RELATIONSHIP BETWEEN EXCESSIVE PRODUCTION RATE AND PRODUCED GROUNDWATER QUALITY

Musaed N. J. Al-Awad
Petroleum Engineering Department, College of Engineering, King Saud University
P.O. Box 800, Riyadh 11421, Saudi Arabia,
Fax. No. 4674422, E-mail: malawwad@ksu.edu.sa

ABSTRACT
Ground water is a vital source for fresh water in Saudi Arabia and the surrounding Gulf Countries. It is well known that fresh water density is lower than that of saline water containing appreciable amounts of dissolved salts. Therefore, water quality in the top of the aquifer is superior to the water in the bottom of the aquifer due to the effect of density and gravity segregation. Normally, there is a margin of separation between fresh and saline water is known as the fresh water-saline water contact.

Producing fresh water (from the top of aquifer) by excessive pressure drawdown forces the saline water to move faster towards the producing wellbore in a process called upconing. The top of the cone (maximum height) is function of pressure drawdown (pumping). Several incidences have been reported indicating that the quality of groundwater in many wells in the Kingdom of Saudi Arabia has deteriorated perhaps due to saline water upconing caused by high pressure drawdown. Therefore, pressure drawdown must be carefully selected so that good quality fresh water is produced without upconing the saline water into the producing wellbore.

In this study, a general equation governing water upconing process in groundwater wells is presented. Water upconing process is examined on a Saudi groundwater aquifer. Furthermore, a comparison study is made for pressure drawdown using vertical and hypothetical horizontal wells producing from the same aquifer.

Thus, optimum pressure drawdown reduces the degree of fluid disturbance (upconing and saline water intrusion) that may occur due to high pressure drawdown caused by excessive water production from aquifers.

KEYWORDS
Groundwater, Aquifer, Upconing, Horizontal well, Pressure drawdown, Water quality, Saline water.

INTRODUCTION

Saudi Arabia (2.25 million square kilometers) in general is one of hottest and most arid countries in the world, with an average maximum summer temperatures of $46^{o}C$ and an average rainfall of 120 mm/year. Water resources in Saudi Arabia are conventional which includes groundwater and surface water, and non-conventional such as desalinated seawater and treated waste water. About 88 percent of the water consumption in Saudi Arabia is met by groundwater. The western coastal plain (Tihama) receives 60 percent of the country's total rainfall. Rainfall in this region provides an average supply of approximately 1.85 billion cubic meters of water, accounting for approximately nine percent of the total annual water consumption. Desalinated water production is approximately two and a half million cubic meters per day, constituting approximately 2.5 percent of annual water consumption [1]. **Table 1** lists the major aquifers in Saudi Arabia [2]. All wells drilled in these formations for groundwater production are vertical [3]. Aquifers listed in **Table 1** are formed millions of years ago. Most of these aquifers are not receiving recharge at the present leading to depletion and water quality deterioration with time [4]. Water deterioration can be attributed to natural saline water intrusion or saline water upconing caused by excessive drawdown.

DRINKING WATER QUALITY

Water fit for human consumption should not contain constituents, which would affect its color, odor or appearance. It should be free from foreign bodies such as soil, sand and impurities that are visible to the naked eye. The total hardness should be less than 500 ppm [5].

Incidences have been reported indicating that the groundwater quality in many parts of the Kingdom of Saudi Arabia are deteriorating due to saline water upconing caused by high pressure drawdown. For example, the quality of groundwater produced from Neogene groundwater aquifer in Al-Hassa in the eastern province deteriorated sharply due to saline water intrusion [6]. Similar situations were observed in Ha'il aquifers [7] and in the central province in Minjur aquifer [4] due to excessive pressure drawdown (pumping).

OBJECTIVE OF THE STUDY

The objective of this study is to present an engineering method that can be utilized for the prediction of optimum fresh water production rates with no saline water intrusion (upconing) in both vertical and horizontal wells. This method is presented in the following section.

WATER UPCONING THEORY

Upconing is a term used to describe the mechanism underlying the upward movement of high salinity water into the producing well. Upconing can seriously impact fluids distribution caused by density and gravity action over millions of years in aquifers. Once this equilibrium is disturbed, it needs very long time for these fluids to regain their initial equilibrium.

Upconing is primarily the result of movement of high-density water (saline water) in the direction of least resistance towards the vertical or horizontal production wells as shown in **Figures 1** and **2** [8 and 9]. For vertical wells, water upconing is highly dependent on specific gravity difference ($\Delta\gamma$, dimensionless) between fresh water (γ_{w1}, dimensionless) and saline water (γ_{w2}, dimensionless), formation average permeability ($\overline{k}$, Darcy), radius of the drainage area (r_e, m), wellbore radius (r_w, m), depth of wellbore penetration into the fresh water zone (d, m), fresh water viscosity (μ_w, cp), water formation volume factor (β_w, dimensionless) and fresh water zone thickness (h, m). By the combination of the above parameters, critical production rate in vertical wells (Q_{vc}, m^3/day/well) above which saline water upconing occurs, can be calculated as follows:

$$Q_{vc} = 0.801 \frac{\bar{k}\, \Delta\gamma \,(h^2 - d^2)}{\mu \beta_w \, \ell n(r_e / r_w)} \qquad \ldots(1)$$

For horizontal wells, additional factors are considered such as half of the major axis of drainage area (a, m), length of the horizontal well (L, m), horizontal well drainage radius (r_{eh}, m) and effective wellbore radius (r_{we}, m). Similarly, by the combination of the above parameters, critical production rate in horizontal wells (Q_{hc}, m^3/day/well) above which saline water upconing occurs, can be calculated as follows [8]:

$$a = \left(\frac{L}{2}\right)\left[0.5 + \sqrt{0.25 + \left(2r_{eh} / L\right)}\right]^{0.5} \qquad \ldots(2)$$

$$r_{we} = \frac{r_{eh}\left[\frac{L}{2a}\right]}{\left[1 + \sqrt{1 - \left[L/(2a)\right]^2}\right]\left[\frac{h}{2r_w}\right]^{\left(\frac{h}{L}\right)}} \qquad \ldots(3)$$

$$Q_{hc} = 0.801 \frac{\Delta\gamma\, \bar{k}\left(h^2 - d^2\right)}{\mu \beta_w \, \ell n(r_{eh} / r_{we})} \qquad \ldots(4)$$

From **equations 1** and **2**, it can be observed that the height of saline water upcone (h minus d) is directly proportional to the magnitude of the production rate (i.e. pressure drawdown) as shown in **Figures 1** and **2** for vertical and horizontal well respectively. Equations 1 and 2 were used to predict water upconing in the Wasia aquifer based on the technical data presented in **Table 2**. It must be noticed that fresh water-saline water contact (interface) and densities must be measured accurately using well logging tools and chemical analysis respectively in order to get realistic predictions of saline water upconing using the above equations.

RESULTS AND DISCUSSION

Water upconing analysis for the Wasia aquifer is performed based on the technical data presented in **Table 2**. **Figures 3** and **4** show the relationship between fresh water production rates, saline water upconing height (h-d), length of wellbore penetration into the fresh water zone (d) and fresh water zone thickness ratio (d/h). It can be seen that as the penetration of the wellbore into the fresh water zone increased more saline water will upcone into the production wellbore and mix with the fresh water causing poor water quality production. Therefore, for good water quality production, the wellbore penetration into the fresh water zone should be kept minimum.

During fresh water production, saline water upconing effect will be small if the average permeability of the aquifer is high enough to allow for fast fresh water recharge from the surrounding drainage area. By doubling the value of aquifer average permeability, the critical fresh water production rate with no upconing is also doubled as shown in **Figure 5**. Thus, high fresh water production rats can be applied in high permeability aquifers. Similar effect on fresh water production rate can be noticed due to the difference between the specific gravities of the fresh water and the saline water as shown in **Figure 6**. Higher saline water specific gravity yields higher gravity (weight). Therefore, higher fresh water production rates can be applied when high specific gravity saline water exists below the fresh water.

It is well known that a horizontal well yields similar or more production rate as four vertical wells yield based on h/L ratio from identical drainage areas of the same pressure drawdown as shown in **Figure 7** [3]. Therefore, higher fresh water production rates with no saline water upconing can be applied in horizontal water wells as shown in **Figure 8**. More details about the utilization of horizontal well technology in groundwater projects are documented in reference 3.

ECONOMICAL FEASIBILITY

Horizontal drilling technology has advanced tremendously over the past twenty years. Drilling costs have dropped markedly with experience, but horizontal wells still cost 15 to 250 percent more than conventional vertical wells [10]. As a compensation for the additional cost, horizontal well might replace four vertical wells at the same drainage area and tremendously reduce pressure drawdown caused by fluids production as shown in **Figure 7**. In general horizontal drilling extremely increases production and reduces overall drilling and completion costs.

CONCLUSIONS

Based on the analysis conducted in this study, the following conclusions are obtained:

- Fresh water quality is highly affected by undesigned production rates.
- Minimum well penetration into fresh water zone should be applied in groundwater aquifers.
- The utilization of horizontal wells provides higher water production at minimal disturbance of water level and formation properties.
- Saline water upconing in aquifers is highly affected by formation average permeability and saline water specific gravity and height.
- Aquifer's average permeability and fresh water-saline water interface must be defined precisely.

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العلاقة بين الإنتاج الجائر و جودة المياه المنتجة من مكامن المياه الجوفية

أ. د./ مساعد ناصر جاسم العواد
قسم هندسة النفط – كلية الهندسة – جامعة الملك سعود
ص . ب ٨٠٠ الرياض ١١٤٢١ المملكة العربية السعودية

ملخص:
تعتبر المياه الجوفية مصدر حيوي للمياه العذبة في المملكة العربية السعودية ودول الخليجي العربي. ومن المعروف أن كثافة الماء العذب أقل من كثافة الماء المحتوي على كميات من الاملاح الذائبة. ولذلك فأن عذوبة وجودة الماء الموجود في أعلى المكمن الجوفي للماء أكبر منها في الماء الموجود في قاع المكمن بسبب قانون الأنفصال بين السوائل نتيجة الجاذبية و إختلاف الكثافة. وعادة ما يكون هناك خط وهمي يفصل بين الماء المالح والماء العذب.

إن إنتاج الماء العذب من أعلى المكن بقيم عالية لضغط السحب سوف يؤدي الى حركة الماء المالح من اسفل المكمن الى الأعلى بحركة تسمى الحركة المخروطية. وتعتمد سرعة ارتفاع مخروط الماء المالح على قيمة ضغط السحب. ولقد تم تسجيل عدد من الحالات التي تشير الى تناقص في عذوبة المياه المنتجة من بعض آبار المياه الجوفية في المملكة العربية السعودية قد تكون ناشئة عن الحركة المخروطية للماء المالح من اسفل المكن الى الأعلى نتيجة معدلات الإنتاج العالية للماء. ولذلك يجب الحرص عند إختيار مقدار ضغط السحب للحصول على مياه عذبة ذات جودة عالية دون حصول حركة مخروطية للمياه المالحة.

تم في هذه الدراسة بيان القانون العام الذي يربط الحركة المخروطية للماء المالح مع التغير في قيمة ضغط السحب بسبب الإنتاج وتم تطبيق ذلك على مكمن مياه جوفي للمياه العذبة في المملكة العربية السعودية.

ومن ثم عملت مقارنة بين مقدار التغير في ضغط السحب الناشئ عن إنتاج الماء من بئر عمودي وآخر أفقي افتراضي في نفس المكمن وتأثير ذلك على الحركة المخروطية للماء المالح إلى الأعلى.

وعلى ذلك فان اختيار مقدار مناسب لضغط السحب المتولد عن إنتاج الماء العذب سوف يقلل من الاضطرابات الناشئة عن الحركة المخروطية للمياه المالحة إلى الأعلى والتي تحدث بسبب الإنتاج الجائر وبالتالي تتم المحافظة على جودة الماء المنتج. كما أن تقنية البئر الأفقي سوف تسهم كثيرا في الحد من هذه المشكلة.

Table 1 Major groundwater aquifers in Saudi Arabia [3].

Aquifer name (Rock type)	Water depth, m	Thickness, m	Productivity, 10^3 m^3/day	Location
Saq (Sandstone)	150 – 1500	650	8640	Central-North
Wajid (Sandstone)	150 – 900	600	3456 – 6912	Southern
Tabuk (Sandstone and Shale)	60 – 2500	1072	1296 – 1728	Central-North
Minjur (Sandstone)	1200 – 2000	315	5184 – 10368	Central
Dhruma (Sandstone and Limestone)	100	375	5184 – 10368	Central
Biyadh (Sandstone)	30 – 200	425	2160 – 4320	Northern
Wasia (Sandstone and Shale)	100 – 800	150	7344 – 9504	Central-East
Umm-Er-Radhuma (Limestone)	100 – 400	330	4320 – 8640	Eastern
Dammam (Limestone)	160 – 200	80	605 – 1900	Eastern
Neogene (Sandstone and Limestone)	50 – 100	100	4320 – 8640	Eastern

Table 2 Technical data for Wasia groundwater used in upconing calculations.

Average permeability (k) = variable (0.5, 1.0 and 1.5 Darcies).

Fresh water zone thickness (h) = 366 m.

Wellbore penetration into fresh water zone (d) = variable with maximum value of 366 m.

Single vertical well drainage radius (r_{ev}) = 423 m.

Single horizontal well drainage radius (r_{eh}) = 846 m.

Length of horizontal well (L) = h, 5h and 7h, m. Wellbore radius (r_w) = 0.1143 m.

Fresh water viscosity (μ_w) = 1 cp. Fresh water specific gravity (γ_{w1}) = 1.0.

Salt water specific gravity (γ_{w2}) = variable with maximum value of 1.05.

Water formation volume factor (β_w) = 1.0.

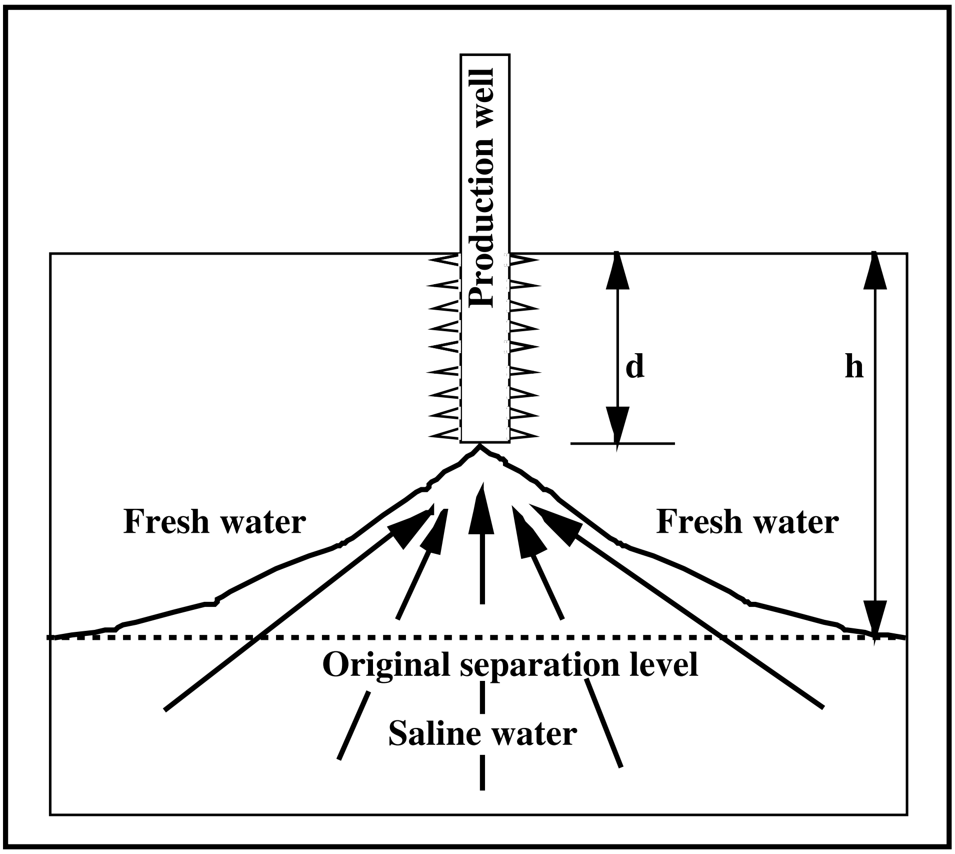

Figure 1 A schematic diagram of upconing phenomenon in a vertical well.

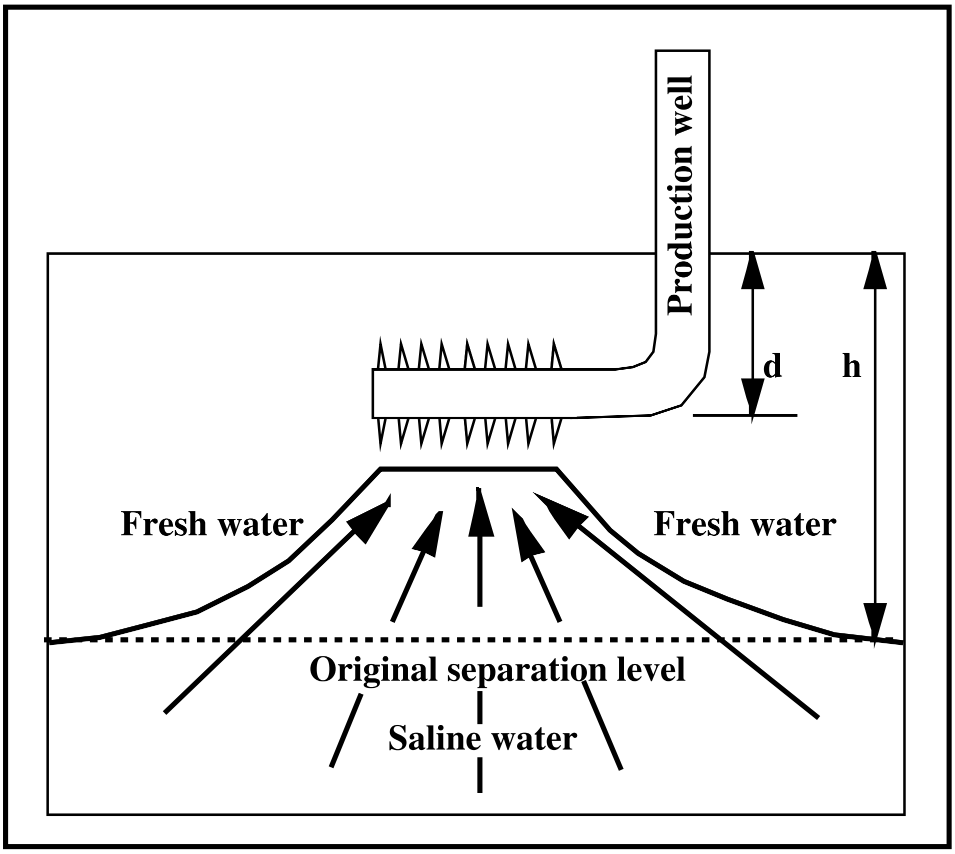

Figure 2 A schematic diagram of upconing phenomenon in a horizontal well.

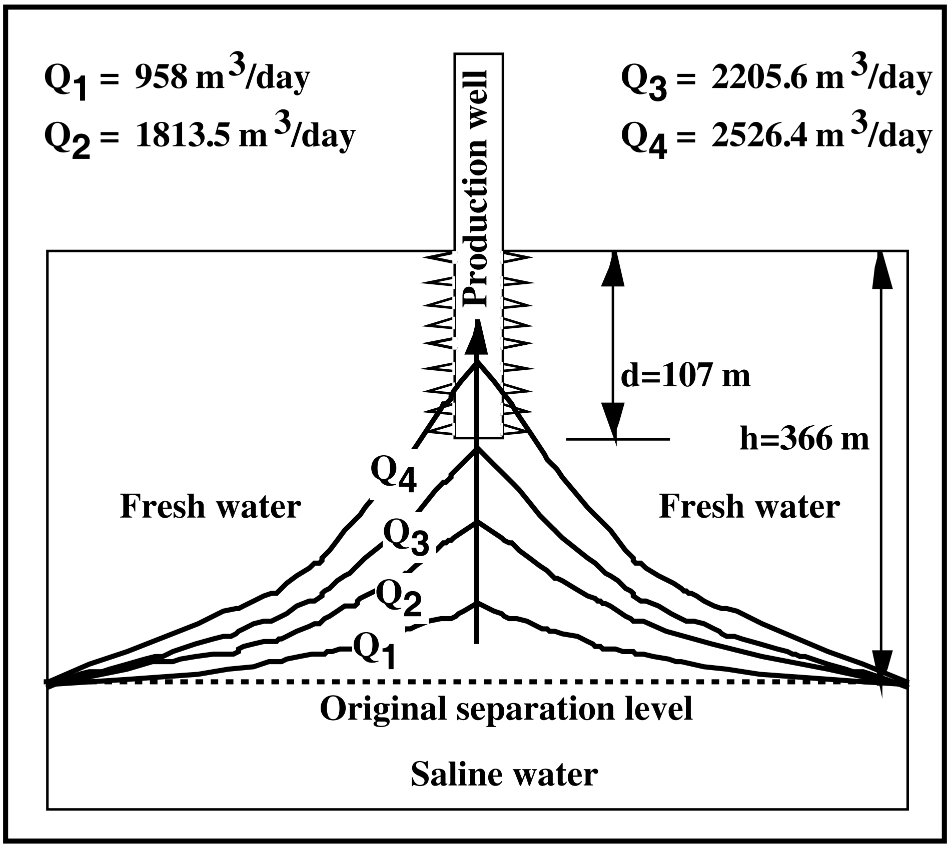

Figure 3 Upconing process example caused by water production in a vertical well in the studied Saudi groundwater aquifer.

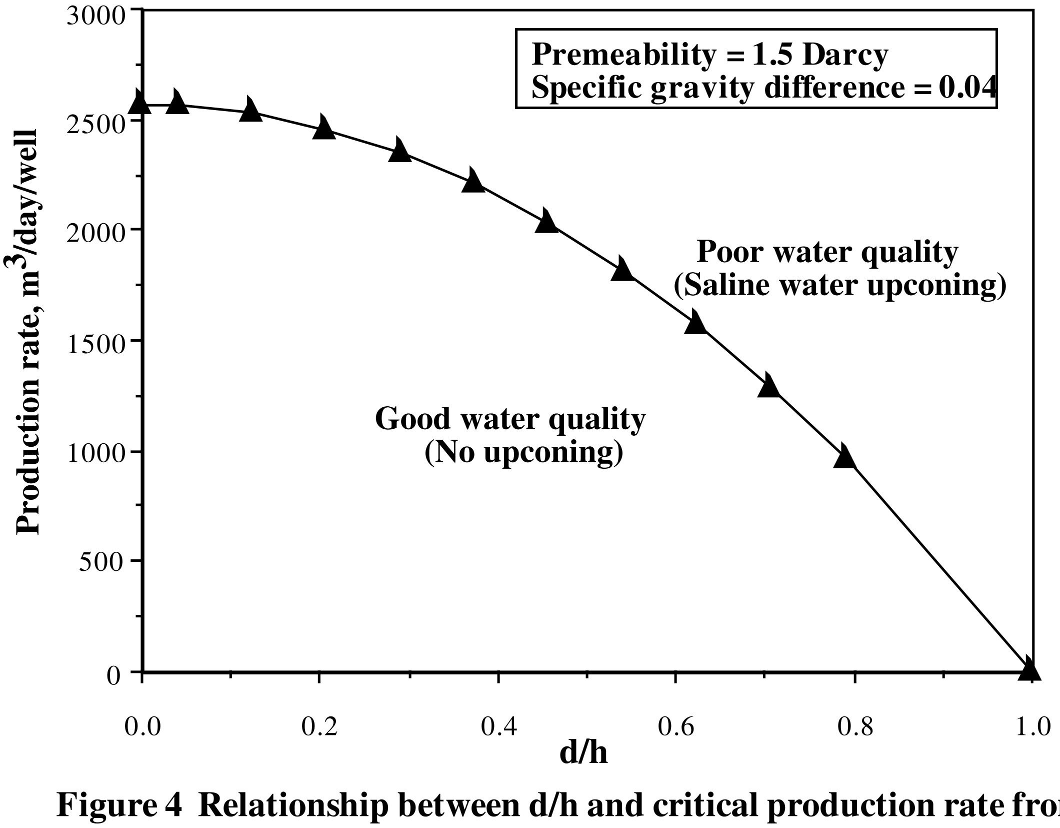

Figure 4 Relationship between d/h and critical production rate from a vertical well in the studied Saudi groundwater aquifer.

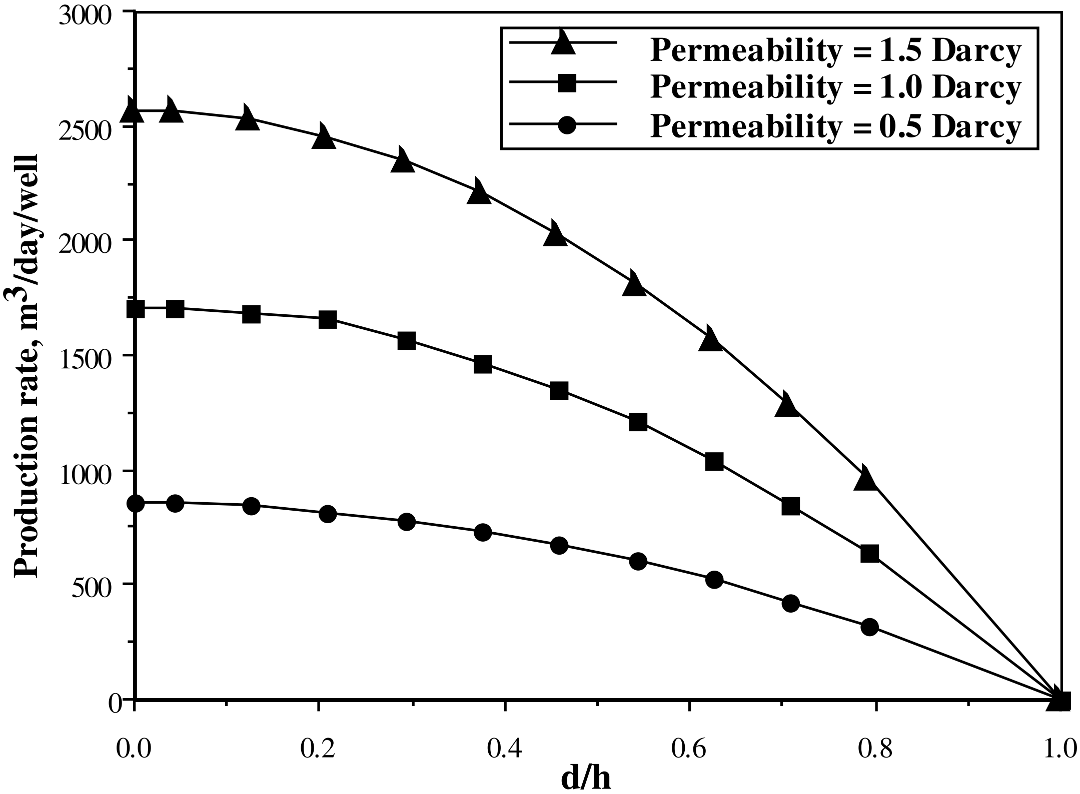

Figure 5 Relationship between d/h and critical production rate from a vertical well in the studied Saudi groundwater aquifer at various permeabilities.

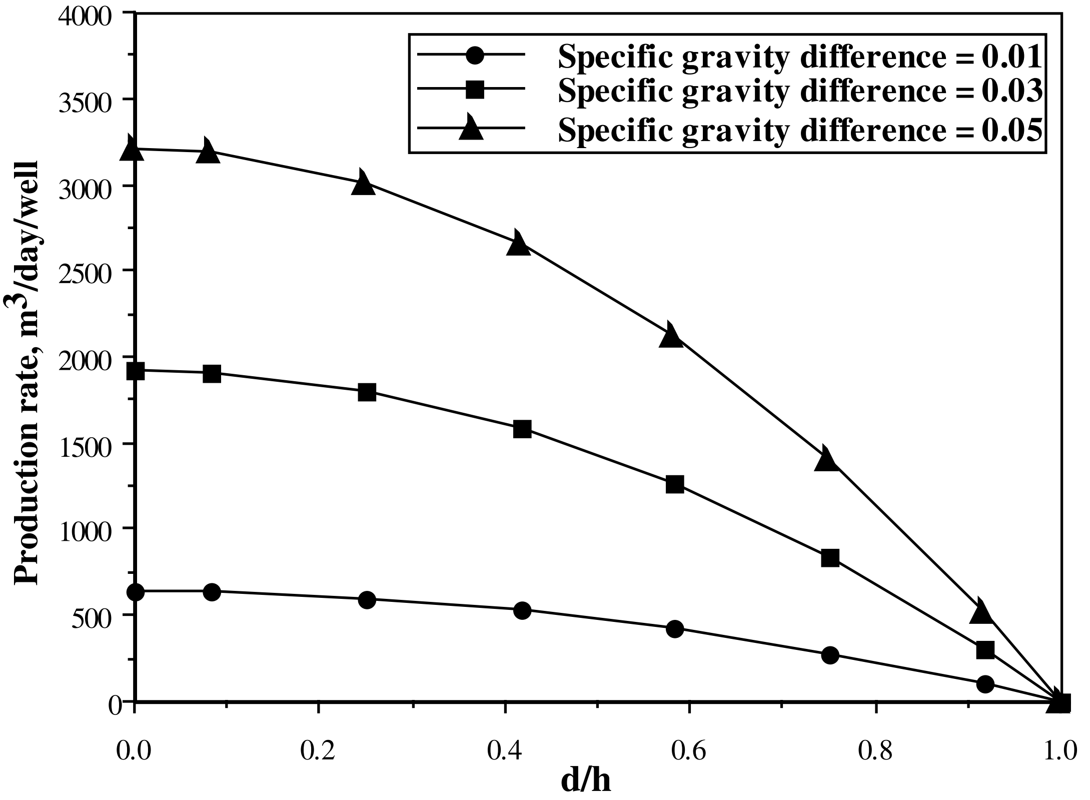

Figure 6 Relationship between d/h and critical production rate from a vertical well in the studied Saudi groundwater aquifer at various specific gravity difference.

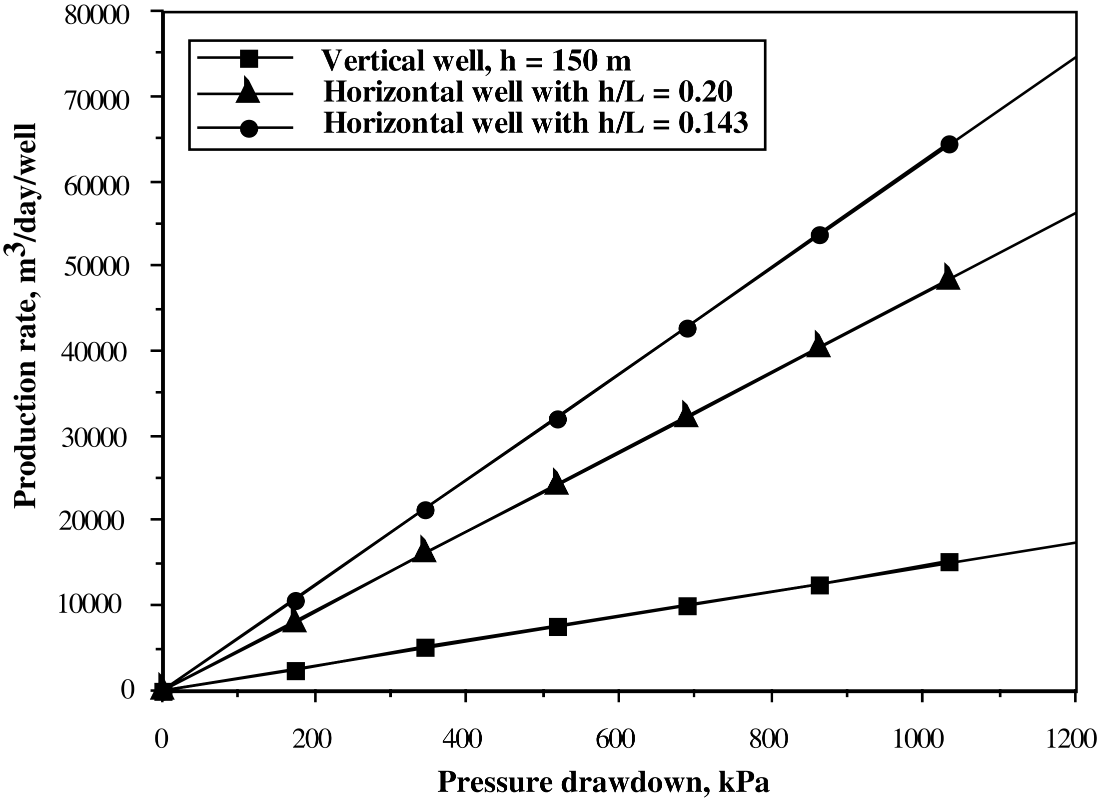

Figure 7 Relationship between pressure drawdown and production rates from vertical and horizontal wells.

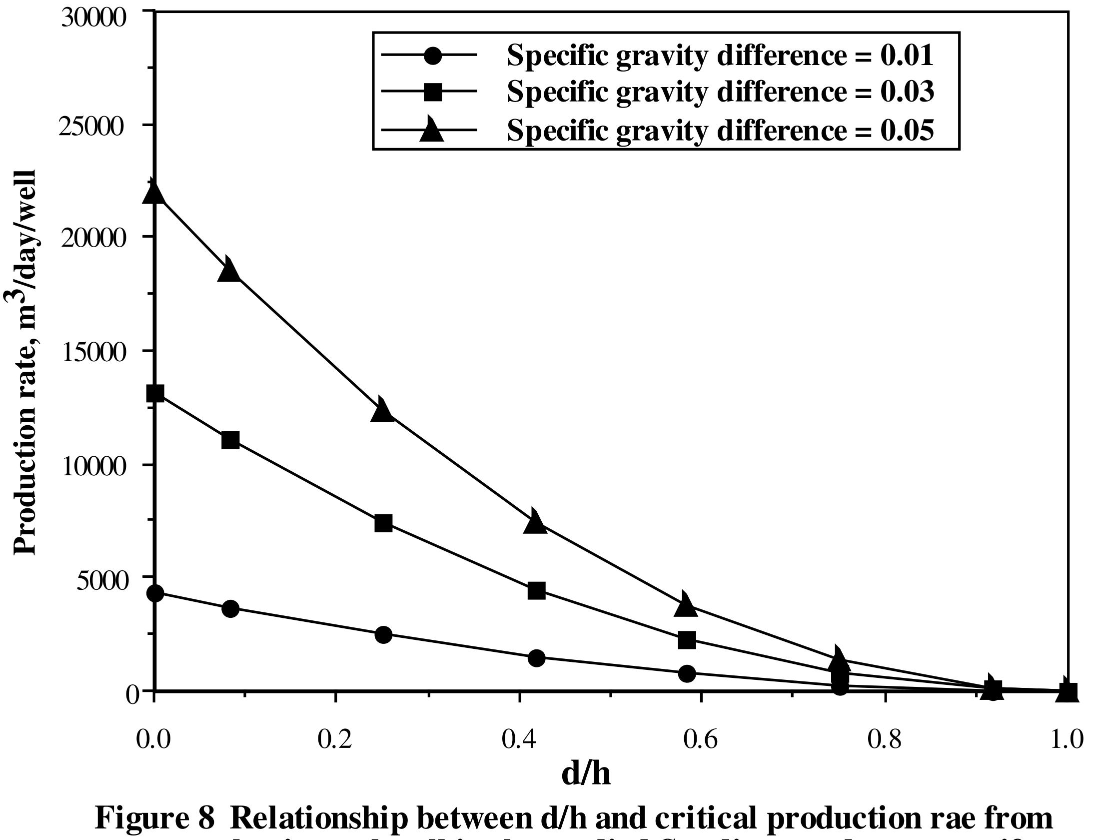

Figure 8 Relationship between d/h and critical production rae from a horizontal well in the studied Saudi groundwater aquifer at various specific gravity difference.