 at the beginning of Azarshahr plain and the end of Azarshahr plain is 0.005 in output close to the Urmialake. In 2005, hydraulic gradient is 0.020 at the beginning of Azarshahr plain and the end of Azarshahr plain is 0.007 in output close to the lakeUrmia.

Table 1: Details of Groundwater Resources of Azarshahr Plain [27]:

Average discharge flow	Lake water level	Maximum of groundwater table	Average of (b)	Average of (i)	Average of(T)	Average of (H)	Average of (S)	Average of(K)	Azarshahr plain
250974 $\frac{m^3}{d}$	1277	1430	15629	14×10^{-3}	1088	76.3m	3	14.27 m/day	1995
294103 $\frac{m^3}{d}$	1273	1430		12×10^{-3}		78.4m		13.88 m/day	2004

RESULTS AND DISCUSSION

Freshwater discharge flow per length unit in the Azarshahr plainin 1995:

$$q=T.I= [1088.65(\frac{m^3}{m.day})/86400(\frac{day}{s})]\times 14.75\times 10^{-3}= 1.857\times 10^{-4}(m^3/s)/m \quad (21)$$

K=T/H= Coefficient of transmissibility/Mean maximum water levels of the lake

$$= 1088.75(m/day)/ 76.3(m) = 14.27\ \frac{m^2}{day}$$

Height the aquifer level to sea surface,h_f and height interface between freshwater and saltwater to sea surface for a distance x = 1000 meters in coast, h_s:

$$h_f=\sqrt{\frac{2\beta qx}{k(1+\beta)}} = 7.408m\ ,h_s= \sqrt{\frac{2qx}{\beta k(1+\beta)} + \frac{1-\beta}{1+\beta}\frac{q^2}{\beta^2 k^2}} = 299m \quad (22)$$

By the Ghyben - Herzberg relationship we have: h_s = 296.31 m

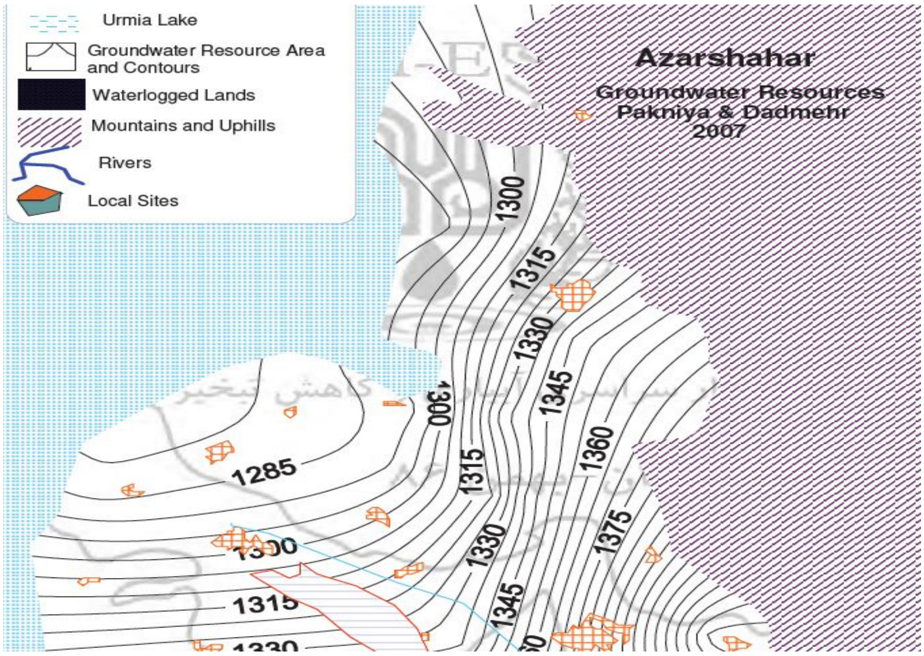


Figure 8: Map of Groundwater level Curves in Azarshahr Plain in 1995 [27].

Freshwater flow per length unit in the Azarshahr plain in 2005:

$q= T.I= [1088.65(\frac{m^3}{m.day})/86400(\frac{day}{s})]\times12.63\times10^{-3}= 1.591\times10^{-4}(m^3/s)/m$ (23)

K=T/H= Coefficient of transmissibility/Mean maximum water levels of the lake

$= 1088.75(m/day)/78.4(m) = 13.887 \frac{m^2}{day}$

Height the aquifer level to sea surface, h_f and interface between freshwater and saltwater to sea surface for a distance x = 1000 meters in coast, h_s:

$h_f=\sqrt{\frac{2\beta qx}{k(1+\beta)}}= 6.491m, h_s = \sqrt{\frac{2qx}{\beta k(1+\beta)} + \frac{1-\beta}{1+\beta}\frac{q^2}{\beta^2k^2}} = 74.68m$(24)

Freshwater flow per length unit in the end of Azarshahr plain and around Teimourloo Village in 1995:

$q= T.I =[17.3(\frac{m^3}{m.day})/86400(\frac{day}{s})]\times5\times10^{-3}= 1\times10^{-6}(m^3/s)/m$, (25)

K=T/H= Coefficient of transmissibility/Mean maximum water levels of the lake=

17.3 (m/day)/ ((1330 (m) =Groundwater level in Teimourloo Village) – (1277.3976.3 = Groundwater level in Urmia lake (m))) = $0.328 \frac{m^2}{day}$

Height the aquifer level to sea surface, h_f and interface between freshwater and saltwater to sea surface for a distance x = 1000 meters in coast, h_s:

$h_f=\sqrt{\frac{2\beta qx}{k(1+\beta)}}= 3.583m, h_s = \sqrt{\frac{2qx}{\beta k(1+\beta)} + \frac{1-\beta}{1+\beta}\frac{q^2}{\beta^2k^2}} = 145m$ (26)

By the Ghyben - Herzberg relationship we have: h_s =143.33m

For the salt water does not in trudemore than x=1,000 m to the coast, the pumping of existing wells can be obtained by [1] relationship andh_s= 25 m:

$q^2(\frac{1-\beta}{\beta k})+ 2xq- (h_s^2)\ \beta k(1+\beta)=0$(27)

After solving the above relationship the amount of with drawable water per length unit in Azarshahr plain and around Teimourloo Village in 1995is obtained:

$q =3 \times 10^{-8}(\frac{m^3}{m.s})$

Amount of remained withdrawable water per length unit in Azarshahr plain and around Teimourloo Village in 1995for future operationis obtained

$q= 1.0\times10^{-6}(\frac{m^3}{m.s})- 3\times10^{-8}(\frac{m^3}{m.s})= 9.7\times10^{-7}(\frac{m^3}{m.s})$

There are 756 wells in Azarshahr plain and around Teimourloo Village that provided the annual amount of with draw able water ifh_s = 25 mas follows:

$[9.7 \times 10^{-7} (\frac{m^3}{m.s}) \times 86400(s) \times 365(day) \times 1000(m)]\times756\times10^{-6}=23.125\times10^6m^3$

According to the Annals information of water in the Azarshahr region in 2007-2008there is 21.4 million cubic meters of discharge in the area by 756 wells. Therefore, development of this area is not possible for a distance of less than 1,000 meters from the sea.

CONCLUSIONS

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 Azarshahr aquifer and allowable development of exploitation of this area have been calculated. These data show that with assumption of the maximum advancing sea water in coastal aquifers in existing conditions 1000metersand height interface between freshwater and saltwater to sea surface, $h_s = 25\ m$, the development of exploitation in this area is not possible for a distance of less than 1,000 meters from the sea.

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How to cite this article

Mehdi Nezhad Naderi, Masoud Reza Hessami Kermani, Gholam-Abbas Barani. Possibility of Groundwater Operation in Coastal Aquifers for Prevention of Seawater Intrusion.Bull. Env. Pharmacol. Life Sci., Vol 2 (11) October 2013: 30-38