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The flow and transport parameter estimation of groundwater in a laboratory-scale sand tank aquifer

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Abstract. A laboratory study was conducted on groundwater reservoir to characterize the hydrogeological conditions and performance of wells in an unconfined aquifer using laboratory experiments and real-time groundwater level data. A single-well step-drawdown pumping test was conducted using a two-dimensional sand tank aquifer model, followed by Hunts-Bierschenk's graphical analyses. The step-drawdown pumping test revealed 25% well losses and 75% aquifer losses, demonstrating high well efficiency, while the well efficiency value of 75% indicated that the well was appropriately designed and developed. The laboratory results suggested that the contact point of the aquifer's laminar flow and well-face had only slight turbulent flow. A well development factor of 0.46 reflected the effective development of the well. The hydraulic conductivity (K) value was 0.037cm/s. Our approach thus demonstrated the potential of the pumping test of a single-well step-drawdown at the laboratory scale for the estimation of safe and sustained yield from the well for groundwater exploitation within an unconfined aquifer under similar conditions in the future.

1. Introduction

Increasingly important role in providing water to the civilian population and has been used as a reliable source of water for a variety of purposes, such as domestic, irrigation, and industrial, across the world. Therefore, the aquifer condition needs to be understood for the proper management of this vital water resource [1]. The estimation of field representative flow of groundwater and transport parameters is extremely difficult, mostly due to the groundwater aquifer heterogeneity and the local investigation scale of most characterization methods [2].

The hydraulic characteristics and the potential of groundwater in aquifers are maintained by the subsurface deposit lithostratigraphy, the groundwater depth, saturated (aquifer) thickness, and aquifer hydraulic properties. To analyze the groundwater availability for a variety of purposes, step-drawdown (SD) aquifer pumping tests or well performance test are very apt.

A single-well SD test has been reported as an effective method to determine the well performance criteria [3], including the aquifer and well loss coefficient sand well efficiency, which helps estimate the optimal pumping rate (or the maximum yield) under varying water-level conditions [4]. The SD test is a simple, quick, and an inexpensive pumping test. The abstraction rate from the well in a SD test shows a rise in steps (minimum 3 steps) and covers a broad range of flow rate from that equal to or greater than that necessitated by the design flow. In the test, the well has to be pumped at step-increasing discharge



rates (Q), followed by estimation of the modification in the drawdown (water levels) at every step until a steady state of drawdown was achieved [5].

The pumping test should involve steps that allow drawdown in the pumping well for stabilization, which generally requires 0.5–2 h for each step [4]. At each step, the rise in the pumping rate (Q) and drawdown (or the water level reduction) were noted. The drawdown was measured and categorized as either well loss or aquifer loss.

The SD test was performed as described in a previous study [6], where the author primarily focused on the determination of the well drawdown when pumped at a different rate than that used during the pumping test. Accordingly, the following equation was proposed for the drawdown in a pumped well:

$$Drawdown = aquifer \ losses + \ well \ losses \tag{1}$$

The author suggested that the first term be called aquifer losses(or linear losses), which can be described as head losses resulting from the groundwater aquifer formation resistance, and the second term be called well losses(or non-linear losses), which can be described as head losses caused by the turbulent flow in the area surrounding the well screen. Pumping test is essential in in situ studies on hydraulic groundwater aquifer properties by pumping water and by monitoring the resultant water table drawdown. Important hydrogeological parameters can be obtained using these parameters, including the hydraulic conductivity and specific storage.

Wells are used as water intake bodies for several activities. The estimation of hydraulic parameters of groundwater aquifer is one of its main applications in managing the groundwater reservoir [7].

- Following the above review the, the principal objective of this work can be stated as follows:
 - Evaluation of the aquifer and well responses to different pumping rates via the estimation of well performances.
 - Estimation of well losses, well efficiency, well development factor, aquifer losses, and the optimal pumping rate under diverse water-level conditions.
 - Estimation of aquifer characteristics such as hydraulic conductivity of the aquifer.

This work was to test a homogenous sand tank aquifer in order to estimate the flow of groundwater and transport parameters. The originality of this work is in its laboratory scale and in the fact that it is equipped with a groundwater level simulator. The objectives listed earlier were fulfilled by undertaking a hydrogeological research involving a single-well pumping test yielding data that can be analyzed graphically. In the analyses, the groundwater levels, logging data, and the experimental conditions were also examined.

2. Materials and methods

2.1. The Sand tank design

To investigate the effects of aquifer and well losses on well efficiency, we constructed a tank aquifer model (dimensions: 175-cm long, 18-cm width, 0.5-cm height) from 1-cm thick Perspex. The Perspex screen was covered with a fine stainless steel mesh and then installed to divide the tank aquifer into 3 chambers, figure 1. The middle (main) chamber was of length 1.75m, and this chamber was filled up to sand aquifer (nearly 50-cm thickness). Next, the first and the third chambers (at either side) were provided a source of water, as per the constant head boundary conditions of an aquifer. The first chamber (upper panel) maintained a 30-cm of constant head during the experiment, while the third chamber (lower panel) maintained a25-cm of constant head. The sand tank aquifer maintained its shape without any observable structural change. Silica sand was filled into the middle chamber (B) so as to build a homogeneous isotropic porous aquifer. During packing, the silica sand was fully compacted to avoid trapping of any air bubbles.



Figure 1. The experimental apparatus set-up. Sketch map. A and C are the 30-cm upstream and 25-cm downstream constant heads, respectively; B is the sand aquifer. The hydraulic heads were monitored via pressure sensors and logged in a system.

To simulate groundwater exploitation, a partially penetrating pumping well of an internal diameter 1.5 cm was used. The pumping well was made from a pipe (polyvinyl chloride) [PVC] that was partially screened from10 cm from the bottom. The well was located 35-cm away from the right side of the middle chamber. The pumping well was connected with a peristaltic pump via a tube in order to ensure that the groundwater could be pumped out at a constant rate from the groundwater aquifer. Pressure sensor (red points in figure 1) was connected to the back of the sand tank. The pressure sensor was connected to a computerized data-logging system that could record the real-time data on the groundwater level at every 30 s. In this experiment, we focused on the horizontal and vertical directions.

2.2. Porous medium

Silica sand was used as the porous medium in the model of sand tank aquifer. Sieve analysis was performed with a vibrator-type sieve shaker (ASTM C136). For the sandy material, the particle size of d10 was 0.262mm, and d60 was 0.48 mm. For the silica sand, the uniformity coefficient (d60/d10) was 1.83. The particle size analysis suggested that the porous medium was homogeneous.



Figure 2. Sieve analysis of Fine Aggregate.

2.3. Method

The experimental work was conducted to collect groundwater well data. SD pumping test was conducted in a well 35-cm away from the right portion of the middle chamber of the sand tank aquifer model. The pumping rate was measured via a peristaltic pump connected to the well by a tube.

2.3.1. SD test, performance and analysis

The SD test was theoretically formulated and analyzed in 1947by Jacob [6] and later modified by Hantush–Bierschenk [8, 9]. In this study, we assumed a homogenous and isotropic aquifer and a well that could fully penetrate the unconfined groundwater aquifer. For the groundwater level with a smaller drawdown than the thickness of an aquifer, the components of total drawdown in a pumping well and its relation to the pumping rate have been suggested elsewhere [6] through the following equation:

$$Sw = BQ + CQ^n \tag{2}$$

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Where: S_w : total drawdown (cm), Q: pumping or discharge rate (ml/s), B: formation or aquifer loss coefficient (s/cm²), BQ: a component of the drawdown owing to the formation or aquifer loss with the aquifer's laminar flow (cm), C: the well loss coefficient (s²/cm⁵), CQ²: the component of drawdown owning to the turbulent flow or well loss.

The parameter assumes values of 1.5-3.5, based on the pumping rate (Q). Jacob [6] proposed the A value of n = 2, which is well accepted worldwide [10].

The SD pumping test included pumping in five successively increasing rates (duration/step = 30 min), conducted after the well construction in order to investigate the aquifer loss (B) and well loss (C) coefficients, which are required to determine the well efficiency (EW), as per Hantushand -Bierschenk [8, 9]. The procedure is explained below:

- 1. First, plot the observed well drawdown S_w against the corresponding time *t* (t on the logarithmic scale) on semi-log paper (figure 2).
- 2. Next, use the plotted data to extrapolate the curve at every step till the end of the next step.
- 3. For each step, the increments of drawdown ΔS_w should be calculated (i) considering the difference between the recorded drawdown at a fixed time slot Δt , taken from the beginning of every step, and the corresponding drawdown on the extrapolated curve of the last step.
- 4. Then, determine the values of S_w (n) corresponding to the discharge Q(n) from the equation, S_w (n) = $\Delta s_w(1) + \Delta s_w(2) + ... + \Delta s_w(n)$. After this, calculate the ratio S_w (n)/Q(n) for each step.
- 5. Now, the values of $S_w(n)/Q(n)$ versus the corresponding values of Q(n) (figure 3) should be plotted on a linear paper and a line be created through these points.
- 6. Now, the slope of the line $\Delta Sw(n)/\Delta Q(n)$ should be determined to obtain the C value.
- 7. Next, the extent of the line at Q=0 axis should be determined.
- 8. The interception point on the (S_w/Q) axis provides the B value.

2.3.2. Well efficiency

Well efficiency (Ew) is the ratio of measured theoretical drawdown (the groundwater aquifer head loss, BQ) and the actual drawdown (the total drawdown, Sw) in the pumped well. In other words, well efficiency is the related head loss minus the laminar flow/the total head loss ratio (laminar plus turbulent flow). Rorabaugh (1953) [11] suggested the following equation for calculation:

$$E_w = 100 \frac{\left(\frac{Q}{Sw}\right)}{\left(\frac{Q}{BQ}\right)} \tag{3}$$

Where:

Eq. (3) can be rewritten as:

$$E_w = (BQ/Sw) * 100 \tag{4}$$

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The value of well efficiency of $\geq 70\%$ is considered acceptable in terms of appropriate design and development of the well [12]. When the CQ2 (well loss term) is zero, the well efficiency is 100%. There are many factors that affect well efficiency, including the gravel pack size, the drilling method, the design of the screen, and the development methods employed. Reduced well efficiency could have been due to the very small screen openings, which lead to only partial penetration of the aquifer as well as to inappropriate screen length or well development. The closing of the pore spaces in an aquifer can also occur due to the infiltration of fine and/or salty materials.

2.3.3. Well development factor

This factor can be represented as the well loss/aquifer loss ratio, multiplied by 100. The Bierschenk's classification states that the [9], development factors <0.1 indicate extremely effective development, 0.1-0.5 indicate "effective" development, 0.5-1.0 indicate fairly effective development, while >1.0 indicate ineffective development. Hence, the following equation can be used to calculate the well development factor:

$$(C/B) * 100$$
 (5)

2.3.4. Optimum pumping well

Determining the optimum pumping rate is mainly based on the well efficiency, and the procedure consists of the following two steps:

- Calculate well efficiency E_w for all pumping rates
- Plot graph between efficiencies and pumping rates, and select the pumping rate (Q) value that corresponds to>70% efficiency or more [12]. Figure 4 presents the flowchart of the proposed methodology.

2.3.5. Hydraulic conductivity (K)

The hydraulic conductivity (K) was determined by using an in situ method. Under the steady-state flow condition, between two points in an unconfined aquifer located at distance r0 and R from pumping well and average head $(h_1 + h_0)/2$, in situ hydraulic conductivity (K) value in the sand tank aquifer was determined using the Dupuit formula [13].

$$k = Q \ln(R/r_0) / \pi (h_0^2 - h_1^2)$$
(6)

Where,

Q= discharge rate of the pumped well (ml/s)

R = horizontal distance between the axes of the pumped well and the head point of down-stream (figure 1) (in cm).

r₀=the radius of pumping well (figure 1) (in cm).

 h_0 = the height of the water level at the point where the down-stream is above the aquifer bottom (in cm). h = the height of the water level before the pumping well.

Sw= the drawdown of the water level after the pumping well. h_1 =h-Sw



Figure 3. Diagram of drawdown of the water table in the nearness of a pumped well.



Figure 4. A flowchart illustrates the methodology.

3. Results and Discussion

The groundwater well data collected before and during the SDPT was applied for the investigation of the hydrogeological parameters of the groundwater aquifer and well performances, including the data on well location and depth, water table, and the data accumulated during the periods of geophysical logging and experimental observations.

3.1. Hydrogeological parameter estimation

The estimations related to aquifer characteristics and well performance were based on the SDPT tests of the well. The data interpretations were subjected to the assumptions that the groundwater aquifer is unconfined, homogeneous, and isotropic; the pumping well could penetrate the entire thickness of the aquifer; and the water table was horizontal before pumping (figure 1).

3.2. Auifer loss and Well loss coefficient calculation

Groundwater Aquifer loss coefficient was calculated to be $B = 1s/cm^2$, while the well loss coefficient was $C = 0.46 s^2/cm^5$. According to the classification of well loss coefficient in a previous study [10] and considering the association between well conditions and coefficient values ($C < 0.5 min^2/m^5$), it seems that the tested well was appropriately designed and developed.

$\Delta T=30 \min$



Figure 5. Step-drawdown test curves by, Hantush_Bierschenk s, method.



Figure 6. Step drawdown test linear relation.

B = 1.2 s/cm² C = 0.5 s²/cm³

3.3. Well efficiency calculation

The well efficiencies E_w of 75% was calculated for the well. A high well efficiency can lower the pumping expenditure, as >70% efficiency is acceptable and indicative of appropriate design and development of a well [12].

Step	Discharge	Observed	Aquifer	Well	Calculated	Well
no.	(Q) ml/sec	Drawdown	Loss	Loss	Drawdown	Efficiency
		(S) cm	BQ	CQ^2	$BQ + CQ^2 cm$	E_w %
1	0.8	1.55	0.96	0.32	1.28	75.0
2	0.9	1.64	1.08	0.4	1.49	72.0
3	1.1	1.72	1.3	0.6	1.9	68.4
4	1.2	1.8	1.4	0.7	2.1	66.6
5	1.5	1.9	1.8	1.1	2.9	62.0

 Table 1. Calculation of total drawdown and well efficiency.

3.4. Well development calculation

A development factor of 0.46 was calculated for the well. According to the classification system suggested by a previous study [9], the value of <0.5 for a factor reflected effective development of the well.

3.5. Optimum pumping well calculation

The optimum pumping well of 0.8ml/s was calculated for the well. A high pumping well can reduce the well efficiency (figure 7).



Figure 7. Optimum pumping rates.

3.6. Hydraulic conductivity calculation

Hydraulic conductivity (K) value calculated from the Dupuit formula figure 4:

$$K = \frac{Q ln\left(\frac{R}{r_{\circ}}\right)}{\pi (h_{\circ} - h_{1})}$$
(7)

Where:

Q: The optimum pumping well =0.8 ml/s, R: the radius of influence =140.75cm, R0: the radius of the well=0.75 cm, Sw: from figure 8 =1.55cm, h0: head of down-stream =25cm h_1 : h-S_w =24.45cm

The hydraulic conductivity (K) was 0.037cm/s. This value reflects high aquifer productivity [5] and good water accessibility to the pumping well.



Figure 8. Average groundwater fluctuation of monitoring well (pumping test at Q= 0.8 ml/sec and drawdown (S_w) =1.55cm).

4. Conclusion

A hydrogeological investigation for the selected well in sand tank aquifer model in laboratory experiment, including SWPT was designed for the estimation of the performance criteria of the well and for the characteristics aquifer that control the occurrence of the reservoir of groundwater. The performance of the well was estimated graphically by using the Hantush–Bierschenk method in order to estimate the drawdowns as a result of aquifer and well loss. The results of the pumping test indicated the predominance of the laminar flow in the aquifer, wherein the losses borne by the aquifer were much greater to those by the well. Our results thus demonstrate the acceptable efficiency for a well (75%), indicating the appropriate design and development of the well. The optimum pumping well value was 0.8 ml/s. Hydraulic conductivity value (0.037cm/s) was estimated from the pumping test data, which indicated that the aquifer was productive and, moreover, an effective pumping well could be completed in an aquifer.

The laboratory sand tank groundwater level simulator setup thus proved to be extremely useful to illustrate hydrogeological concepts in classroom demonstrations. This tank is an important addition to research and teaching in numerous ways as a tool in the Earth Science department.

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