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ORIGINAL ARTICLE

Evaluation of unconfined aquifer parameters from flow to partially penetrating wells in Tailan River basin, China

Emmanuel Kwame Appiah-Adjei · Longcang Shu · Kwaku Amaning Adjei · Minjing Deng · Xiaohui Wang

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Abstract Effective evaluation, management and abstraction of groundwater resources of any aquifer require accurate and reliable estimates of its hydraulic parameters. This study, therefore, looks at the determination of hydraulic parameters of an unconfined aquifer using both analytical and numerical approaches. A long-duration pumping test data obtained from an unconfined aquifer system within the Tailan River basin in Xinjiang Autonomous Region in the northwest of China is used, in this study, to investigate the best method for estimating the parameters of the aquifer. The pumping test was conducted by pumping from a radial collector well and measuring the response in nine observation wells; all the wells used in the test were partially penetrating. Using two well-known tools, namely AquiferTest and MODFLOW, as an aid for the analytical and numerical approaches, respectively, the parameters of the aquifer were determined and their outputs compared. The estimated horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific yield for the analytical approach are 38.1–50.30 m/day, 3.02–9.05 m/day and 0.204–0.339, respectively, while the corresponding numerical estimates are 20.50–35.24 m/day, 0.10–3.40 m/day, and 0.27–0.31, respectively. Comparing the two, the numerical estimates were found to be more representative of the aquifer in the study area since it simulated the groundwater flow conditions of the pumping test in the aquifer system better than the analytical solution.

Keywords Tailan River basin · Pumping test · Unconfined aquifer · Partial penetration · MODFLOW · Moench solution

Introduction

Groundwater flow in any aquifer medium is highly dependent on the hydraulic properties of the geologic medium (i.e. rock or soil) and the boundary conditions imposed on the groundwater system. To evaluate the groundwater resources of any media, therefore, it is essential to have a good estimate or understanding of the hydraulic properties of that media, which are invariably the aquifer parameters that control groundwater flow and mass transport in that media. These aquifer parameters are also very important in developing plans for groundwater abstraction and numerical groundwater flow models for predicting future resource availability and management.

Generally, the standard and commonly preferred method for estimating aquifer parameters, by most hydrogeologists, is thorough analyses of pumping test data using type curves (Moench 1994). This is because the use of these type curves, which are derived from models of assumed flow governing equations and sets of boundary conditions, is a very convenient and inexpensive way to evaluate hydraulic

E. K. Appiah-Adjei (✉) · L. Shu · K. A. Adjei · X. Wang
State Key Laboratory of Hydrology, Water Resources
and Hydraulic Engineering, Hohai University,
No.1 Xikang Road, Nanjing 210098, China
e-mail: emmaappiah_adjei@yahoo.com

E. K. Appiah-Adjei
Department of Geological Engineering, Kwame Nkrumah
University of Science and Technology, Kumasi, Ghana

L. Shu
College of Hydrology and Water Resources,
Hohai University, No. 1 Xikang Road, Nanjing 210098, China

M. Deng
Department of Water Resources of Xinjiang,
Xinjiang 830063, China

parameters of an aquifer. Thus, there are several available model type curves for analysing pumping test data from aquifers of different flow regimes, boundary conditions and pumping test designs. The commonly available analytical solutions for analysing pumping test data from unconfined aquifer formations were presented by Boulton (1963); Neuman (1972, 1975), and Moench (1993). These solutions are more complex than the solutions (e.g. Theis 1935) for analysing confined aquifers because the number of parameters derived from them are greater due to the effect of delayed yield in unconfined aquifers. Using any of these solutions to analyse pumping test in unconfined aquifers makes it possible to derive parameters like the vertical and horizontal hydraulic conductivities (K_v and K_h), storativity (S), and specific yield (S_y) of the aquifer (e.g. Moench 1993). However, all the four parameters are rarely determined together because obtaining an accurate fit of a theoretical curve of any of the analytical solutions to an observed time-drawdown data is a very difficult and time consuming process. Thus, there is often some compromise of a parameter(s) for the others during the curve-fitting process for parameter estimations. Generally, the accuracy of the results obtained from using any of these analytical solutions or their corresponding model type curves depend on the validity of the assumptions invoked in the models, the accuracy of the curve-fitting process, and the relative importance of extraneous effects on the field data (Moench 1994). Typically, most of the model type curves are developed based on the assumption that the aquifer formation is homogeneous and that they would, commonly, be used to analyse individual observation well data separately (Kruseman and de Ridder 1994).

Another approach for estimating aquifer parameters from pumping test data, as an alternative to the analytical approach of type curves, is by the use of numerical models. These models when applied make it possible to eliminate some of the simplifications and assumptions on which analytical solutions are based (Lebbe et al. 1992). Unlike the analytical models, numerical models allow specific hydrogeological conditions (like multiple aquifer–aquitard formations, layers of different hydraulic conductivity, complex aquifer boundary conditions, etc.), nature of the test wells, and other site-specific features of the test area to be included in the setup for the modelling process. The accuracy of this modelling process is enhanced, aside ensuring the accuracy of input data and assumptions, by specifying proper temporal and spatial discretizations for the model domain (Wiel et al. 2011).

The main objective of this study is to apply analytical and numerical models on the pumping test data obtained from partially penetrating wells in an unconfined aquifer at the Tailan River basin of northwest China. The purpose of this study is to determine a reliable and accurate estimate of the hydraulic parameters, i.e. vertical and horizontal hydraulic conductivities, storativity, and specific yield—of the aquifer system in the area for effective abstraction and sustainable management of the resource, which is the backbone for economic development in the area.

Study area description

The study area is within the Tailan River basin located at the western part of the Tianshan Mountains and the north marginal zone of the Tarim basin in Xinjiang Autonomous Region at northwest of China (Fig. 1). Generally, the basin terrain slopes from the north to the south and is divided into five geomorphologic units; viz. middle-low mountainous area, intermountain deep stripping area, low mountain anticlinal region of Gumubiezi, mountain front alluvial–pluvial fan area, and alluvial–pluvial plain area (Sun et al. 2011; Wang 2010).

The total drainage area of the basin is about 3,871 km^2 and is part of the arid regions of China with a typical continental arid climate of scarce precipitation and strong evaporation potential. Annual precipitation of the area ranges from 100 to 250 mm while the annual pan-evaporation is from 1,000 to 1,800 mm. Also, the mean annual temperature, mean annual wind speed and the maximum wind speed of the area are 7.9 °C, 1.7 m/s and 40 m/s, respectively (Sun et al. 2011; Wang 2010). According to Wang (2010), the mean annual runoff of the basin is about 742 million cubic meters and is unevenly distributed; June to August accounts for 69.9 %, September to November accounts for 16.6 %, December to February accounts for 4.5 %, and March to May accounts for 9 %. Yang (2005) indicates that glacier thawing runoff contributed nearly 50 % of river discharge in 1970s, but this value appears to be around 21 % in recent times (Wang 2010).

The basin area is mainly underlain by variegated sandstone, shale, siltstone and conglomerates amongst other formations of pre-tertiary era. Local structural features in the area were developed as a result of tectonic activities in the depression unit at the northern margin of the Tarim basin; hence folds and faults are common structures in the area. Overlying the structured formations in the area, however, are thick and uneven unconsolidated quaternary sediments, which are widely distributed over the whole basin. The quaternary sediment thickness ranges from 170 to about 700 m and it is mainly a multi-layered formation with abundant groundwater storage (Wang 2010). Piedmont alluvial–pluvial fan deposits, which are widely distributed in the basin and composed of coarse gravel and silty sand sediments, serve as the aquifer formation in the area. The thickness of the aquifer, which is unconfined, varies from 170 to 250 m (Wang 2010). The terrain morphology and geological structures controls groundwater

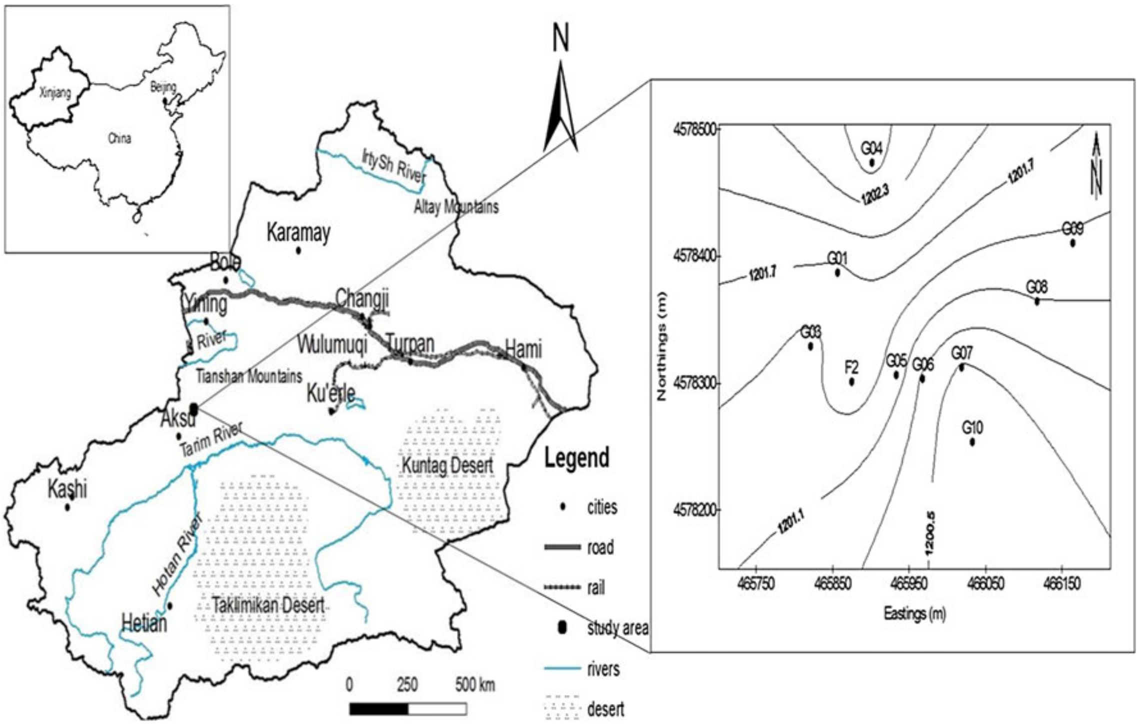


Fig. 1 Study area location in Xinjiang, China, with distribution of the pumping (F2) and observed (G01–G10) wells on ground elevation contours in m asl

recharge, runoff and discharge in the basin. Recharge to the aquifer in the basin is mainly from the precipitation, seepage from irrigation canals and glacial thawing. According to Sun et al. (2011), the precipitation only recharges the aquifer system in areas where the groundwater depth is shallower than 5 m. The local economy of the area is mainly agriculture and it depends a lot on the groundwater resources due to limited availability of surface water resources in the area as result of its peculiar climatic conditions. Thus, effective management of the groundwater resource in the basin is very important for sustainable development of the local economy.

Methods

Pumping test description

The pumping test for this study was conducted for a total duration of 21 days (i.e. 16 days of pumping and 5 days for recovery) in the unconfined alluvial–pluvial aquifer formation of the Tailan River basin at a variable pumping rate. The approximate area of the test is within latitudes 41°20′15″ to 41°20′31″N and longitudes 80°35′21″ to 80°35′52″E. This test was conducted following standard procedure as outlined in many literature (e.g. Kumar 2008; Kruseman and de Ridder 1994; Fetter 2001) using a pumping well (F2) close to the edge of the alluvial fan and nine observations wells, which were distributed at various radial distances around the pumping well (Fig. 1).

Summarized data on the wells used in the test and a schematic drawing of the pumping test set up at the study site are presented in Table 1 and Fig. 2, respectively. The pumping well used in the test was a radial collector well consisting of a 3.5 m diameter vertical caisson at 30 m deep into the aquifer with eight small diameter horizontal laterals around it at 3.2 m from the bottom and at 1.9 m interval upwards to a depth of 9.35 m from the bottom. The length and diameter of each lateral was 30 and 0.15 m, respectively. All the wells used in the test did not penetrate through the full thickness of the aquifer formation and the diameter of each observation well was 0.121 m.

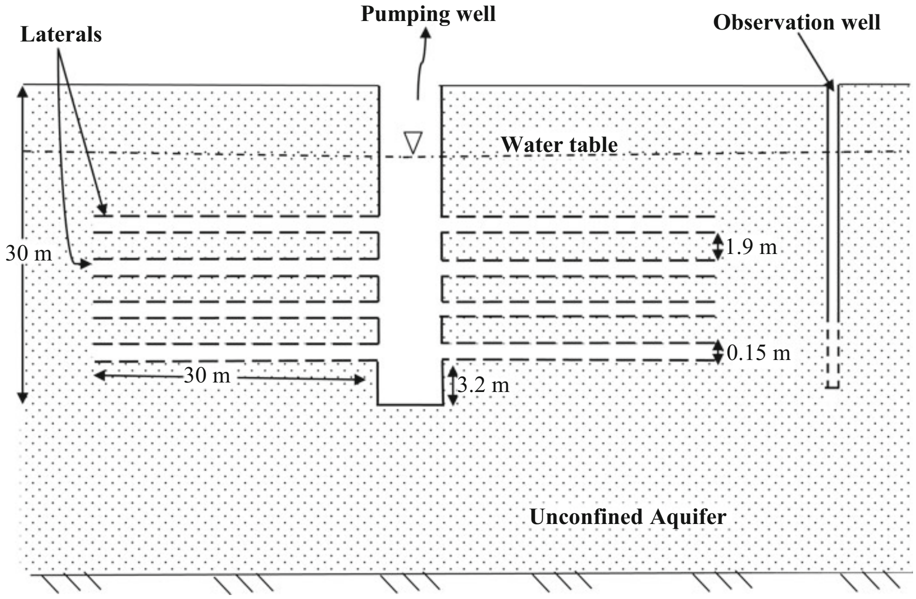
Time-drawdown and -recovery data were recorded in the pumping and all the observation wells, simultaneously, using mini-diver automatic loggers. The time interval for the measurements in wells F2, G03 and G05 were the same (i.e. at 1 min) and a little different from the other wells (i.e. 30 min) within the first 60 min of both the pumping and recovery periods. Outside this duration, measurements were made at the same time interval in all the wells starting with 30 min time step and increasing gradually as the drawdown or recovery in the wells became smaller. Manual drawdown/recovery measurements were, also, made at random time intervals within the test period as a check on

Table 1 Location and dimensional data of the wells used for the pumping test

Well	Distance from F2 (m)	Longitude (E)	Latitude (N)	Ground elevation (m asl)	Initial water level (m asl)	Well depth (m)	Water column depth in well (m)
F2	–	80°35′32.3″	41°20′20.3″	1,201.757	1,194.458	30.00	22.85
G01	89.0	80°35′31.5″	41°20′23.1″	1,202.255	1,194.538	21.00	13.91
G03	59.0	80°35′30.0″	41°20′21.2″	1,201.895	1,194.247	24.68	17.61
G04	175.0	80°35′33.4″	41°20′25.9″	1,203.369	1,194.834	17.78	9.91
G05	58.0	80°35′34.8″	41°20′20.5″	1,201.581	1,194.467	28.00	21.21
G06	93.0	80°35′36.3″	41°20′20.4″	1,201.205	1,194.397	18.65	12.30
G07	145.0	80°35′38.5″	41°20′20.7″	1,200.885	1,194.542	18.62	12.70
G08	250.0	80°35′42.7″	41°20′22.4″	1,201.543	1,194.840	7.65	1.40
G09	308.8	80°35′44.7″	41°20′23.9″	1,201.858	1,194.995	15.00	8.65
G10	164.7	80°35′39.1″	41°20′18.8″	1,200.631	1,194.285	29.30	23.35

m asl means meters above sea level

Fig. 2 Schematic diagram of the pumping test set up at the study site indicating water table before pumping (not drawn to scale)



the accuracy of the automatic data loggers. The pumped water from F2 was diverted to a channel of known cross-section area from which the velocity of water flow was measured simultaneously as the drawdown recordings for pumping rates estimation. The data from the loggers together with the pumping rates were then collated and processed for quality checks and subsequent analyses.

Preliminary pumping test analyses

Plots of time-drawdown/recovery measurements from all the observation wells used in the test together with the pumping rate are shown in Fig. 3. Preliminary analysis of the plots indicate that with the exception of well G04, all the wells exhibited fairly continuous drawdown up till after 5,730 min where they begun to fluctuate and the drawdown increased sharply due to increased pumping rate with lots of variability.

The cause of the sharp rise in well G04 earlier (i.e. at 340 min) could not be attributed to the pumping rate since it was fairly constant within that period (i.e. 0–5,730 min) and none of the other observed wells happen to have experienced a similar rise. The gradual fall of its drawdown after the rise also takes out the possibility of it being an error in measurement. Therefore, it was not included for further analyses in the study since its peculiar nature makes it more like an 'outlier' to the rest of the data. The time-drawdown data from the other wells were analysed to estimate the hydraulic parameters of the aquifer formation using both analytical and numerical approaches.

Analytical approach

The pumping test data from the study area aquifer was analysed using the Moench (1993) analytical solution. This

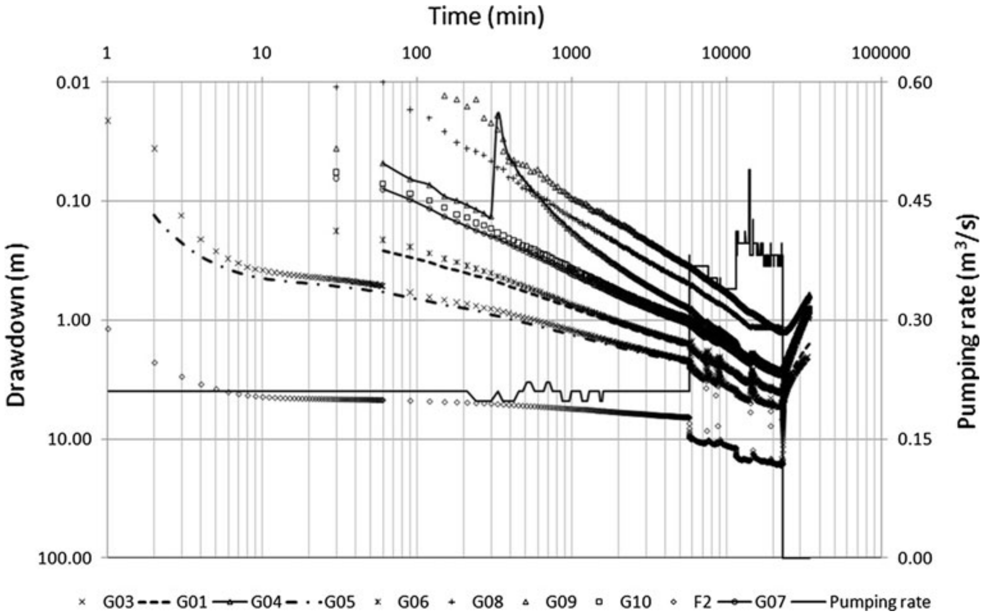


Fig. 3 Time-drawdown/recovery measurements from the observed wells with the pumping rate

solution is an enhancement of the Neuman (1972) solution and is designed for determining hydraulic parameters of flow toward a fully or partially penetrating pumped well(s) in anisotropic homogeneous unconfined aquifers. Therefore, it is more suitable for the condition of the pumping test, especially with regards to the partial penetrations of all the test wells. The solution also takes into account the storage in the pumped well, skin at the pumped well screen, and delayed response of observation piezometers. However, it does not include unsaturated zone hydraulic characteristics but allows for gradual drainage from the zone above the water table, which is accomplished by introducing a finite series with exponential terms in the water table boundary condition (Moench 2008).

In this study, the AquiferTest 3.02 software (produced by Waterloo Hydrogeologic Incorporated) was used as aid in estimating the aquifer parameters of the study area with the Moench solution. The software has an easy-to-use windows-based interface and consists of a wide range of models for graphical analysis and reporting of pumping and slug test data. The choice of this software was, mainly, based on the fact that it is well-known, used widely, and has been used for similar studies in other basins in China. Using the software, the procedure for the Moench type curve analysis of the pumping test data involved (1) inputting the data described in Table 1, screen length, pumping rates, and the time-drawdown data; (2) automatic curve matching of a type curve to a time-drawdown data using least squares regression method; and (3) manual refining of the curve-matching process for a better fit to obtain the estimates of the aquifer parameters. Due to limitations in the AquiferTest, the laterals of the collector well could not be appropriately represented as was in the field conditions. However, their location from 3.2 m at the bottom of the large diameter caisson upwards to 9.35 m was assumed to be the screen length (i.e. 6.15 m of screen length).

All the time-drawdown data sets from the observation wells, except well G04, were used in the Moench type curve analyses. The eight observed wells data were analysed with the Moench solution as follows: (1) all the observed well data sets together in one composite plot; (2) each observed well data alone; and (3) paired wells together based on similarity of the time-drawdown curves (Fig. 3). The essence of the composite and paired wells along the usual individual well analysis was to be able to obtain a better estimate of the average aquifer properties of the study area and a good understanding of the homogeneity or otherwise of the aquifer formation. Prior to parameter estimations in all the three ways above, a sensitivity analysis was conducted to determine the influence of the well parameters (Table 1) on the expected outputs (i.e. hydraulic conductivity and specific yield). It was realized from the test that the depth of water column in the pumping well and distance to observed wells have very significant influence on the outputs; hence, their appropriate values were used in the estimations. A screen length of 5 m for all the observation wells during the pumping test was also applied for the analysis.

Due to the significant variations in the pumping rate after the 5,730 min (refer Fig. 2), type curve analyses for the aquifer parameter estimations were restricted to the data measured from 0 to 5,730 min (i.e. about 4 days). According to Kruseman and de Ridder (1994), 3 days of pumping for an unconfined aquifer is good enough to be used to evaluate its hydraulic parameters although they advocate for longer periods for the aquifer to reach steady state. Hence the choice of analysing the data for the chosen period is not expected to have any adverse effect on the results. More so, the Moench solution (1993) used, in here, requires average rate of pumping as input; thus the period chosen was more appropriate for the analyses.

Numerical approach

In order to estimate the hydraulic parameters of the study area using numerical approach, the Visual MODFLOW version 4.3 for practical applications in three-dimensional groundwater flow and contaminant transport modelling by Schlumberger Water Services was employed. This integrated finite difference modelling package combines MODFLOW (MacDonald and Harbaugh 1988), MODPATH (Pollock 1989) and MT3DMS (Zheng and Wang 1999) codes together with WinPEST amongst others in a graphical interface for solving hydrogeological problems. The MODFLOW component within the package was used in analysing the pumping test data from the study area.

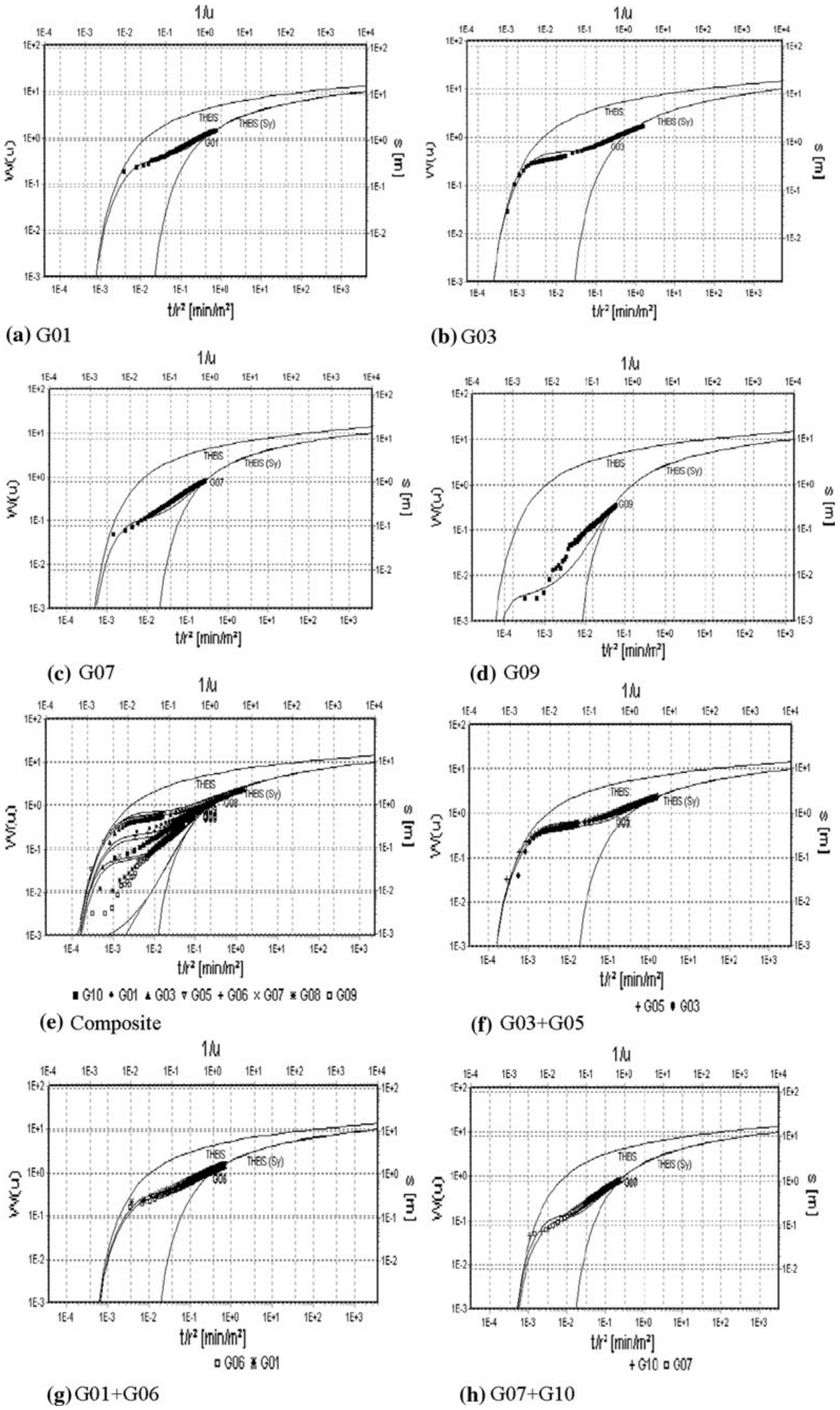
A finite difference numerical model of the pumping test conditions representing the physical properties of the aquifer formation and the test wells was designed and constructed in Visual MODFLOW environment using the graphic user interface. The model domain had a size of 1,110 m by 1,110 m with a depth of 170 m. The pumping well was located at the centre of the model domain with the observation wells at their respective coordinate locations. A piezometric contour map (not shown) constructed with the initial water levels of the test wells (Table 1) indicated different water levels at the north and south of the test area, albeit very small, and both decreasing slightly towards the west. However, in a pumping test, flow in the test area is expected to move towards the pumping well except in areas outside the influence radius of the pumping well. Therefore, the boundaries of the model domain were defined as a constant head and were all at distances of about 550 m from the pumping well. Water levels were read from the piezometric map and used for all the constant head boundaries. The model domain was discretized into a grid of 111 rows, 111 columns and 9 layers with equal spacing over the whole model area except around the pumping well where it was refined. The thicknesses of each of the top eight layers was designed to conform to the nature of pumping well as indicated in Fig. 2. Thus, the laterals of collector well were located in the 2nd, 4th, 6th and 8th layers, which all had a thickness equal to the diameter of the laterals. Within each of these layers, the diameter and length of the laterals were appropriately represented and zoned as having the same properties while the other areas of these layers were assigned properties in consonance with the other layers in the model domain. In all, the model domain had over 12,000 active cells serving as the basic units for data input. The main inputs into the model included (1) ground surface elevation map of the pumping test area generated with the elevation data in Table 1 and a specified constant bottom elevation of 1,030 m; (2) initial head map generated with the initial heads from all the test wells; (3) variable pumping rates from the pumped well; and (4) water level measurements from the observed wells used in the pumping test.

Assigning the collector well zone with very high hydraulic conductivity and the other zones in the model domain with the analytically estimated hydraulic parameters, WinPEST was activated to automatically calibrate the model with the MODFLOW-2000 engine using the time-drawdown data in the observed wells. The simulated heads from this process did not match well with observed heads; hence, a manual calibration by trial and error method was undertaken afterwards to fine-tune the automatic calibrated model. This was done by adjusting the automatic calibrated hydraulic conductivities, specific yield, and specific storage several times and re-running the model at each adjustment. The goal throughout this manual calibration fine-tuning process was to ensure that the model could simulate the observed values to obtain a good fit with minimal deviations. Thus, the normalized root mean square value (nRMS), which is a standard measure of the fit of calibration (i.e. according to the Visual MODFLOW 4.3 manual), was checked alongside the observed and simulated head-time graphs to ensure that an acceptable calibrated fit has been achieved. The model calibration was stopped when a good match was obtained between the simulated and observed heads at a low nRMS value. To verify whether the calibrated model adequately represents the aquifer formation of the study area, a validation test was carried out for the calibrated model using the recovery data from the observed wells.

Results and discussion

Analytical approach

The results of the curve matching with the time-drawdown data are presented in Fig. 4. Generally, the type curves indicate a good fit for the late time data for most of the time-drawdown curves whilst that for the middle and early time segments deviate quite significantly, except for wells G03 and G05 that had a fairly good fit in those segments as well. These fits were obtained after the parameter ratios S/S_y and K_v/K_h, which control the early and middle segments, respectively, of the type curves were varied several times to obtain the best fit of the observed data to their respective



(a) G01 **(b)** G03

(c) G07 **(d)** G09

(e) Composite **(f)** G03+G05

(g) G01+G06 **(h)** G07+G10

Fig. 4 Time-drawdown of some observed wells fitted to their corresponding Moench type curves

Table 2 Estimated aquifer parameters using the analytical approach

Wells	K_h (m/d)	K_v (m/d)	S_y	K_v/K_h	S/S_y
G01	41.8	4.18	0.364	0.10	0.035
G03	38.1	6.68	0.417	0.18	0.009
G05	49.1	8.84	0.380	0.18	0.007
G06	42.8	4.28	0.355	0.10	0.035
G07	36.4	3.64	0.288	0.10	0.025
G08	47.7	5.72	0.190	0.12	0.007
G09	54.8	4.93	0.162	0.09	0.040
G10	55.1	5.51	0.204	0.10	0.030
Average	45.7	5.47	0.295	0.12	0.024
Composite	52.6	7.89	0.257	0.15	0.012
G01 + G06	43.8	4.38	0.339	0.10	0.035
G03 + G05	50.3	9.05	0.363	0.18	0.009
G07 + G10	38.1	3.81	0.257	0.10	0.030
G08 + G09	50.3	3.02	0.204	0.06	0.007
Average	45.6	5.07	0.291	0.11	0.020

type curves. Thus, the inability of the type curves to match well with the time-drawdown curves at the early and middle segments means the estimated aquifer parameters K_v (and the calculated S value) may not have been accurately estimated since they were estimated on the basis of the two ratios. The inability to get a best match in those segments may also be due to the nature of the pumping well, which could not be represented appropriately in the analyses set up in the software but may have influenced the determination of the parameters.

A summary of the aquifer parameters estimated, analytically, are presented in Table 2. The results of the individual analyses of the observed wells show that the horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield, K_v/K_h and S/S_y of the aquifer formation range from 36.4 to 54.8 m/day, 3.64 to 8.84 m/day, 0.162 to 0.417, 0.09 to 0.18 and 0.007 to 0.04, respectively. The analyses of the paired wells and composite plot of all the wells also yielded different aquifer parameter values from each other and the individual well estimates. A comparison of the average estimated parameters for the individual wells with the estimated parameters for the composite wells indicate that they are all significantly lower with the exception of S_y, which is slightly higher. However, the averages of the estimated parameters from the paired wells are all slightly lower than the average parameter estimates from the individual wells and does not conform to the higher composite estimations. This is an indication that there exist some degree of heterogeneity and anisotropy in the aquifer. Hence, the basic homogeneity and isotropic condition assumptions in the Moench solution, which was applied in the analyses, may have influenced the estimated results in a certain direction.

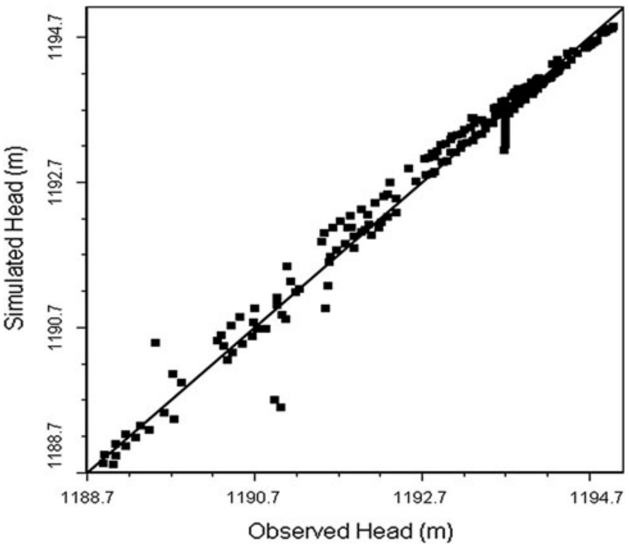


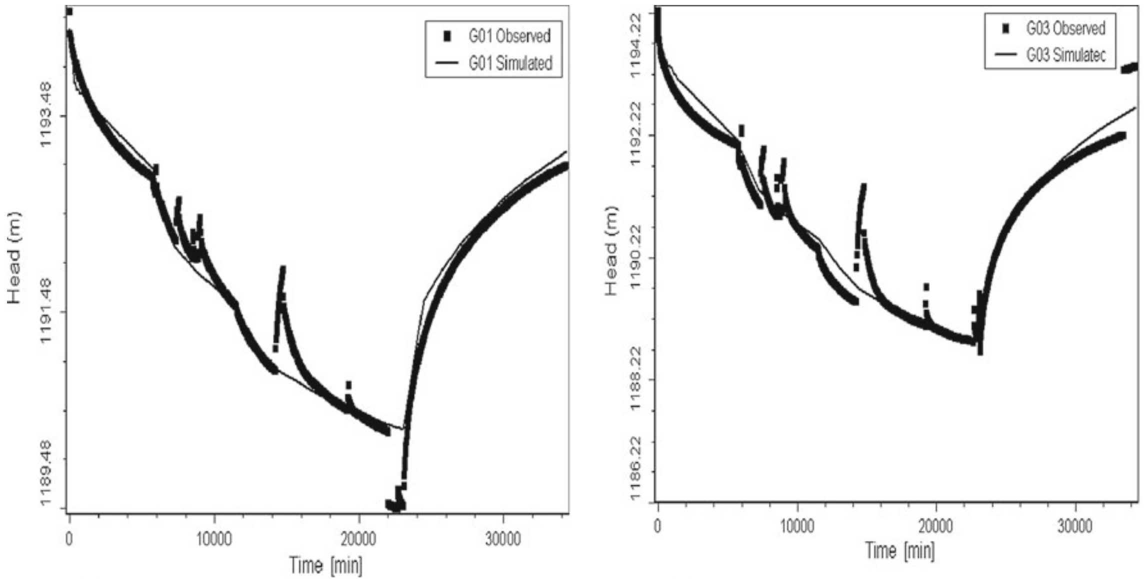
Fig. 5 Simulated and observed heads for the calibration period

Following from Moench's studies (1994) that composite plots of time-drawdown data analyses with type curves gives 'better average' of aquifer parameters than individual analyses, the average parameters of the paired wells could be used as the representative aquifer parameters of the unconfined formation in the study area. This is because (1) the estimated hydraulic conductivity values of the individual plots shows the formation to be fairly heterogeneous; (2) the paired plots had similar time-drawdown curves (see Fig. 3) and thus reacted in a similar way to pumping; (3) each paired well happened to be at almost the same radial distance from the pumping well; and (4) the paired wells better matched the type curves than the composite wells (Fig. 4e–h); hence, their average estimates should be more representative than a composite of all the wells.

Numerical approach

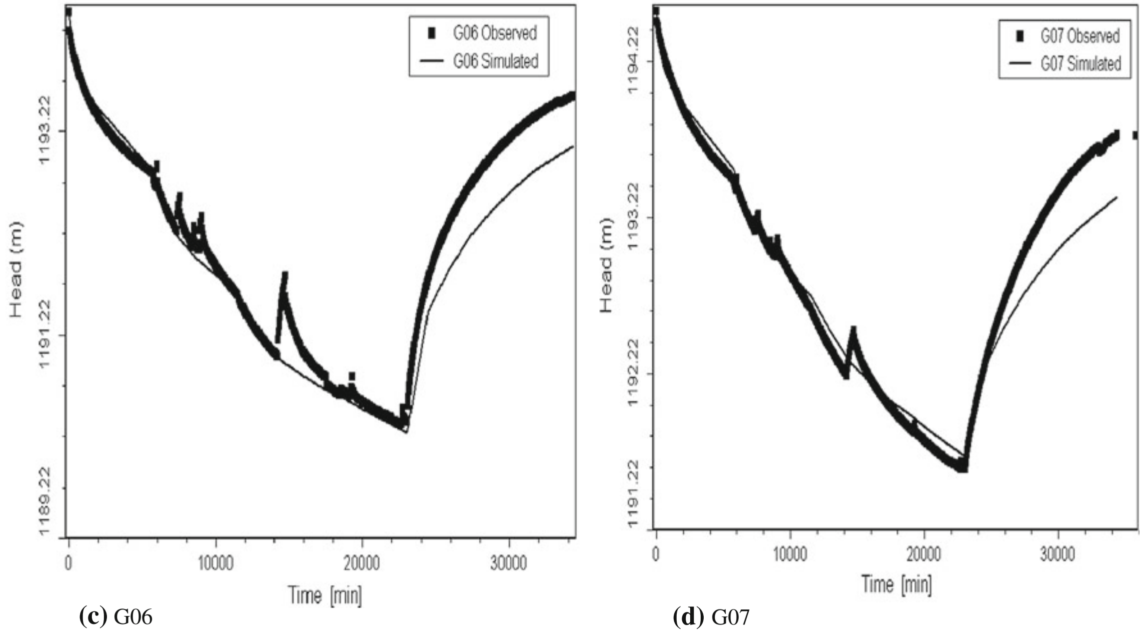
Typical results of the model simulations are shown in Figs. 5 and 6. The scatter of the simulated heads against the observed heads (Fig. 5) of the calibrated model shows that most of the points either lie along or follow the trend of the regression line with few deviations. The fit of the regression line through all the calibrated data points gives a nRMS value of 1.85 %, a standard error of estimate (SEE) of 0.004 m and a correlation coefficient of 0.98. This calibration output was deemed more acceptable for the model since a very good overall match was obtained between the observed and simulated heads with time at each of the wells (Fig. 6).

The model validation results also indicate a good correlation between the simulated and observed heads for all the wells with nRMS, SEE and correlation coefficient



(a) G01

(b) G03



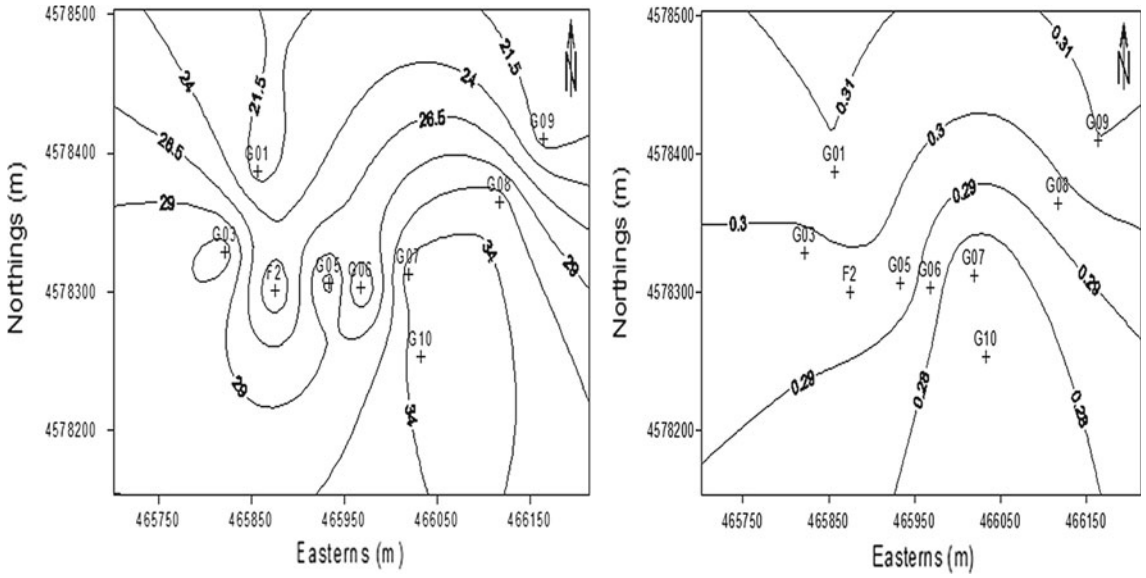
(c) G06

(d) G07

Fig. 6 Comparison of simulated and observed heads from some wells used in the study area

values of 5.05 %, 0.008 m and 0.94, respectively. A comparison of the simulated and the observed heads with time in all the wells indicate that there is a good match (Fig. 6) between them as well. However, the pumping periods were better simulated than the recoveries. The simulated recoveries in most of the wells appear to deviate significantly from the observed, although they follow the same trend as the observed values in all the wells. This, therefore, indicates that the model can produce the observed heads better during the pumping period than when recovering. The ability of the model to simulate the observed heads in the validation process in a similarly good manner like the calibration process indicates that the hydraulic parameters of the calibrated model are representative of the pumping test condition in the study area.

Thus the hydraulic parameters of the unconfined formation of the study area are estimated through the numerical approach to be 20.50–35.24 m/day, 0.10–3.40 m/day, 1.46–8.85 × 10^{-5}/m, and 0.27–0.31 for horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storativity and specific yield, respectively. The average K_h estimate by the model is 29.23 m/day with a standard deviation of 6.54 while that for the S_y is 0.29 at a standard deviation of 0.07. Figure 7 presents contour maps showing



(a) K_h (in m/d) **(b)** S_y

Fig. 7 Distribution of model simulated K_h (in m/d) and S_y of the study area

the distribution of the parameters K_h and S_y in the pumping test area. The two parameters vary away from the pumping well but without any distinct radial distance correlation.

Sensitivity analysis is an integral part of any modelling process and is usually carried out to determine how each model input parameter influences the output. Thus, a sensitivity analysis was performed to evaluate the effects of the calibrated model parameters—viz., the vertical and horizontal hydraulic conductivities, specific yield and specific storage—on the simulated heads in the observed wells. Each of these parameters was varied equally (i.e. at 15, 30 and 45 % increments) while keeping the others constant, and the model was run to observe how each influenced the simulated heads in the calibrated wells. The results showed that the horizontal hydraulic conductivity has a great influence on the simulated heads followed by the specific yield and then the vertical hydraulic conductivity and specific storage, which have minimal influence on the simulated heads.

Comparison of methods

Comparing the hydraulic parameters of the unconfined aquifer estimates from the numerical and analytical approaches, it is observed that the hydraulic conductivity estimates from the latter are significantly higher than the former while their estimates of the specific yield were much closer. The closeness of the specific yield values is not particularly surprising because its determination from the analytical solution is more dependent on the late time-drawdown data, which was well matched during the type curve analyses process and, therefore, appropriately estimated. Since, the numerical simulation also produced a reasonably good match of the observed data, then it can be deduced that it also appropriately estimated the specific yield; hence the closeness in the specific yield value in both approaches. Generally, the numerical approach visually simulated the heads in the observed wells quite better at all times than the analytical solution. In fact, the model deviations were far lower for all the wells at all the simulated times. Also, the numerical process made it possible to validate the estimated parameters with the recovery measurements from the wells and, therefore, provides an advantage for evaluating the aquifer parameters over the analytical method.

Studies by Sun et al. (2011) using hydrogeological and section maps of the aquifer formation in the study area estimates the specific yield of the formation to range from 0.006 to 0.236, which is slightly lower than its estimate in both the analytical and numerical approaches from this study. The horizontal hydraulic conductivity estimates from the numerical model of this study falls within the range of 2.24–36.53 m/day given by Sun et al. (2011), but the analytically estimated values are significantly above it. The analytically estimated vertical hydraulic conductivity is also higher than those for the numerical approach. More so, the storativity value for the analytical process (i.e. 0.006) is higher than that for the numerical simulation (i.e. 0.0025). The differences in the parameter estimates of the two approaches may be due to limitations of the analytical approach to appropriately factor in the nature of radial collector pumping well in its process. This limitation may have caused time-drawdown curves not to fit well with the early and middle time segments of the type curves, which control the estimation of the parameters.

Conclusions

This study has evaluated analytical and numerical approaches for estimating the hydraulic parameters of an unconfined aquifer formation using pumping test data from partially penetrating wells. The Moench analytical solution (1993) was used to analyse the data from the observed wells of the study area individually, in pairs, and as a composite of all the wells. This showed that paired analyses of wells in the formation provide a better estimation of the aquifer parameters than analysing the wells individually or as a composite. It also established that the aquifer under study was heterogeneous and anisotropic following from variations in the conductivity values from the observed wells at different radial distances complimented by their pairings. The parameters of the unconfined aquifer within the basin was thus estimated, analytically, to be 45.6 m/day, 5.07 m/day, 0.291, and 0.006 for horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield, and storativity, respectively. However, the estimated parameters by this approach may not be accurate since it was limited in defining the nature of the pumping well. Also, the time-drawdown curves did not fit well with the early and middle time segments of the type curves.

The numerical model, on the other hand, was able to simulate the time-drawdown data of all the observed wells better than the analytical type curves. Its estimate of horizontal hydraulic conductivity was within the range estimated by Sun et al. (2011) using hydrogeological and section maps of the aquifer formation. More so, its specific yield estimate was about the same as that produced by the analytical solution; this was the only parameter that was apparently well estimated by the analytical solution. Thus, the estimates from the numerical model (i.e. 20.50–35.24 m/day, 0.10–3.40 m/day, $1.46–8.85 \times 10^{-5}$/m, and 0.27–0.31 for horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage and specific yield, respectively) are deemed more appropriate to be used as aquifer parameters of the pumping test area.

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References

Boulton NS (1963) Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. Proc Inst Civ Eng 26:469–482

Fetter CW (2001) Applied hydrogeology, 4th edn. Prentice-Hall Inc, New Jersy

Kruseman GP, de Ridder NA (1994) Analysis and evaluation of pumping test data, 2nd edn. Intern Institute for Land Reclamation and Improvements, Wageningen

Kumar CP (2008) Aquifer parameter estimation. Slideshare Present Yourself Publishing. http://www.slideshare.net/cpkumar/aquifer-parameter-estimation-2490221. Accessed 27 Dec 2010

Lebbe L, Mahauden M, de Breuck W (1992) Execution of triple pumping test and interpretation by an inverse numerical modelling. Appl Hydrogeol 4:20–34

MacDonald MG, Harbaugh AW (1988) MODFLOW, a modular three dimensional finite- difference groundwater flow model. In: US Geological Survey Techniques of Water-Resources Investigations, Book 6, Chap. A1

Moench AF (1993) Computation of type curves for flow to partially penetrating wells in water-table aquifers. Ground Water 31(6):966–971

Moench AF (1994) Specific yield as determined by type curve analysis of type curve data. Ground Water 32(6):949–957

Moench AF (2008) Analytical and numerical analyses of an unconfined aquifer test considering unsaturated zone characteristics. Water Resour Res 44. doi:10.1029/2006WR005736

Neuman SP (1972) Theory of flow in unconfined aquifers considering delayed response of the water table. Water Resour Res 8(4):1031–1045

Neuman SP (1975) Analysis of pumping test data from anisotropic unconfined aquifers considering delayed yield. Water Resour Res 11(2):329–342

Pollock DW (1989) MODPATH, Documentation of computer programs to compute and display pathlines using results from US Geological Survey modular three-dimensional finite difference groundwater flow model. US Geological Survey Open Report 89-381

Sun D, Zhao C, Wei H, Peng D (2011) Simulation of the relationship between land use and groundwater level in Tailan River basin, Xinjiang, China. Quat Int 244(2):254–263

Theis CV (1935) The relation between lowering of piezometric surface and the rate and duration of discharge of a well using groundwater storage. Am Geophys Union Trans 16:519–524

Wang X (2010) Hydrogeology report of the Tailan River basin, Xinjiang, China. Unpublished Report (in Chinese)

Wiel VMJ, Coulthard TJ, Macklin MG, Lewin J (2011) Modelling the response of river systems to environmental change: progress, problems and prospects for palaeo-environmental reconstructions. J Ear Sci Rev 104:167–185

Yang Z (2005) Glacier water resources in China (in Chinese). Gansu Science and Technology Press, Lanzhou

Zheng C, Wang PP (1999) MT3DMS: a modular three-dimensional multispecies model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems; documentation and user's Guide. Contract Report SERDP-99-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS