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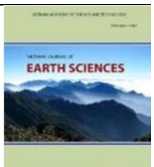

Study on groundwater abstraction by horizontal drains for minimization of saltwater upconing from below

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ABSTRACT

In many places in Vietnam central region, the fresh coastal sand dune aquifers have an interface with salty water below, so upon groundwater (GW) abstraction, there is a risk of salty water upconing to the abstraction facilities. With the same abstraction rate, the horizontal drains shall significantly reduce the groundwater level (GWL) drawdown, which significantly reduces the development of saltwater upconing. The results analysis for the design of groundwater abstraction facilities in Thach Tri commune, Thach Ha district, Ha Tinh province have shown the effectiveness of the solution. For infinite distributed aquifers, the GWL drawdown in the facility area with the abstraction rate of 100m^3/day by eight 4m- and 8m-long horizontal drains is from 11.7% to 16.8% lower in comparison to a vertical well, respectively, (GWL drawdown in vertical well is 0.733m, GWL drawdown in center of 4m-long horizontal drains is 0.646m and in 8m-long horizontal drains is 0.603m). For 1km × 1km aquifer bounded by no-flow boundaries, GWL drawdown in the vertical well and in the center of eight 4m-and 8m-long horizontal drains are 1.344m, 1.293m and 1.255m, respectively. This is corresponding to GWL drawdown decrease of 3.8% and 6.6% in comparison to the vertical well. The reduced GWL drawdown in abstraction facilities of horizontal drains will in some extent reduce the level of salty water upconing and therefore increase the time of abstraction of fresh water.

Key words: Groundwater (GW); Horizontal drain; Saltwater upconing.

1. Introduction

Coastal plain areas in Vietnam have an important role in socio-economic development thanks to the favorable geographical characteristics. Unfortunately, the areas are constantly facing with natural unfavorable phenomena such as coastal erosion, typhoons, droughts, soil and water salinization etc. (Truong, 2015) and man-made environmental pollution due to improper production technology and mineral excavation (Truong Minh Duc, 2015).

One very specific characteristic of the Central coastal plains is the existence of elevated coastal sand dunes which are valuable aquifers to supply a precious fresh water for the people demand, and the stability of which is very essential for the protection of the coastal plain from destruction by the ocean activity (Nguyen Ngoc Quynh, 2012). The groundwater in the coastal sand dunes is not every fresh: the water may be salty in some depth

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and in some spatial areas which may approach the groundwater abstraction facilities.

Upon abstraction of groundwater (GW) from aquifers having an interface with saltwater below or having hydrogeological windows with salty aquifers below etc. there is always a potential of saltwater upconing to the abstraction facilities. Pictures of saltwater upconing under different conditions may be viewed in Figure 1 (Marta Faneca Sanchez et al., 2015).

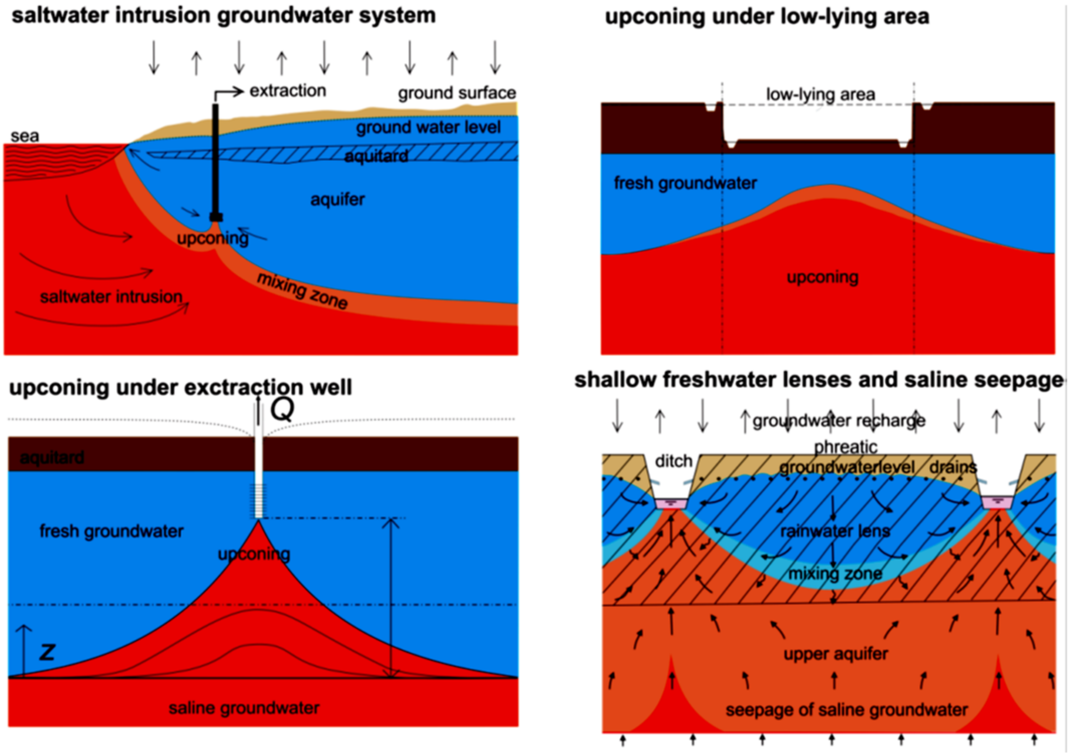

Figure 1. Saltwater upconing from below to groundwater abstraction facilities (Marta Faneca Sanchez et al., 2015)

Dagan and Bear (1968) had developed a method of determining saltwater upconing from below to a vertical GW well without dispersion mechanism using linearized perturbation. The method gives a solution of the height of (h) of saltwater upconing which is proportional with the good abstraction rate (Q) (Figure 2). Application of this method gives the shape of saltwater upconing over which the salt concentration is the same, i.e., it does not represent a real picture of variable salt concentration within the cone. However, this method proves to be important for the design of GW abstraction facilities in the aquifers having an interface with saltwater below for solution in terms of abstraction rate and abstraction time without saltwater upconing to the wells.

Diersch et al. (1984) developed a finite element modeling for determining saltwater upconing of the problem presented by Dagan and Bear (1968) by both mechanisms: advection and dispersion with density difference effect as shown in Figure 2. The modelling results have shown that the effect of density difference and of hydrodynamic dispersion have created a picture of varied salt concentration over the upconing shape and that the saltwater upconing to the well is faster than the method of Dagan and Bear (1968) gives. However, the saltwater which reached the well has not high salt concentration.

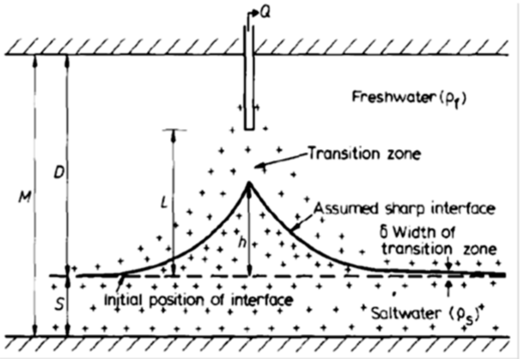

Figure 2. Elements of saltwater upconing to a GW well (Dagan and Bear, 1968)

If instead of a vertical point well-having abstraction rate of Q a system of horizontal drains with a total length of L with a unit abstraction rate Q/L then the height of the saltwater upconing would be much smaller. However, the saltwater upconing height is not linearly proportional to Q/L due to flow superimposition effect. This paper shall determine GW flow field for a vertical GW well and horizontal drains which have the same abstraction rate in order to access the effect of the horizontal drains in reducing the saltwater upconing from below to the abstraction facilities in the coastal sand dune aquifer in Ha Tinh province.

It is worthwhile to brief on the practice of the horizontal well technology. Horizontal well is able to decrease water level drawdown while still being abstract the same abstraction rate. Horizontal drilling was developed by industry for oil recovery, utility placement, mining, and construction dewatering (CPEO, 2010). Over 1,000 horizontal wells have been cataloged as of 1999. Horizontal wells are sometimes preferable to vertical wells because they provide greater access to contamination that is moving horizontally, or reach subsurface areas without damaging surface structures.

For the case where pumping is cyclic, the saltwater upconing is due to dispersion and the freshwater lenses are finite, Pieter S. Pauw Sjoerd et. Al. (2015) had carried out an analysis regarding the quantification of saltwater upconing using analytical solutions as a computationally fast alternative to numerical simulations. Comparisons between analytical calculations and numerical simulations have been presented regarding three aspects: (1) cyclic pumping; (2) dispersion; and (3) finite horizontal wells in a finite domain a freshwater lens. The authors had analyzed various hydrogeological conditions and pumping regimes within a dry half year. The results show that in order to maintain a low level of salinity in the well during a dry half year, the dimensionless analytically calculated interface upconing should stay below 0.25 of the distance from the horizontal well to the bottom of the lens.

In many circumstances, horizontal wells have improved performance (Kushtanova G. G., 2015), such as if the aquifers have bottom water drive then the horizontal wells prevent coning without introducing the flow restriction seen in partial penetration wells. Under such conditions, the groundwater flow temporal regime is not as unique as the case of conventional vertical well: (1) during the early pumping time the regime is radial flow in the vertical plane; (2) when the sealing upper and lower limits are reached, a linear flow behavior is observed; (3) later, the flow lines converge from all directions towards well producing a horizontal radial flow regime. The author had suggested such regimes must be taken into account in the testing data analysis and flow pattern analysis for various purposes.

2. Study area and proposed GW abstraction facility

2.1. *Sand formation in the geological stratigraphy*

The coastal sand formation can belong to one of the following 5 geological sequences: (1) Early Pleistocene; (2) Early-Middle Pleistocene; (3) Late Pleistocene; (4) Early-Middle Holocene and, (5) Late-Modern Holocene (Nguyen Tien Hai, 2004). Each of the sand geological formation sequences is corresponding to one cycle of marine regression-transgression: coarser grain sizes at the beginning of marine regression and finer grain sizes at the beginning of marine transgression. The coastal sand dunes belong to the 5th geological formation sequence, which is corresponding to the late Holocene (Nguyen Xuan Truong and Nguyen The Tiep, 1998) (Nguyen Tien Hai, 2004).

The coastal sand dune aquifer in Ha Tinh province is one of the seven geological aquifers in Ha Tinh and has a potential in water supply (Nguyen Van Dan et al., 1996). The dune consists of fine sands to coarse sands, mainly medium. The dune sands' characteristics may be referred to the dune sand in Quang Binh are as follows: mostly single mineral composition of quartz (97%-99%), from fine to medium, sometimes coarse grain sizes, well sorting and high abrasion level and the sand dunes have surface elevation 0-20m (MSL) (Nguyen Tien Hai et al., 2004). In Ha Tinh coastal areas, the sand dunes have an average thickness of 13m. The groundwater well unit pumping rate is from 0,17l/sm to 0,77l/sm, which are corresponding to well-pumping rate from 95m3/day to 432m3/day. The study area is Thach Tri commune, Thach Ha district that is about 9km from Ha Tinh city to the North East (Figure 3).

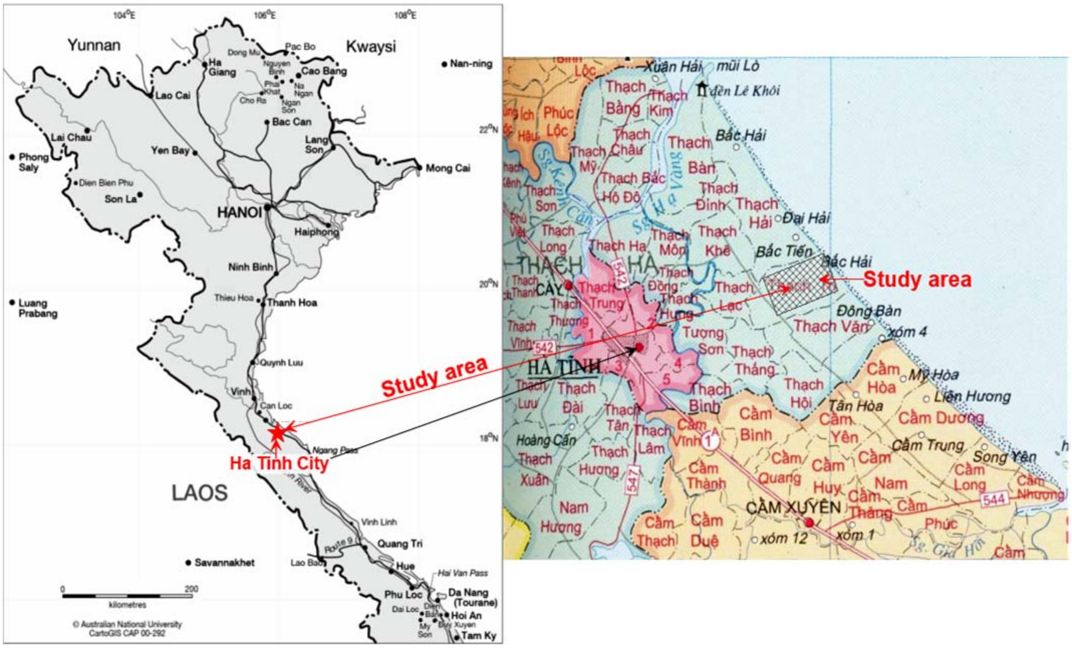

Figure 3. Map of Northern Vietnam and study area

2.2. *Hydrogeological site exploration*

The exploration area is the coastal sand dunes in Thach Tri commune, Thach Ha district, Ha Tinh province (Figure 4) which have the following characteristics. The ground surface elevation is from 5m to 15m. The sand dunes have a width varying from 300m to 2,300m and have an exposed area of about 34 km^2. This is fine to medium grained quartz sand of yellowish-gray color, with crushed shell in many places. The sand dune thickness varies from 3m to 15m, in average 11.5m. Two pumping tests, 38 hydrogeological survey points, and 4 geophysical profiles were carried out in the sand dunes. The analysis and interpretation of the data showed that the lower part of the sand dune aquifers is a brackish water with an increasing thickness of brackish water to the coast (Figure 5). The two pumping tests (one is in Quang Lac hamlet, Thach Lac commune, Thach Ha district and another is in Cam Hoa commune, Cam Xuyen district) was carried out for determining hydrogeological parameters: aquifer thickness 12.5m; hydraulic conductivity 15.3m/day and specific yield 0.105.

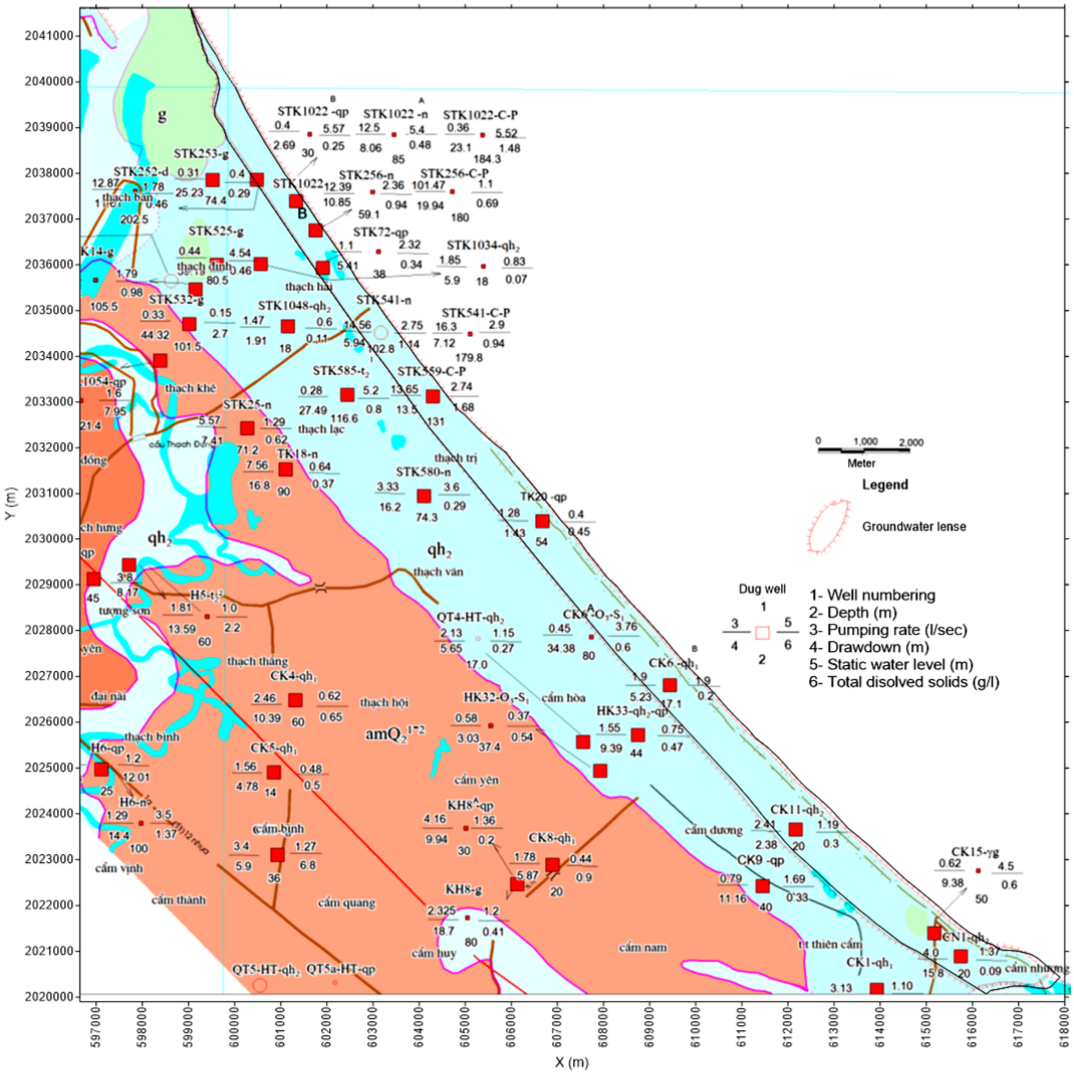

Figure 4. Coastal sand dune distribution in Thach Ha and Cam Xuyen districts

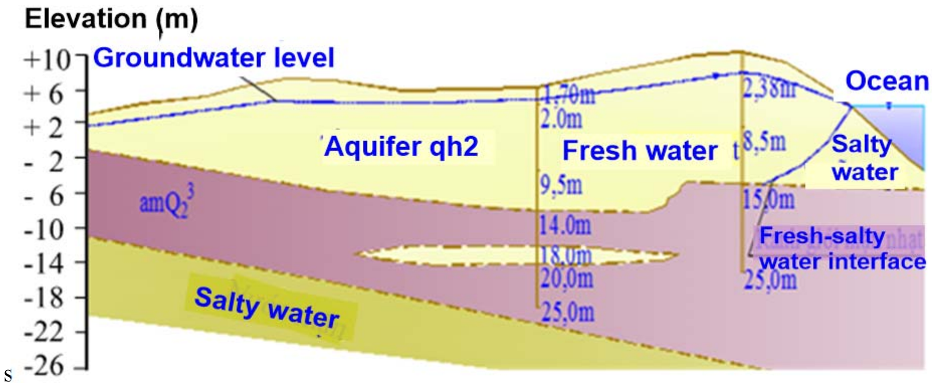

Figure 5. Hydrogeological cross section of the study area

2.3. Groundwater abstraction facility

The GW abstraction facility consists of a well-tank (a 2m-diameter well with water-proof wall) which collects water from horizontal drains. Eight horizontal drains (Figure 6) at the depth of 3.5m below initial GWL. Two alternatives in regard to the length of the horizontal drain: 4m and 8m. It is worthwhile to note that the depth of the horizontal drains can be changed based on the results of below-mentioned hydrodynamic analysis.

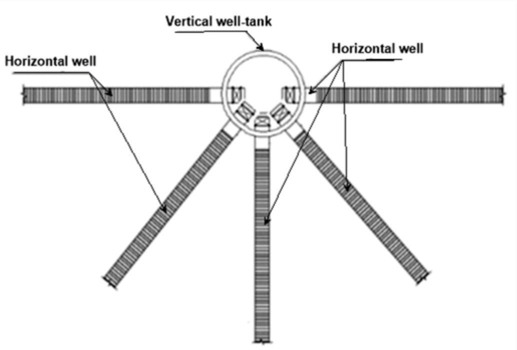

Figure 6. Plan view of horizontal drains

For the purpose of comparison of different abstraction facility types, the most unfavorable case in regard to GW potential and salinization is used: There is no rainwater recharge to the aquifer and evaporation from the GW is zero since the GWL depth is more than 2.5m the evaporation from the sand is constant and equal to 0.4 potential evaporation from the ground surface (Soylu et al., 2011); and the aquifer is unconfined and the below layer of amQ$_2^3$ clay, silt, silty sand and sandy clay is impermeable.

3. Laboratory experiment and analysis

3.1. Experiment, analysis of water collection and discharge of Johnson screen

An analysis was conducted to determine the water conductivity (flow capacity) of the Johnson screens. JS49 screen has an outer diameter 49.5mm, a slot size 0.508mm and an open area 33.3%. JS90 screen has an outer diameter 88.9mm, a slot size 0.508mm and an open area 13.8%. These screens have the thickness of 5mm (which is corresponding to roughness of about 5mm). The 8m-long screen laid with a slope of 0.01 and under the differential water level (ΔH) between the two ends of 0.04m gave flow rate of 0.2829m^3/s (24,439m^3/day). The flow regime was turbulent with the Reynolds number of 837. Therefore, eight 8m-long and 4m-long drains are entirely capable of conducting water with a target flow of 100m^3/day.

An experiment was conducted to determine the unit water flow (q) over 1m of the length of the Johnson screen inside two types of sands: (1) coastal fine to medium sands, and (2) coarse sands having 50% of particle size 0.02mm - 2mm. Experiment results are shown in Table 1 and in Figure 7 for fine-medium sands, and in Figure 8 for coarse sands. From the results of experiments, it is commented that in the fine-medium sands the unit flow rates of JS49 and JS90 screens are not significantly different, and in coarse sands there is almost no difference.

Table 1. Unit flow rates through Johnson screens (m^3/m.day)

	Fine-medium sands		Coarse sands	
	Unit rate *q* (10m^3/m.day)		Unit rate *q* (10m^3/m.day)	
ΔH (m)	JS49	JS90	JS49	JS90
0.00	0.000	0.000	0.000	0.000
0.10	0.296	0.296	0.451	0.540
0.20	0.581	0.581	0.743	0.812
0.30	0.921	0.921	1.127	1.182
0.40	1.286	1.286	1.552	1.615
0.50	1.688	1.688	1.994	2.017

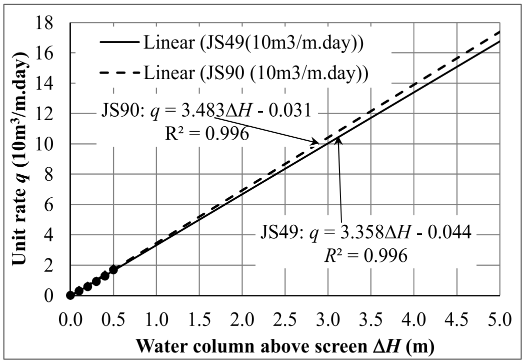

Figure 7. Unit flow rate q (m^3/m.day) of Johnson screen in fine-medium sands

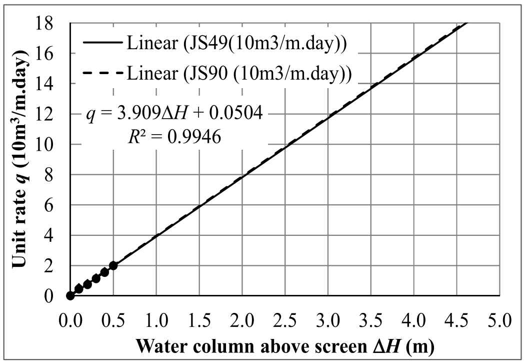

Figure 8. Unit flow rate q (m^3/m.day) of Johnson screen in coarse sands

For central coastal areas in general and Thach Ha district, Ha Tinh province in particular, the coastal sand dunes have a thickness of more than 10m. If with an allowable GWL drawdown not greater than a half of aquifer thickness, especially for the areas where there is saltwater beneath the aquifer, the GWL drawdown should be limited to less than a half of aquifer thickness. At the same time, it is necessary to ensure that the water column above the horizontal drains is sufficiently large enough to supply the necessary flow (according to the analysis results in Figure 5, only 1m of water column above the horizontal drains shall give 1,100m^3/day from 8 horizontal 4m-long drains). This is much more than the designated GW abstraction rate of 100m^3/day.

3.2. Groundwater abstraction rate analysis

The Theis method had been used to determine the GWL drawdown at a certain location for the average thickness of the aquifer throughout the whole region, taking into account the GWL drawdown caused by vertical wells or horizontal drains. The formula (see Fletcher, 1987) determines the GWL drawdown is as follows:

$$s = \frac{Q}{4\pi K b_{avg}} \ln \frac{2.25 K b_{avg} t}{S_y r^2} \qquad (1)$$

In which: ln is natural logarithm; *is* GWL drawdown (m) at any distance r from the abstraction well; Q is abstraction rate (m^3/day); K is hydraulic conductivity (m/day); b_{avg} is average aquifer thickness; t is time counted from the beginning of abstraction (day); r is distance from abstraction well to the calculation point; S_y is aquifer specific yield.

Use the flow superimposition principle to calculate the flow of horizontal drains, in which horizontal drains are considered as a series of successive point-wells and the GWL drawdown of the water level (s) at a certain point is equal to the sum of all GWL drawdowns caused by each point-well along the drain (Figure 9):

$$s=\frac{q}{4\pi K b_{avg}}\int_{L_1}^{L_2}\ln\frac{2,25Kb_{avg}t}{S_y r_l^2}dl \qquad (2)$$

In which: s - GWL drawdown (m) ; q- unit rate of the horizontal drain (m^3/m.day); L_1 , L_2 - the two ends' coordinates of the horizontal drain (expressed in terms of given coordinates x,y); r_l = distance (m) from calculation point to a point-well in the drain.

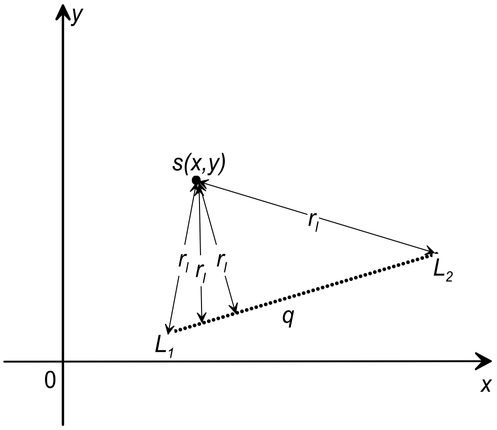

Figure 9. Illustration of flow superimposition principle applied to horizontal drain

The GWL drawdown at some point caused by several horizontal drains is calculated by summation of GWL drawdown caused by each horizontal drain in accordance with formula (2). The flow superimposition principle is also applied for analysis in the case of the finite-distributed aquifer where there are different boundary types such as the boundary of the First kind, of the Second kind etc. with the introduction of image wells.

As the water flow into horizontal drain is a function of the water column above the drains as described above, the entire calculation time (10,000 days) is divided into a number of time steps (e.g. time step equals to 10 days) and flow rates through the drain are calculated through the water level determined at the previous time step. A computer program written in Fortran language had been compiled to perform these calculations.

3.3. Different aquifer conditions and abstraction systems for comparison

Two different aquifer conditions are considered: (1) the aquifer has an infinite distribution, and (2) the aquifer is bounded by a no-flow boundaries. The results of GWL drawdown calculation in the case of traditional vertical wells and horizontal drains in the above two aquifer condition cases are used to analyze the advantages of the groundwater abstraction by horizontal drains.

Three different abstraction systems are analyzed (Figure 10): (1) System 1: vertical well of a diameter of 2m; (2) System 2: eight 4m-long horizontal drains to collect water to the well-tank of diameter of 2m; and (3) System 3: eight 8m-long horizontal drains to collect water to the well-tank of diameter of 2m.

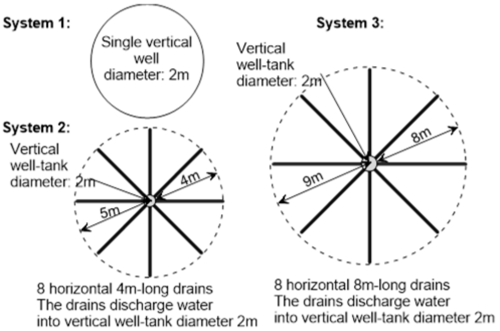

Figure 10. Schemes of three groundwater abstraction systems

The following input data are used in the analysis: abstraction time: t = 10,000 days (27 years); the horizontal drains are located at a depth of about 3.5 meters below the initial GW level and has an inclination slope of 0.01; target abstraction Q = 100m^3/day; the water flow rate for horizontal drains is determined by the formula shown in the above sections through the water column above them: if the obtained flow rate to be greater than 100m^3/day, then flow rate of 100m^3/day is used; if the obtained flow rate is less than or equal to 100m^3/day, then that flow rate is used.

4. The study results

The study results showed that for the infinite aquifer at a distance of more than 20 meters from the center of the abstraction system, the GWL drawdowns in all three cases of three systems are almost the same. In addition, the GWL drawdowns in the center of the abstraction systems are most concerned due to the risk of formation and development of saltwater upconing from below. Therefore, only the central area of 20m × 20m shall be used for presentation.

For infinite distributed aquifer:

At the end of the 27th year of abstraction, the GWL drawdown at the vertical well (system 1) is 0.733m (Figure 11, 12), at the center of the system 2 is 0.646m (Figure 11), at the center of the system 3 is 0.603m (Figure 12) (Table 2 and Figure 15). For system 1 and 2, the GWL drawdowns at distance of 5 meters (i.e. from the tail of the horizontal drains) or more from the center of the systems are more or less the same. For system 1 and 3, the GWL drawdowns at distance of 9 meters or more from the center of the systems are more or less the same. The GWL drawdowns in the center of the system 2 and 3 are lower than the GWL drawdown in the system 1 about 11.7% and 16.8%, respectively. The total length 64m of the horizontal drains of system 3 is two times longer than system 2, but had decreased GWL drawdown only 5.1%.

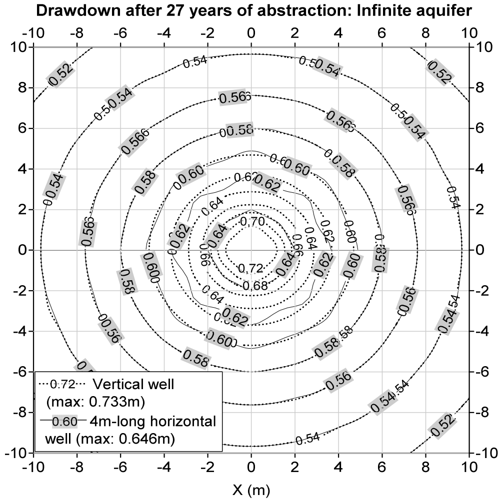

Figure 11. GWL drawdown after 27 years of abstraction: infinite aquifer-single vertical well and eight 4m-long horizontal drains

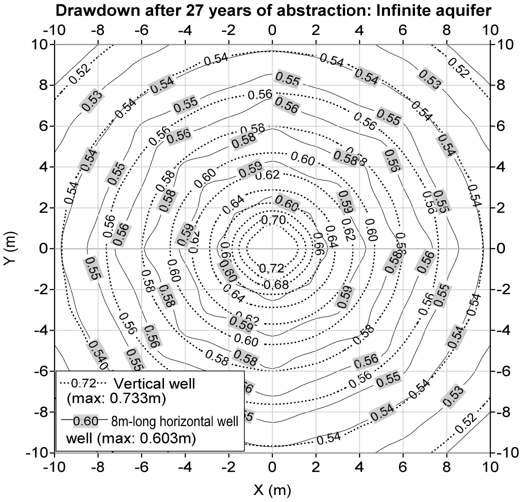

Figure 12. GWL drawdown after 27 years of abstraction: infinite aquifer-single vertical well and eight 8m-long horizontal drains

1km × 1km aquifer bounded by no-flow boundaries

At the end of the 27th year of abstraction, the GWL drawdown at system 1 is 2.313m (Figure 13&14), at system 2 is 1.293m (Figure 13) and system 3 is 1.255m (Figure 14). Table 2 and Figure 16). The GWL drawdowns in the center of the system 2 and 3 are lower than the GWL drawdown in the system 1 about 44.1% and 45.7% respectively. Unlike the case of infinite aquifers, in this case the GWL drawdown caused by the three systems are large different.

Table 2. GWL drawdown through center of abstraction systems

X (m)	Vertical well	Eight 4m-long horizontal drains	Eight 8m-long horizontal drains	X (m)	Vertical well	Eight 4m-long horizontal drains	Eight 8m-long horizontal drains
Infinite aquifer				1km × 1km aquifer bounded by no-flow boundaries			
-10	0.537	0.537	0.538	-10	2.121	1.185	1.186
-9	0.546	0.546	0.548	-9	2.130	1.194	1.196
-8	0.556	0.556	0.558	-8	2.140	1.204	1.207
-7	0.567	0.567	0.567	-7	2.151	1.215	1.216
-6	0.580	0.580	0.576	-6	2.163	1.228	1.224
-5	0.595	0.597	0.584	-5	2.179	1.246	1.232
-4	0.613	0.615	0.591	-4	2.197	1.263	1.240
-3	0.637	0.629	0.598	-3	2.221	1.277	1.247
-2	0.671	0.640	0.604	-2	2.255	1.289	1.253
-1	0.729	0.645	0.606	-1	2.313	1.293	1.255
0	0.729	0.644	0.606	0	2.313	1.293	1.255
1	0.729	0.644	0.606	1	2.313	1.293	1.255
2	0.671	0.640	0.604	2	2.255	1.289	1.253
3	0.637	0.629	0.598	3	2.221	1.278	1.247
4	0.613	0.615	0.591	4	2.197	1.264	1.241
5	0.595	0.598	0.584	5	2.179	1.247	1.233
6	0.580	0.580	0.576	6	2.163	1.230	1.225
7	0.567	0.567	0.568	7	2.151	1.217	1.217
8	0.556	0.556	0.559	8	2.140	1.205	1.208
9	0.546	0.546	0.548	9	2.130	1.196	1.198
10	0.537	0.537	0.538	10	2.121	1.187	1.188

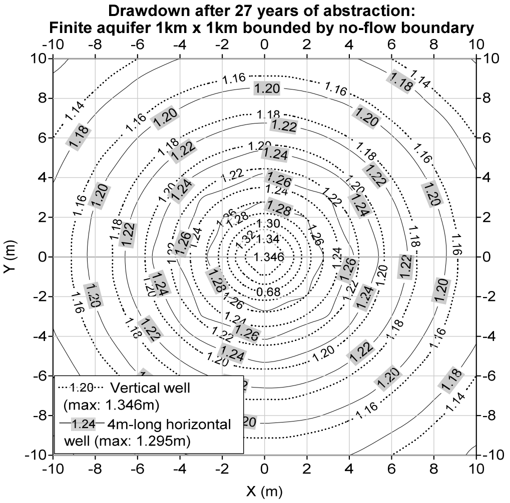

Figure 13. GWL drawdown after 27 years of abstraction: 1km × 1km aquifer-single vertical well and eight 4m-long horizontal drains

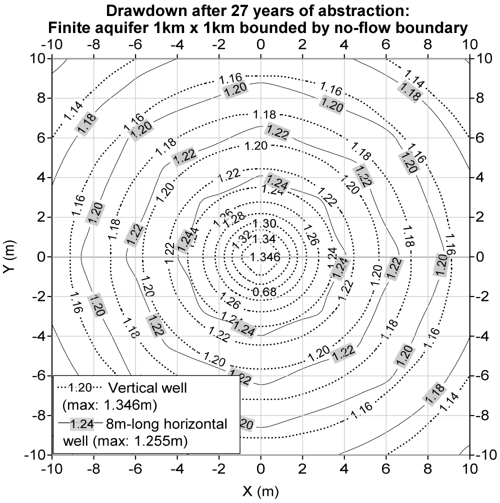

Figure 14. GWL drawdown after 27 years of abstraction: 1km × 1km aquifer-single vertical well and eight 8m-long horizontal drains

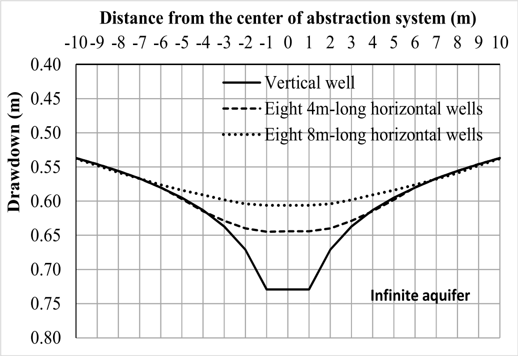

Figure 15. GWL drawdown through center of abstraction systems: infinite aquifer

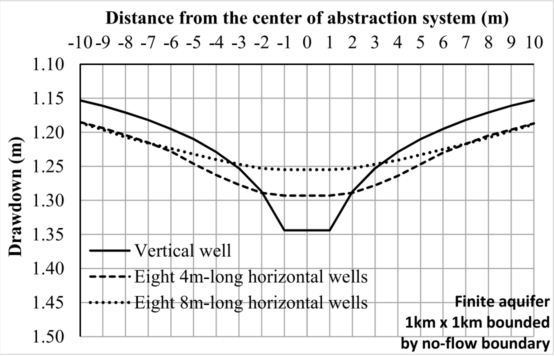

Figure 16. GWL drawdown through center of abstraction systems: 1km × 1km aquifer bounded by no-flow boundaries

With the different GWL drawdowns caused by the three GW abstraction systems, the saltwater upconing from below the systems significantly reduced from system 1 to system 2 and 3. Figure 17 illustrates that saltwater upconing is very close to the GW well in system 1, but for system 2 and 3 the saltwater upconing are rather far from horizontal drains.

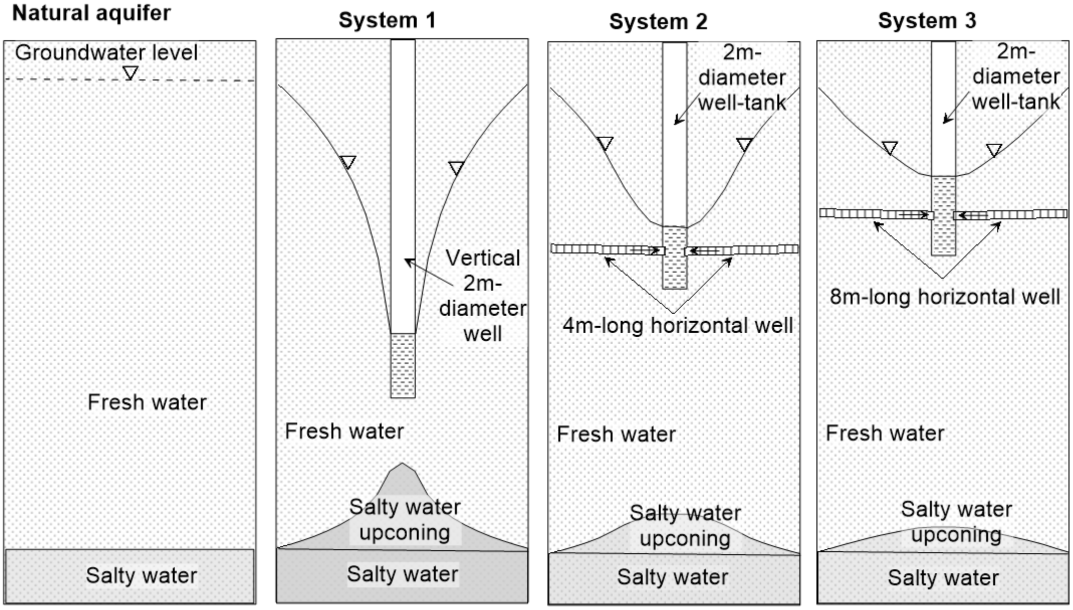

Figure 17. Sizes of saltwater upconing for different groundwater abstraction systems

5. Discussions and concluding remarks

From the results of the study the following discussions can be addressed:

The GWL drawdowns created by GW abstraction facilities are site-specific dependent upon aquifer distribution area, kinds of boundary conditions, boundary values and hydrogeological parameters. The actual picture of the GWL drawdowns can only be determined by the concrete modeling (either analytical or numerical modeling) for the abstraction facilities. Such quantitative analyses are necessary to be carried out for supporting the selection of the best design in term of well pumping rates and water level drawdown in regards to saltwater upconing.

Reducing the GWL drawdown in the abstraction area even in a small value can slow very much the saltwater upconing from below with a time in years because the aquifer vertical dispersion is much smaller than the horizontal dispersion. Therefore, it is necessary to design of horizontal drains so that the lowest possible GWL drawdown can be achieved while required abstraction rate is ensured.

It is very practical that more study on the formation and development of saltwater upconing at different GWL drawdowns and distances from the abstraction facilities' bottom to the below saltwater interface boundary.

The following concluding remarks can be drawn from the results of the quantitative analysis of the study:

For aquifers with infinite distribution area: the GWL drawdowns in the abstraction area (system 1: single well and system 2&3: horizontal drains) and the surrounding areas are not very much different. Specifically, the GWL drawdowns in the center of the system 2 and 3 area lower than system 1 about 11.7% and 16.9%, respectively. The total length of the horizontal drains increased two times (from 32 meters for system 2 to 64 meters for system 3) had led to a decrease of 5.9% in GWL drawdown.

For 1km × 1km aquifer bounded by no-flow boundaries: the GWL drawdowns in the abstraction area (system 1: single wells and system 2&3: horizontal drains) are much smaller. Specifically, the GWL drawdown in the center of the system 2 and 3 are smaller than system 1 in 3.8% and 6.6%, respectively. The total length of the horizontal drains increased two times (from 32 meters to 64 meters) had led to a decrease in the GWL drawdown only by 2.96%.

For finite aquifers with boundary types such as the boundary of the First kind, of the Second kind etc., the above results can be used to carry out analysis for the design of the abstraction facilities to minimize the saltwater upconing magnitude from below.

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