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Numerical Modeling of the Injection Capacity of Desalination Brine Disposal Wells

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الملخص العربى :

تعد تكلفة إنشاء آبار الحقن مرتفعة بصورة واضحة مقارنة بآبار السحب لذلك من الضروري عمل تصميم مناسب لها في المراحل الأولى من التخطيط لدراسة إمكانية الحقن؛ و لقد تناولت هذه الدراسة مشكلة التخلص من المياه زائدة الملوحة الناتجة من محطات التحلية عن طريقة الحقن بالظغط في آبار الحقن. و لتحقيق هذا الهدف تم عمل نموذج رياضي باستخدام برنامج (SEEP/W) لمحاكأة العلاقة بين التصرف و الضغط في بئر الحقن و قد تم التحقق من صلاحية نتائج النموذج عن طريق مقارنتها بنتائج اختبار حقن فعلي تم تنفيذه في الساحل في منطقة الزعفرانة بالقرب من الساحل الغربي لخليج السويس في مصر. و قد اظهرت النتائج قدرة النموذج على إمكانية تمثيل العلاقة بين التصرف و الضغط بصورة واضحة عند استخدام بئر الحقن. كما يعرض ايضا هذا البحث كيفية استخدام هذا النموذج لدراسة تأثير معاملات تصميم البئر على سعة الحقن. و قد أشار التقييم المبدئي أن استخدام نماذج المحاكاة تساهم كأداه هامة لتخطيط و تقييم آبار الحقن و هذا هام جدا لتقييم سهولة و إمكانية الحقن قبل إنشاء البئر.

ABSTRACT:

Injection wells have significant high construction cost as compared to withdrawal wells. Hence, it is very important to ensure a proper design of the injection well in the early planning stage for the feasibility of the injection. This study investigates the problem of pressurized injection of desalination brine in injection wells. A numerical modeling approach is constructed using SEEP/W package to simulate the pressure-discharge relationship in the injection well. The model is verified against observed data from a real injection test that was conducted in a coastal area at Zafarana region near the western coast of the Gulf of Suez in Egypt. The results showed that the model could fairly explain the pressure-discharge relation in the injection well. The paper presents also the use of developed model to investigate the effect of well design parameters on the injection capacity. Our initial assessment indicates that the developed approach constitutes a valuable tool for the planning and assessment of injection wells. This is important to assess the injection feasibility early before well construction.

KEYWORDS: Injection; Wells; Modeling; Desalination; Brine

1. INTRODUCTION

The urban growth and industrialization expansion along the coast translate into an increase in the water demand and more wastes in the environment. Thus, the ability to meet the water demand from the conventional sources became very limited due to the growing and large water demand from the coastal cities. Hence recent attention has been given to depend on desalinated seawater. Desalination has been practiced for many years. Desalination plants use sophisticated systems to effectively distil seawater, producing highly pure water. The by-product of these processes, is the concentrated seawater or brine. For the desalination process to continue as an acceptable and viable technique of producing water, adequate management for disposal of the brine must be developed (Ladewig & Asquith, 2011). Indeed the proper brine (waste) management and handling could be costly in the terms of resources and time (El Haggar, 2010). In Egypt, particularly in the coastal regions, where disposal in the sea is not permitted due to environmental regulations, disposal of brine becomes problematic and costly. One disposal alternative in that case is discharging into a public nearby sewage system. In case there is no available public sewage system (which is the case in most costal private developments and resorts), the owners sometimes transfer the brine via trucks to the nearest public sewage which is very costly. Another alternative that proved to be effective recently is the use of deep injection wells (Ladewig & Asquith, 2011; Charisiadis, 2018). This method of disposal (deep injection or disposal) is looked upon by many managers as an economically attractive alternative (Rima et al., 1971). Deep injection of waste disposal is a low cost method compared to other methods of disposing when there is no public sewage system available, in addition, its relative high success rate is one of the reasons for its earlier growth (Lehr, 1986). An injection well is an open-ended shaft device at which hazardous or non-hazardous waste stream is injected, into safe porous permeable geologic strata below the underground surface of drinking water (USDW). Rock formations are usually limestone/sandstone or dolomite (Class, 2001). In 1930s, the petroleum industry was the first that introduced injection wells to dispose produced brine associated with the oil and gas industry (Brasier & Kobelski, 1996). A schematic representation of the design parameters of a typical injection well is shown in figure 1.

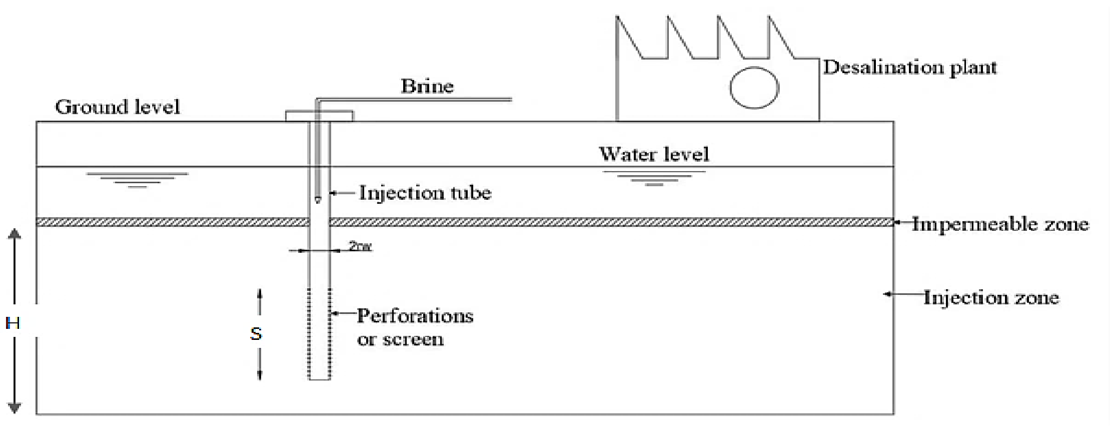

Figure 1. Design parameters of a typical injection well

Deep well injection is the disposal of brine into the voids and pores of the deep underground. The brine is injected down a well which consists of multiple layers of casing. Porous media are then used to contain the brine, while impermeable rock formations like clay and shale are used to prevent vertical movement of the water (Ladewig & Asquith, 2011). The quantity of the brine depends on the capacity of the desalination plant production and its rate of recovery that is expressed as a percentage % from volume of the produced freshwater to the total volume of the saline source water (Charisiadis, 2018). The receiving aquifer must be able to hold and contain the total volume of brine for the expected life time of the desalination plant (Chelme-Ayala et al., 2009). The costs of the deep injection wells for brine disposal as well as the capacities are mainly influenced by the soil hydraulic conductivity as well as the design parameters of the well such as diameter and the depth of the injection (Charisiadis, 2018). The economic and the environmental suitability for any proposed injection well can be determined from testing, surveying, and design of the injection well (Shammas et al., 2009). Injection typical depths to inject fluids ranges from a few hundred to a few thousand feet below the ground surface depending the hazard of the fluid being injected (Lehr, 1986). Disposing of wastewater (brine) through deep injection wells into deep geologic aquifers can pose an economic unfeasibility issue unless the injection procedure is carefully planned and executed from the start to finish (Warner, 1977). In order to predict the performance of the injection wells, a proper injection modeling is needed to relate different variables that affect the injection process (Warner, 1977). To evaluate the suitability of the site for injection, three common steps should be done: acquisition of the comprehensive site data, investigation of potential hydrological problems and simulating of the injection process using models to simulate injection (Rebich, 1993). Injection modeling is important for engineers to reach optimum designs for efficient injection wells. These designs can lead to optimum management of the injection cost. The utilization of specific model relies on the amount of data necessary to precisely simulate a certain injection operation (Rebich, 1993). There is a few numbers of mathematical models available for the simulation of injection wells. However, to the best of the authors knowledge, all these models focus on simulating the effects of injection in the groundwater or tracking the injected plume underground (e.g., Miller et al., 1986; Merritt, 1984; Kipp, 1987; Voss, 1984). Such models are only important if the purposes are to evaluate the injection impacts. Little research work is available in the literature regarding simulating the injection capacity which constitutes a gap that this paper tries to fill.

2. PROBLEM DEFINITION

Since the cost of constructing an injection well is relatively high, it is important to precisely estimate the cost prior to construction in order to assess the feasibility of injection. Accordingly, a proper design of the injection well, with a capacity that can accommodate the brine discharge from the desalination plant, is needed to estimate the cost. This formulates the objective of this paper which is to reach a methodology that can be used for design purposes of injection wells of desalination brine. In order to achieve this objective, the following sections of the paper propose a design methodology using

SEEP/W 2012, verify this methodology, and finally use it to investigate the effects of well design parameters on its injection capacity.

3. SEEP/W MODEL DESCRIPTION

In this study, Seep/W the finite element- based groundwater numerical modeling software which is a subprogram of the Geo-Slope model (CALGAR & ALBERT, 2007) is implemented. Geo-slope international is leading geotechnical modeling software products. Seep/W is one the package of the Geo-studio software which consists of eight software products that enable different modeling tasks from simple, saturated, steady-state analysis to complex, saturated/unsaturated, time variant analyses which cater for analyzing seepage and groundwater flow problems within porous materials. It can help to analysis and design the civil, hydro geological, geotechnical and mining engineering problems (GEO-SLOPE, 2002). Broadly speaking, Seep/W is a useful tool of numerical modeling that helps in solving sophisticated groundwater seepage problems.

Seep /W is a finite CAD element software product used to model local groundwater problems for the purpose of evaluating different scenarios. It is a numerical model which simulates the real physical process of flowing water though porous medium mathematically. This computer model is mainly used for analyzing two-dimensional groundwater seepage problems and it also can be used for axisymmetric analysis with symmetry about a vertical axis of rotation which is always at x-co-ordinate equals to zero (Krahn, 2004) which is used in this study for modeling an injection well to simulate the flow rates contributed by the injection process.

The computed flux for axi-symmetric analysis is per unit radian for element thickness=1.0, therefore, to get the entire flux of the circumferential area the flux value is multiplied by 2π.

Seep/w is formulated mainly for two dimensional problems and the general governing partial differential equation for two-dimensional seepage could be expressed in equation (1) as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \quad \rightarrow \quad (1)$$

Where: H is the total head, K_x and K_y are the hydraulic conductivity in the x and y directions respectively, Q is the flow rate and Θ is the volumetric water content and t is the time (Krahn, 2004). This equation states that the difference between the input and output flow (flux) rates of an elemental volume is equivalent to the change in storage of the soil systems. While under steady-state conditions, the input and output of an elemental volume is the same at all times and $\frac{\partial \theta}{\partial t}$ will be equal zero. Then the equation reduces to be equation (2):

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right) + Q = 0 \quad \rightarrow \quad (2)$$

And the partial governing differential equation which used in the formulation of SEEP/W for this axisymmetric problem in steady state analysis is Richard's equation (3) (Richards, 1931) which states that:

$$\frac{\partial}{\partial z}\left(k(h)\frac{\partial H}{\partial z}\right)+\frac{k(h)}{r}\left(\frac{\partial H}{\partial r}\right)+\frac{\partial}{\partial r}\left(K(h)\frac{\partial H}{\partial r}\right)+S=0 \quad \rightarrow \quad (3)$$

Where H = total head (m)

K = the hydraulic conductivity

Z = the elevation (m)

r = is the radial distance from the Z-axis and S=the applied source or sink term.

When developing a numerical steady-state model using SEEP/W, three fundamental aspects must be determined as inputs to the model are: the geometry, the materials, and the boundary conditions. Head difference is the primary forcing variable in the injection model and the fluid flows occurs from region with high hydrostatic pressure to regions of less hydrostatic pressure. While the output from the model are the flow rates and the head field. After the injection brine flow rate equation is solved, the model could be then solved for different operating scenarios.

4. CASE STUDY

4.1 Description of Case Study

The data used in this study was collected through carrying out an injection test at a resort near the western coast of the Gulf of Suez in Zafaranaa area in Egypt. Location of the injection test is shown in figure 2.

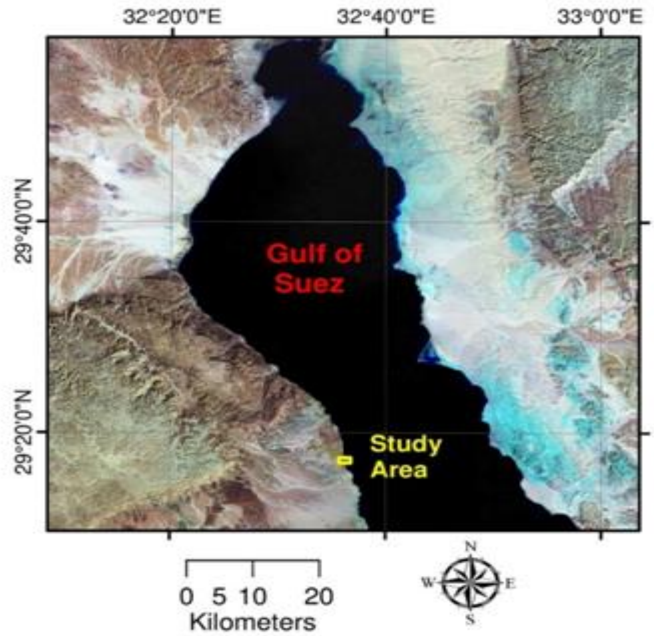

Figure 2. The location of study area

The data of the injection test includes records of discharge versus pressure at the various times during injection. Moreover, the injection well used for the test is with total depth equal to 300 m, 280 mm diameter and with length of the perforated screen equal to 100 m. The simulation area is about 800 m radius around the well and total depth of simulation of 400 m.

The injection zone consists of broken hard clay pieces. The injection zone is about 300m height from the bottom of the well bounded from the top by an impermeable layer of 10m thickness existing at 90m depth from the top. The impermeable soil (which existing at 90m depth from the ground surface) is hard clay with hydraulic conductivity previously estimated from nearby pumping tests as $\mathrm{K} = 8.64 * 10^{-8}\ \mathrm{m/day}$. The ratio between the vertical hydraulic conductivity to the horizontal hydraulic conductivity is assumed to be $^{1}/_{4}$ in the injection zone. Figure 3 shows the data observed from the injection test.

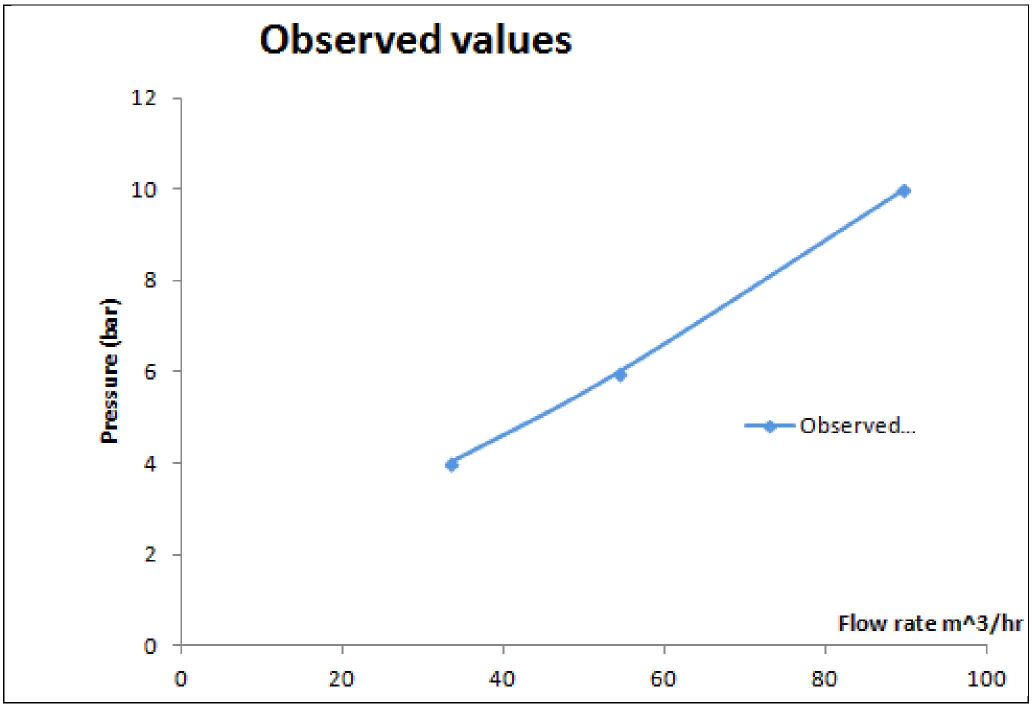

Figure 3. Observed data from the injection test

4.2 Model Construction

In order to get the required results and meet the study objectives, a 2-D radial finite element Seep/w model was developed in the following steps:

Step 1: the first step is determining the soil geometry by creating a geometrical model of the cross section of the evaluated system then defining the soil regions of this cross-section. The simulation process is started by dividing the underground formation into 90m permeable soil then 10m thickness of impermeable soil then the rest of studied depth of the soil is permeable. The mesh is around 800 m long and 400 m in depth and the average ground elevation is 400 m and the difference between the elevation of the static water table and the ground surface was 5m which simulates the condition in the site.

Step 2: After drawing the geometry of the injection well and the injection zone cross-section by using Seep/w drawing components, defining the regions of the injection zone and assigning material of each region, then assigning the boundary conditions. The hydraulic conditions at the boundaries are specified at the boundaries of the model domain. Boundary conditions for Seep/w are upstream and downstream boundary conditions used in the simulation model which are given head boundary conditions. Figure 4 shows the constructed model following the above-mentioned steps.

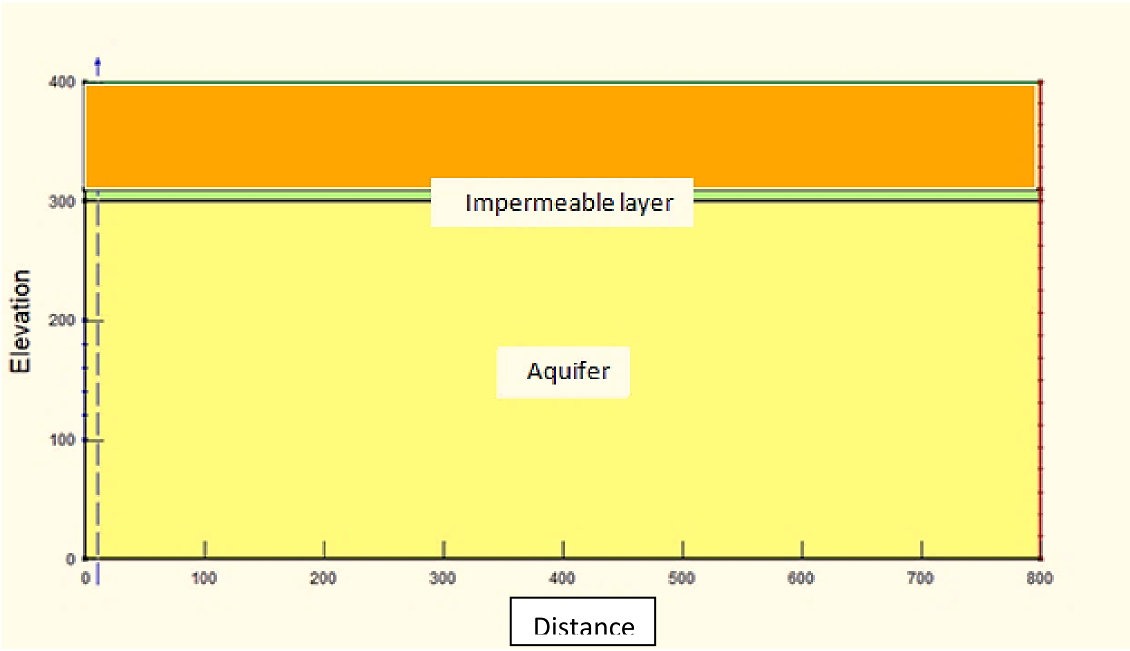

Figure 4. The constructed radial model

4.3 Model Verification

After the completion of the model construction stage, the model was verified using the data of in-situ injection test (observed) results. Adding the head boundary conditions according to the conditions applied in the injection process test. The first steady-state analysis was made and standard values of the soil parameters were adapted for the simulation model by trial and error method until reaching to the minimum root mean square error to make a comparison between the predicted and the observed injection rates and choose the closest values with the minimum root mean square error. This is essential to check if the model is giving an acceptable simulation of injection well or not. The coefficient of hydraulic conductivity (K) is the effective soil parameter which mainly affects the value of the injected brine rates into the underground formation of the injection zone at the study area. Trying different values of the coefficient of soil hydraulic conductivity in each simulation model then calculate the root mean square error by using the following equation (4):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{predicted} - Q_{observed})^2}{n}} \quad \rightarrow \quad (4)$$

Where: $Q_{predicted}$ is the output flow rate from the Seep/w model, $Q_{observed}$ is the actual or the observed flow rate from the in-situ injection test and n is the no. of records. Table 1 shows the applied values of pressures versus the observed discharges (actual) which performed as a step injection test.

Table 1. The applied pressure versus the injected flow rates in the step-injection test.

Pressure (Bar)-From station	Steady State Discharge (m^3/hr)
4	33.53
6	54.43
10	89.59

Figure 5 shows the trial values of the coefficient of the hydraulic conductivity (K) for each soil case against the root mean square error to calibrate the model and choose the best value of the coefficient of the soil hydraulic conductivity which gives the minimum value of RMSE.

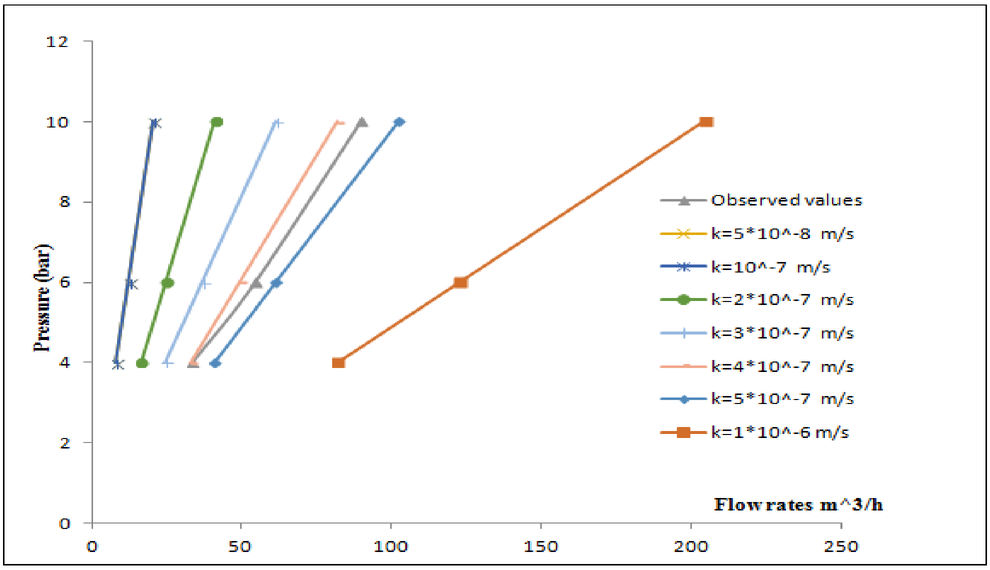

Figure 5. Model calibration

5. EFFECTS OF THE DESIGN PARAMETERS

This section presents the effects of changing the design parameters on the injection capacity of wells. Different simulation runs were made to investigate the effect of changing the diameter of the well, the screen length of the injection well and the aquifer thickness on the injection capacity at different applied heads. The results are as follows.

5.1. Well Diameter

Simulations were conducted by injecting brine into 300m thick broken hard clay aquifer with a coefficient of hydraulic conductivity equals to $K = 0.0036$ m/hr bounded by impermeable layers at the top and bottom. Different values of well diameters are chosen to conduct the simulations for 100 m length of the perforated screen of the deep injection well. As shown in Figure 6, the diameter of the injection well has a slight effect on the injection capacity of the brine.

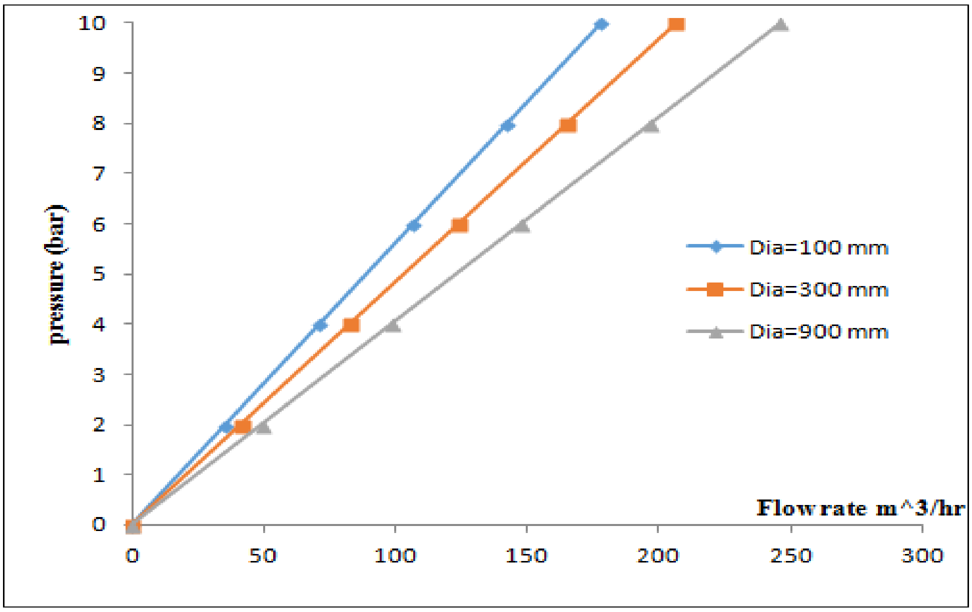

Figure 6. Injection capacity curves for different well diameters (at K = 0.0036 m/hr, S = 100 m, and H = 300 m)

5.2. Screen Length

Results in figure 7 demonstrate the effect of the well screen length on the injection capacity of the brine. Simulations were run by injecting brine into injection well diameter equals to 300mm into broken hard clay aquifer with thickness equals to 300m with a coefficient of hydraulic conductivity equals to $K = 0.0036$ m/hr bounded by impermeable layers at the top and bottom. Different values of well screen length are chosen. The results demonstrate that larger length of well screen leads to a significant increase in the injection capacity of the brine.

5.3. Aquifer Thickness

Different simulations were run in this evaluation by injecting brine into different thicknesses of the aquifer through 300mm of injection well diameter, with 100m of screen length and the coefficient of the soil hydraulic conductivity is equal to $K = 0.0036$ m/hr . It is showed that the increase of the aquifer thickness leads to an increase of the injection capacity until reached to a certain limit at which any further increase of the aquifer thickness leads to no improvement of the injection capacity. This can be explained due to the fully development of the flow at this limit of aquifer thickness. And the further increase in the aquifer thickness will has the same flow area and consequently the same injection capacity. This can be clearly observed on figure 8.

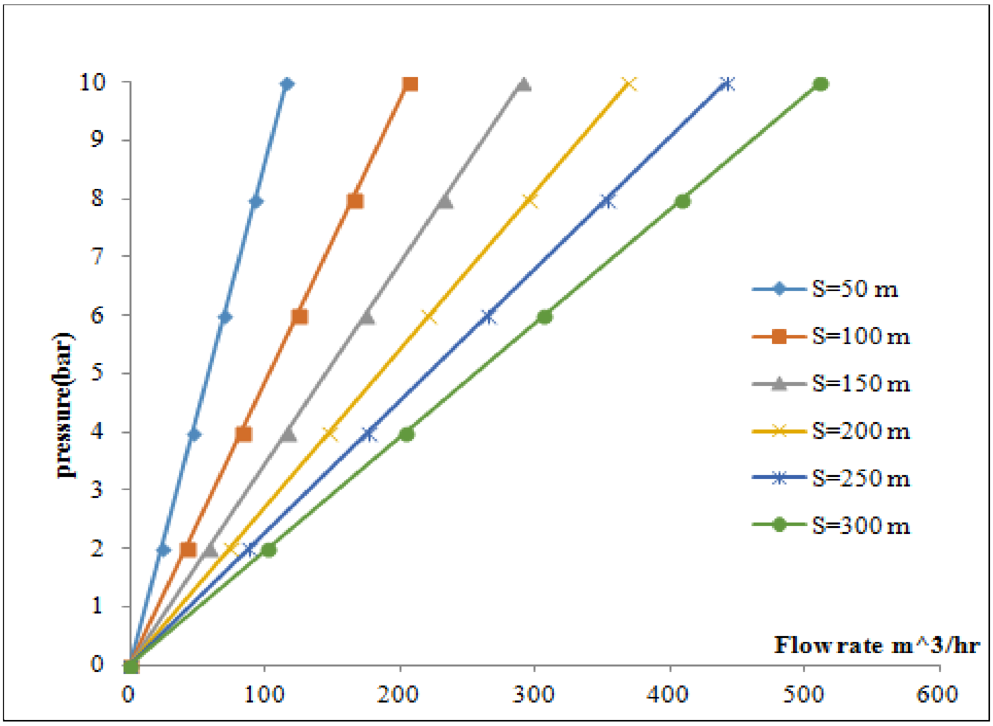

Figure 7. Injection capacity curves for different screen lengths (at K = 0.0036 m/hr, Dia = 300 mm, and H = 300 m)

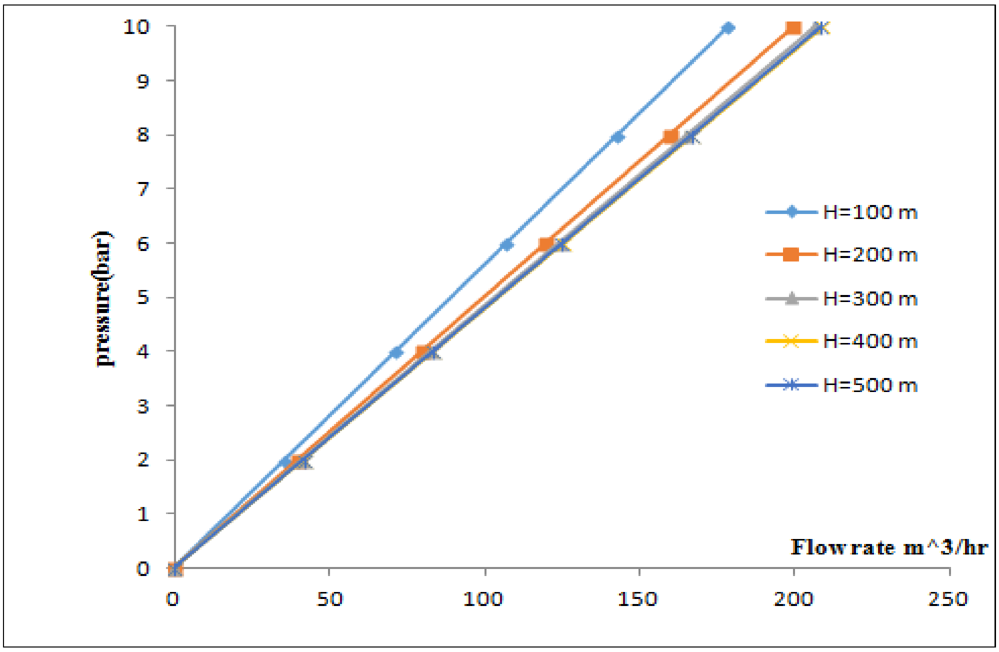

Figure 8. Injection capacity curves for different aquifer thicknesses (at K = 0.0036 m/hr, Dia = 300 mm, and S = 100 m)

6. CONCLUSIONS

Seep/W was developed in this study to simulate the injection process in injection wells for desalination brine. The developed model was verified against real data from a step injection test at the western coast of the Gulf of Suez in Egypt. The model could fairly explain the pressure-discharge relation during the injection. Hence, this approach is recommended to be used for design purposes of injection wells early in the planning stages. This is very important since the cost of injection well construction is significantly high. Hence, it should be carefully estimated early before well construction to properly assess the feasibility of the injection. This illustrates the importance of the developed model.

The developed model was used also in this study to evaluate different design scenarios (well diameters, injection screen lengths, and aquifer thicknesses) to evaluate the effect of well design parameters on the injection capacity. The results showed that a large length of the well screen leads to a significant increase in the injection capacity while the variation in the well diameter has a lesser effect on the injection capacity. Higher aquifer thicknesses lead to higher injection capacity to some extent where any additional increase in the aquifer thickness will has the same capacity since the flow is fully developed over depth and is not affected with increased aquifer thickness. Finally, the soil hydraulic conductivity has the highest effect on improving the capacity of injection.

The current study did not consider long-term injection simulations which may lead to reduction/increase in the injection capacity of the well due to long term factors such as degradation/improvements in the hydraulic conductivity. This long-term effect is recommended for future studies. It should also be noted that Richard's equation (Equation 3) does not consider the nonlinear losses due to any possible turbulence near the well screen. This turbulence effect may lead to additional head losses and consequently a reduction in the injection capacity at a certain pressure difference. A study to evaluate these additional turbulence losses is also recommended for future studies.

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