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Determination of hydraulic parameters of an unconfined aquifer by a single well pumping test

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Abstract

Pumping tests are used for the estimation of the hydraulic parameters of the aquifer. Conventional methods - such as Theis & Cooper-Jacob - that have been developed based on the assumption of homogeneity of aquifers were used for the analysis of these tests. Because of this supposition, the investigation of the pump test data produces representative individual parameter estimates of the volume of disturbed aquifer adjoining the pumping well. Actually aquifers are assorted. Therefore, the apparent flow parameters change as the cone of depression due to pumping progresses over time. In the early days apparent flow parameters reflect local conditions in the vicinity of the well, while in later times, the apparent flow parameters are closer to a weighted average of the disturbed spatial aquifer. In this article, two well-known tools, namely AQTESOLV and MODFLOW, were used as an aid for the analytical and numerical approaches, respectively. The parameters of aquifer were determined and compared using these two techniques. An axisymmetric well model for an unconfined aquifer was developed in Groundwater Vista and simulations were performed using MODFLOW. The method used the observed drawdown as target of calibration at a single observation point to estimate the hydraulic conductivity, storage coefficient, and radius of influence. Pumping test data of number of wells were analyzed and for demonstration purpose results of 2 wells were presented. The results are compared with analytical approach of Neuman and Tartakovsky-Neuman procedure given in AQTESOLV software. The correlation coefficient between observed and predicted head by numerical model for TW1 and TW2 was 0.997 and 0.991, respectively. It showed that the numerical estimations were found to be more representative of the aquifer in the study area since it simulated the groundwater flow behavior of the aquifer system better than the analytical solution.

Keywords: *Hydraulic conductivity, Unconfined aquifer, MODFLOW, AQTESOLV*

Introduction

Aquifer parameters are important in assessing the potential of an aquifer as water resources, and are also necessary for prediction of both short-term and long-term response of an aquifer to different hydraulic and environmental stresses (James and Butler, 2005). Common methods of obtaining in situ hydraulic properties of an aquifer include pumping test. Movement of groundwater is extremely reliant on the hydraulic properties of the aquifer and boundary conditions forced on the system (Appiah-Adjei *et al.*, 2012). Hydraulic conductivity is the major factor controlling movement of the groundwater (Ahmed and Umar, 2009). The magnitude of hydraulic conductivity of the aquifer plays a significant role in modeling of the aquifer for simulating water-table fluctuations. The variability in hydrogeological properties with respect to space plays a significant role in determining the hydrological response of the groundwater system (D'Oria and Fienen, 2012). Variability in the hydraulic conductivity can alter flow paths and groundwater velocities. Conventional methods for estimating aquifer properties are based on testing of aquifers, which provide estimates of effective hydraulic properties over a large area (Rotzoll and El-Kadi, 2008). The investigation of pumping test data is complicated for an unconfined aquifer. Drawdown curves of an unconfined aquifer can be divided into three segments as shown in Figure 1. The first segment indicates the behavior of instantaneous release of water from the storage. In the second part of the curve, the decline of water level with respect to time is comparatively flat because pumping produces vertical gradient near the water table that induces drainage porous matrix. The third segment more pronounced when the flow is fundamentally horizontal; most of the water is supplied by the specific yield, S_y, in the third segment.

For unconfined aquifer the analysis of pumping test is more complicated and it requires more resources so most of the groundwater hydrologist relies on the simplified

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techniques of Cooper and Jacob (1946). Many professionals have determined hydraulic parameters for confined and unconfined aquifers using the Cooper-Jacob method, regardless of the difference between theory and field conditions (Halford *et al.*, 2006). In unconfined aquifer, water is released by compaction of the aquifer, expansion of water, and gravity drainage at the free surface, which is characterized as delayed yield. The theory of unsteady flow in unconfined aquifers which takes into account the phenomena of delayed yield, was first developed by Boulton (1963).

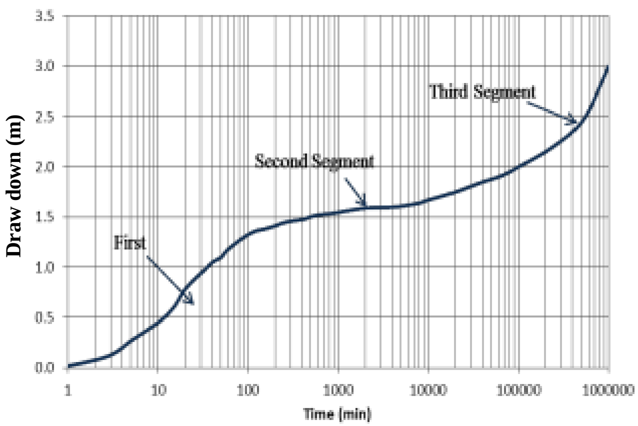

Figure 1: Hypothetical drawdown curve for an unconfined aquifer

The various analysis models differ in their handling of drainage to the pumped aquifer from the overlying unsaturated zone. Boulton models assume no gradual release of water from unsaturated zone, whereas those of Neuman (Neuman, 1987) assume an instantaneous and complete release of water in response to a lowering of the water table. Although these models account for the effects of gravity drainage from the unsaturated zone on the response of water levels in the saturated zone, none of them, with the exception of Kroszynski and Dagan (1975), explicitly represent flow within the unsaturated zone or include unsaturated-zone hydraulic characteristics.

Study area

The study area lies in the Middle of the Rachna Doab of Indus basin in Punjab province, between latitude 72°-46′ to 73°-6′ E and longitude 31°-27′ to 31°-42′ N in the middle of the Punjab (Figure 2). It stretches over an area of about 640 km^2 in the Northeast of the Faisalabad city. The land surface elevation decreases from approximately 181 m above mean sea level (m.a.s.l) in the Northeast part to approximately 174 m in the East-west side. The study area is categorized as semi-arid climate with a distinct rainy season known as the monsoon. The monsoon occurs from July to October. The average annual rainfall in the study area is 450 mm. Over 90% of the precipitation falls during monsoon season. The average annual temperature range varies from 22 to 48°C. The water quality underlying the Faisalabad aquifer is brackish and fresh quality water is being transferred from the project area to Faisalabad. The strata in the study area mainly comprise unconsolidated sediments from coarse sand to fine sand.

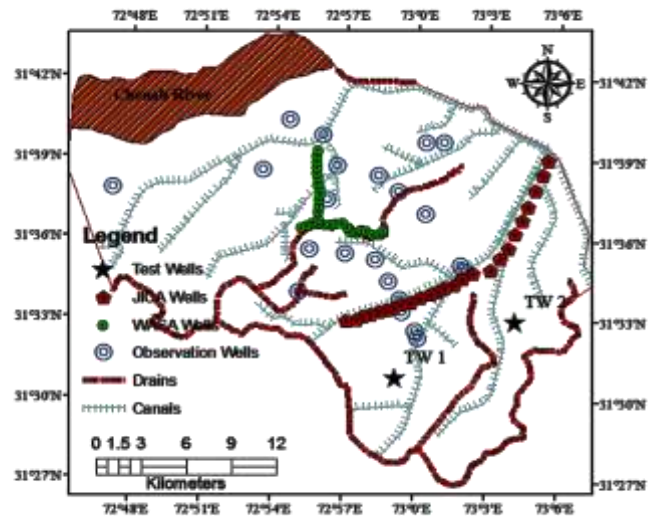

Figure 2: Study area location of Faisalabad pumping water supply well field

Material and Methods

Faisalabad water supply scheme was executed in early ninety when digital computations were limited and coefficients of hydraulic conductivities were determined using graphical method. In order to verify the values determined, the pumping test data were analyzed using two techniques, i.e., (a) analytical techniques of AQTESOLV software, (b) numerical technique develop for a single test well using MODFLOW.

Analytical techniques

Pumping test data were analyzed using AQTESOLV (AQuifer TEst SOLVer) v4.5 software. Pumping test data of two wells i.e., TW1 and TW2 as shown in Figure 2 were analyzed using AQTESOLV. Aquifer saturated thickness for TW1 and TW2 were 61 m each. The pumping rate was 7340 m^3 day^{-1} for TW1 and TW2. Well radius for each well was 25 cm. AQTESOLV software was used to determine the hydraulic parameter of the aquifer using methodology of Neuman (1974) and that of Tartakovsky and Neuman (2007). AQTESOLV provides a graphic interface for data entry that ensures complete and accurate data entry, interactive solution expert that helps to find the right solution for test analysis, and different customizable plots for displaying and analyzing the aquifer test data.

Numerical techniques

In the present study an axisymmetric simulation of pumping well was performed similar to that of Halford *et al.* (2006). They used a long-term pumping data for simulating the drawdown as a function of time by the application of MODFLOW. Drawdown is delayed in the intermittent segment due to the delayed gravity flow and this can be simulated by considering the recharge around pumping well. An axisymmetric radial simulation of a pumped well produced the desired results. A single layer of 61 m thickness unconfined aquifer was assumed. A finite difference groundwater flow model was developed by discretizing the aquifer into a square grid of 85 rows and 85 columns as shown in Figure 3. The central column and row was kept almost equal to the diameter of the well (i.e., 25 cm) and row and column spacing was increased by 25% of the width until a reasonable width was achieved which is maintained up to the external column and row.

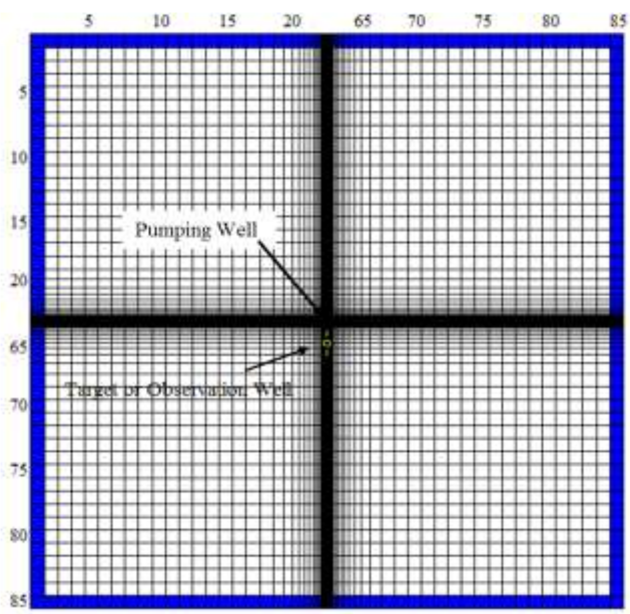

Figure 3: Finite Difference Mesh for Simulation Model

Groundwater Vista (GV) model was used for this simulation. GV has the advantage of simulating the groundwater flow using MODFLOW and automatic calibration using option of PEST (2010). PEST model provides the facility of automatic calibration process. A pumping well was located at the center of the mesh as shown in Figure 3. Constant head boundary was located all around the mesh which simulates the assumption of infinite aerial extent of the boundary. An analytical element was located representing the place of the observation well with reference to the pumping well. Time drawdown data in the observation wells were used as target of the calibration in such a way that observed and computed head were correlated within an acceptable limit.

Results and Discussion

The hydraulic conductivity was estimated using AQTESOLV (v4.5) software and numerical techniques as lay out above. The pump test data of TW1 and TW2 was used for analysis. The location of the test wells is shown in Figure 2. The aquifer parameters were determined using AQTESOLV (v4.5) software. The graphical output of the software is shown in Figure 4 and Figure 5. The comparison of observed and computed head for TW2 is shown in Figure 5.

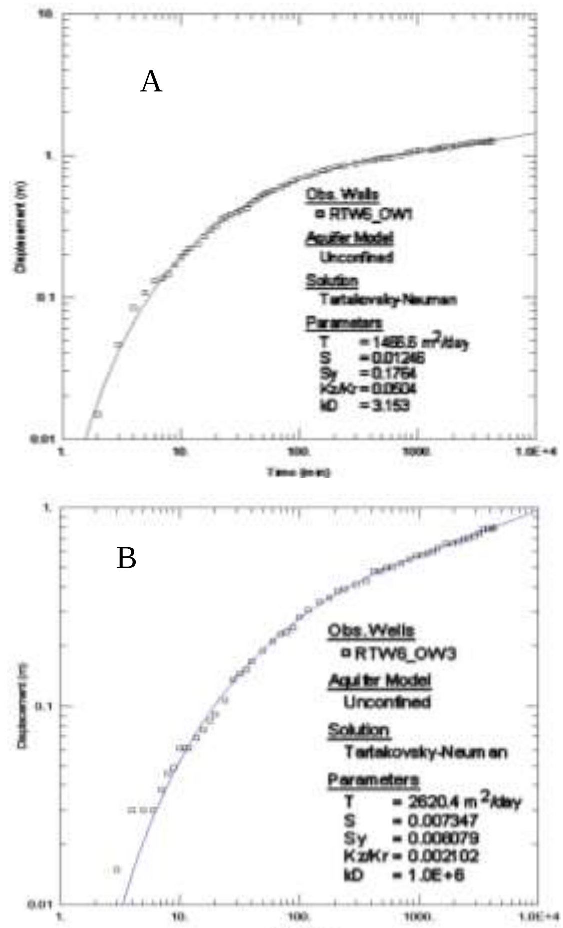

Figure 4: Calibration of Tartakovsky - Neuman Unconfined Pumping Test and Estimation of Hydraulic Parameters (A) TW1 with observation at a distance of 31 m. (B) TW2 with observation at a distance of 61 m

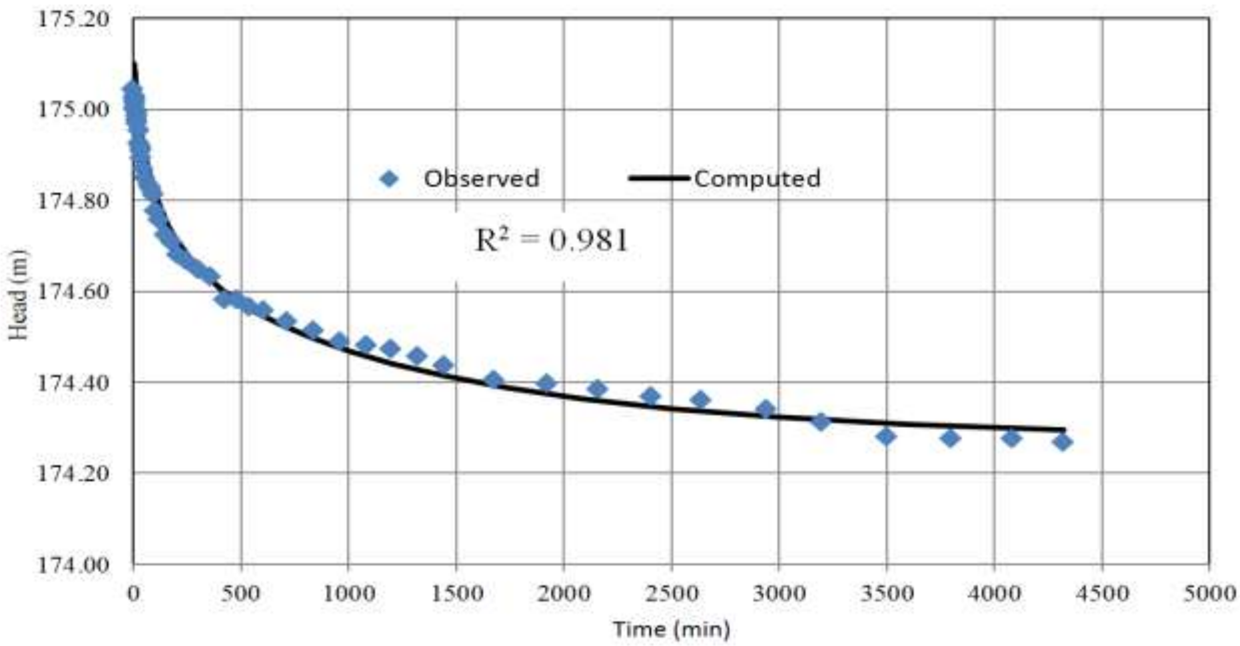

Figure 5: Comparison of simulated and observed head at the observation site for TW2

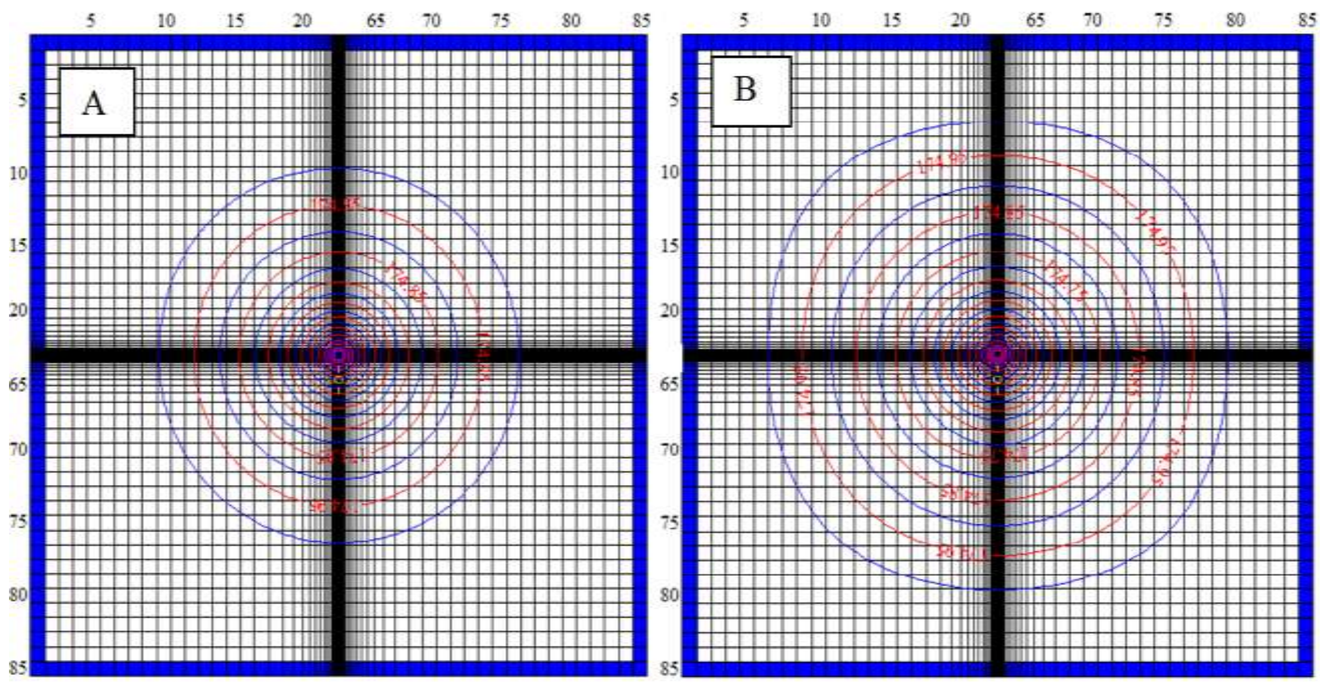

Figure 6: Axisymmetric Simulation showing the radius of influence for TW2 well (A) after one day pumping, (B) after 3 days of continuous pumping at the rate of 7340 m^3 day^{-1}

There was a close agreement between observed and computed head with R^2 value of 0.981. The finite difference mesh as developed for estimation of parameters using numerical technique is shown in Figure 3. The comparisons of the results are given in Table 1. It showed that the results are comparable as determined by both, analytical and numerical techniques. It showed that the hydraulic conductivity determined by using AQTESOLV with

Table 1: Estimated aquifer parameter using the analytical and numerical approach

Pumping Well		**TW1**	
Observation Well		**OW1 located at 31 m from pumped well**	
Parameters (unit)	**Neuman (1999)**	**Tartakovsky-Neuman(2007)**	**Axisymmetric Simulation**
K_h (m day^{-1})	75.80	69.64	61.75
S_s (m^{-1})	3.008×10^{-6}	5.248×10^{-6}	1.000×10^{-3}
S_y	0.0001	0.0001	2.069×10^{-3}
R_o (m)	Not Determined	Not Determined	1000
Pumping Well		TW1	
Observation Well		OW2 located at 91 m from pumped well	
Parameters (unit)	Neuman (1999)	Tartakovsky-Neuman(2007)	Axisymmetric Simulation
K_h (m day^{-1})	37.7	37.64	62.06
S_s (m^{-1})	4.963×10^{-5}	4.963×10^{-5}	4.500×10^{-4}
S_y	0.015	0.015	1.234×10^{-2}
R_o (m)	Not Determined	Not Determined	1000
Pumping Well		TW2	
Observation Well		OW3 located at 31 m from pumped well	
Parameters (unit)	Neuman (1999)	Tartakovsky-Neuman(2007)	Axisymmetric Simulation
K_h (m day^{-1})	24.42	24.42	24.97
S_s (m^{-1})	2.074×10^{-4}	2.074×10^{-4}	4.982×10^{-2}
S_y	0.0128	0.1764	4.900×10^{-3}
R_o (m)	Not Determined	Not Determined	705
Pumping Well		TW2	
Observation Well		OW4 located at 61 m from pumped well	
Parameters (unit)	Neuman (1999)	Tartakovsky-Neuman(2007)	Axisymmetric Simulation
K_h (m day^{-1})	43.64	43.64	62.06
S_s (m^{-1})	1.224×10^{-4}	1.224×10^{-4}	4.500×10^{-4}
S_y	8.079×10^{-3}	8.079×10^{-3}	1.234×10^{-2}
R_o (m)	Not Determined	Not Determined	843

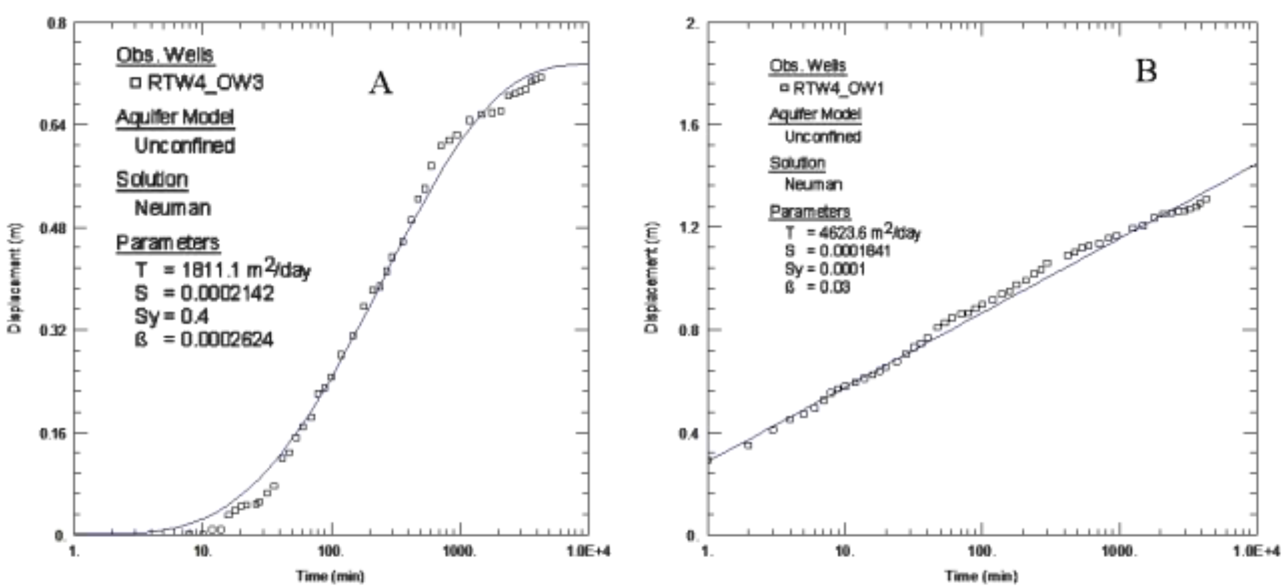

Figure 7: Calibration of Tartakovsky-Neuman Unconfined Pumping Test and Estimation of Hydraulic Parameters (A) TW1 with observation at a distance of 91 m, (B) TW2 with observation at a distance of 31 m

methodology of Neuman (1974) and that of Tartakovsky and Neuman (2007) were 24.42 m day^{-1} and with numerical techniques it is 24.97 m day^{-1} as shown in Table 1.

In analytical technique, radius of influence cannot be determined where as in the numerical techniques it was determined as 705 m. Similarly, while analyzing the data of observation well (OW4) which was spaced 61 m away from TW2, the hydraulic conductivity was 62.06 m day^{-1} and radius of influence was 843 m. The radius of influence for TW1 with both observations well (i.e., OW1 and OW2) was 1000 m as shown in Figure 6. Comparison of these results showed that estimation of aquifer parameter by axisymmetric simulation gives better result and as it also predicts the radius of influence. The correlation coefficient between observed and computed head by numerical model was 0.997 and 0.991 for TW1 and TW2, respectively. In this technique other boundary condition can easily be accommodate.

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