
Evaluation of methods for determination of hydraulic properties in an aquifer–aquitard system hydrologically connected to a river

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Abstract Field and laboratory methods have been used to determine the hydraulic properties in a multiple-layer aquifer–aquitard system that is hydrologically connected to a river. First, hypothetical pumping tests in aquifer–aquitard systems were performed to evaluate the feasibility of MODFLOW-PEST in determining these parameters. Sensitivity analyses showed that: the horizontal hydraulic conductivity in the aquifer has the highest composite sensitivity; the vertical hydraulic conductivity has higher composite sensitivity than the horizontal hydraulic conductivity in the aquitard; and a partial penetration pumping well in an aquifer layer can improve the quality of the estimated parameters. This inverse approach was then used to analyze a pumping-recovery test conducted near the Platte River in southeastern Nebraska, USA. The hydraulic conductivities and specific yield were calculated for the aquitard and aquifer. The direct-push technique was used to generate sediment columns; permeameter tests on these columns produced the vertical hydraulic conductivities that are compatible with those obtained from the pumping-recovery test. Thus, the combination of the direct-push technique with permeameter tests provides a new method for estimation of vertical hydraulic conductivity. The hydraulic conductivity, determined from grain-size analysis, is smaller than the horizontal one but larger than the vertical one determined by the pumping-recovery test.

Résumé Plusieurs méthodes de terrain et de laboratoire ont été utilisées afin de déterminer les propriétés hydrauliques dans un système multicouche “aquifère - couche semi perméable capacitive” connecté hydrologiquement à une rivière. En premier lieu, des pompages d’essai hypothétiques dans des systèmes “aquifère - couche semi-perméable capacitive” ont été effectués dans le but

d’évaluer les potentialités de MODFLOW-PEST pour la détermination de ces paramètres. Les analyses de sensibilité composée ont montré que la perméabilité horizontale de l’aquifère présente la plus grande sensibilité composée, que la perméabilité verticale a une sensibilité composée supérieure à la perméabilité horizontale de la couche semi perméable, et qu’un puits d’exploitation à pénétration partielle peut améliorer la qualité des paramètres estimés. Cette approche inverse a été ensuite utilisée pour analyser un pompage d’essai et la remontée consécutive, effectué à proximité de la rivière Platte au sud-est du Nebraska (Etats-Unis). Les perméabilités et débits spécifiques ont été calculés pour l’aquifère et la couche semi perméable. L’utilisation de techniques par enfoncement (“direct-push”) a permis de générer des colonnes de sédiment; les mesures au perméamètre ont donné des perméabilités verticales concordantes avec celles issues du pompage d’essai. Combiner les techniques par enfoncement avec les mesures au perméamètre fournit ainsi une méthode nouvelle pour estimer les perméabilités verticales. La perméabilité déterminée à partir des analyses granulométriques est inférieure à la perméabilité horizontale, mais supérieure à la perméabilité verticale calculée à partir du pompage d’essai.

Resumen Se han utilizado métodos de campo y laboratorio para determinar las propiedades hidráulicas en un sistema de acuífero-acuitardo de capas múltiples el cual está hidrológicamente conectado con un río. Primero se realizaron pruebas de bombeo hipotéticas en los sistemas de acuífero-acuitardo para evaluar la factibilidad de usar MODFLOW-PEST para determinar estos parámetros. Los análisis de sensibilidad mostraron los siguientes resultados: la conductividad hidráulica horizontal en el acuífero tiene la sensibilidad compuesta más alta; la conductividad hidráulica vertical tiene sensibilidad compuesta más alta que la conductividad hidráulica horizontal en el acuitardo; y que un pozo de bombeo con penetración parcial en una capa del acuífero puede mejorar la calidad de los parámetros estimados. Se utilizó luego el enfoque inverso para analizar una prueba de bombeo-recuperación realizada cerca del Río Platte al suroriente de Nebraska, Estados Unidos. Se calcularon las conductividades hidráulicas y el rendimiento específico para el acuífero y el acuitardo. Se utilizó la técnica de empuje directo para generar columnas de sedimento; las pruebas de perme-

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ámetro en esas columnas produjeron conductividades hidráulicas verticales que son compatibles con las obtenidas en las pruebas de bombeo-recuperación. De este modo, la combinación de la técnica de empuje directo con pruebas de permeámetro aporta un nuevo método para estimar la conductividad hidráulica vertical. La conductividad hidráulica establecida en base a tamaño del grano es más pequeña que la horizontal pero mayor que la vertical determinada mediante la prueba de bombeo-recuperación.

Keywords Inverse modeling · Hydraulic properties · Aquifer–aquitard · Direct-push technique · Vertical hydraulic conductivity · Permeameter test · Pumping test

Introduction

When an aquifer is pumped near a river and a hydraulic gradient forms between the river and the aquifer, the river may discharge surface water to the aquifer, which may induce the concern of well-head protection if the river has been polluted. The vertical groundwater flow beneath the river can be significant when the river partially penetrates the aquifer, thus the vertical hydraulic conductivity in the aquifer is important for controlling the interaction between the aquifer and the river. Hunt (2003) developed an analytical solution to estimate streamflow depletion in an aquifer–aquitard system during pumping, but the solution only applied to the full penetration pumping well and isotropic aquifer which cannot consider the vertical groundwater flow in the aquifer layer. Chen et al. (2005) noted that the vertical hydraulic conductivity in the aquitard plays an important role in determining the ratio of the induced leakage during and after pumping in an aquifer–aquitard system. Therefore, it is necessary to determine the horizontal and vertical hydraulic conductivities in the aquifer, the vertical hydraulic conductivity in the aquitard, and other hydraulic parameters in aquifer–aquitard systems which are hydrologically connected to a river.

Neuman and Witherspoon (1972) estimated the hydraulic parameters in the leaky multiple aquifer systems by placing observation wells in the aquifers as well as the confining units. The analytical solutions of the hydraulic properties in aquifer–aquitard systems have been discussed by Cooley and Case (1973) and Boulton and Strelsova (1975), which took into account the gradual desaturation with a declining water table or anisotropy of the aquifer. Chen and Ayers (1997) proposed an inverse method to determine the hydraulic parameters of a confined leaky aquifer, and their results showed that the inverse method can estimate the hydraulic parameters simultaneously and uniquely. These analytical solutions do not consider the effects of rivers, and some consider only isotropic hydraulic conductivity in aquifer and aquitard layers.

Inverse numerical solutions are capable of simulating multiple-layer flow systems which can take into account

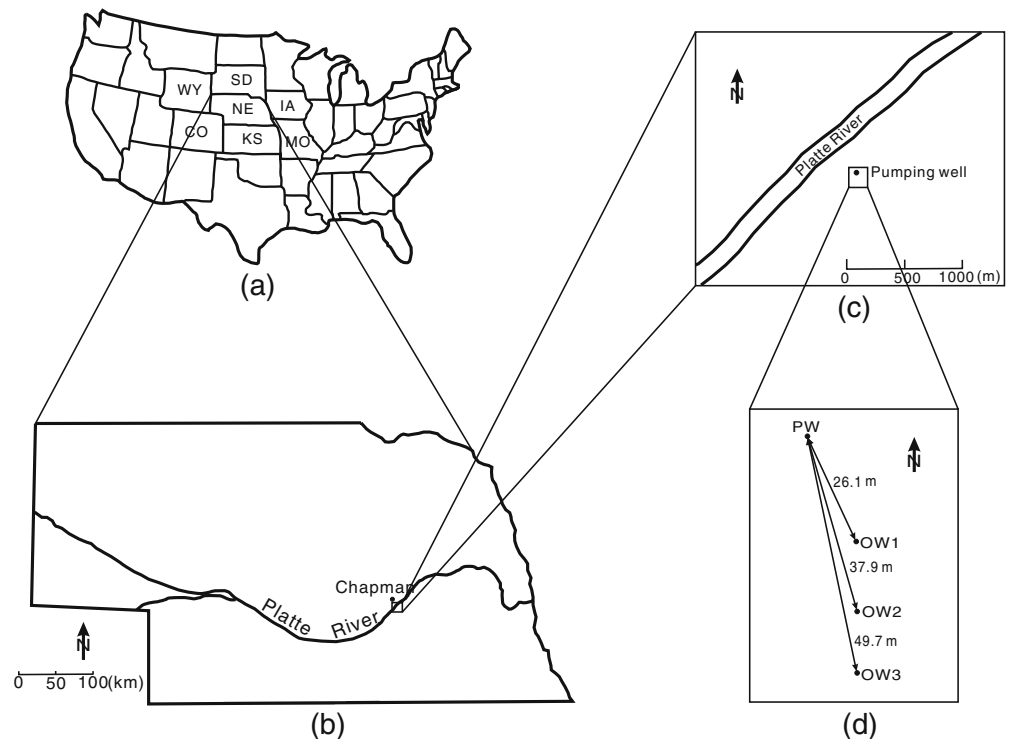
geological heterogeneity, boundary conditions, and surface water systems. The generic groundwater inverse solution is to seek the optimal parameters which produce a good fit between the simulated and measured observations. Inverse approaches such as MODFLOWP (Hill 1992), PEST (Doherty 2004), and UCODE (Poeter and Hill 1998) can be combined with groundwater flow modeling to determine the hydraulic parameters. Hunt and Scott (2005) noted the usefulness of MODFLOW in the analysis of well hydraulics in multiple-layer aquifer–aquitard systems. Lebbe and Breuck (1995) developed an inverse numerical model to interpret the pumping tests in layered groundwater reservoirs, and their results indicated that it is better to use all observations together rather than different observations separately to minimize the difference between the simulated and actual flow system. Hvilshøj et al. (1999) applied inverse numerical models based on the finite-element method to determine the multiple-layer aquifer parameters, which showed that the inverse numerical solution can help analyze the geological heterogeneity in multiple layers and provide more accurate characterization of the hydraulic parameters. However, their results (Hvilshøj et al. 1999) were based on only a few time-drawdown data of the observation wells. A radial groundwater flow modeling approach proposed by Halford and Yobbi (2006) produced more reasonable horizontal hydraulic conductivities in the aquifers and vertical hydraulic conductivities in the confining units compared with the leaky aquifer solution. Although these inverse numerical methods are appropriate in determining the hydraulic properties in aquifer–aquitard systems, they have not provided enough information on aquifer–aquitard systems which are hydrologically connected to a river.

The objective of this study is to evaluate three methods for estimation of the hydraulic properties in a multiple-layer aquifer–aquitard system. First, hypothetical pumping tests in aquifer–aquitard systems are performed to evaluate the feasibility of inverse numerical modeling by MODFLOW-PEST in determining the hydraulic parameters. Then this inverse approach is used to analyze a pumping-recovery test conducted at the Chapman South site near the Platte River in southeastern Nebraska (Fig. 1), where the aquifer–aquitard system is hydrologically connected to the Platte River. Secondly, the direct-push technique was used to collect sediment cores from the aquifer–aquitard system, and laboratory permeameter tests were used to determine the vertical hydraulic conductivities of these cores. Thirdly, sediment samples were also collected and sieved for the analyses of grain-size distribution. Hydraulic conductivities were estimated from the pumping-recovery test for a comparison with the values of hydraulic conductivity derived from laboratory permeameter tests and from grain-size analysis.

Field investigation

The Chapman South pumping-recovery test site is located in Hamilton County, Nebraska. The pumping well is about

Fig. 1 Maps of **a** states in USA (CO Colorado; IA Iowa; KS Kansas; MO Missouri; NE Nebraska; SD South Dakota; WY Wyoming), **b** Nebraska, showing the location of the study area, **c** the location of the pumping well, and **d** plan view of the pumping well (PW) in relation to the observation wells (OW)



400 m from the south bank of the Platte River, the width of which is about 200 m (Fig. 1). The ground elevation at the study site is about 550 m above the mean sea level. The depth to the water table is 7.6 m (25 ft). According to an electrical conductivity (EC) log generated by the direct-push technique near the pumping well (Fig. 2), the EC values vary with depth with a larger EC value indicating less-permeable sediments. The patterns of EC logs suggest that this site is a multiple-layer aquifer–aquitard system. At the study site, a 2.1-m (7 ft) deep aquitard overlies a 7.0-m (23 ft) deep aquifer, which is underlain by a 2.2-m (7 ft) deep aquitard and a 7.0-m (23 ft) deep aquifer (Fig. 2). The aquitard is mainly composed of silt and clay and the aquifer is mainly composed of sand and gravel of Quaternary age. The aquifer–aquitard system is underlain by an aquiclude, which is about 26 m below the ground surface (Fig. 2). Lithologic logs of irrigation wells at the north of the river have suggested that the two sides of the Platte River have the same hydrostratigraphic units.

The pumping well fully penetrates the lower aquifer and aquitard, and partially penetrates the upper aquifer. Three observation wells, with a length of well screen of 90 cm and constructed using a hollow stem auger, were located at the distances of 26.1, 37.9, and 49.7 m to the pumping well. The screens of observation wells 1 and 2 are placed in the lower aquitard, and the screen of observation well 3 is in the upper aquifer. A pumping test began at this site on July 3, 2005 and lasted about 54 h with a constant pumping rate of about 5,180 m³/day (950 gpm, or gallons per minute). A large number of drawdown data were collected in the time interval

between 0.1 and 168 min based on a log scale. According to Chen et al. (1999), early-time drawdown data are needed for determination of higher-quality storage coefficients. After the pumping continued for 168 min, the drawdown data were recorded linearly for every 10 min until the pumping was stopped and recovery data were

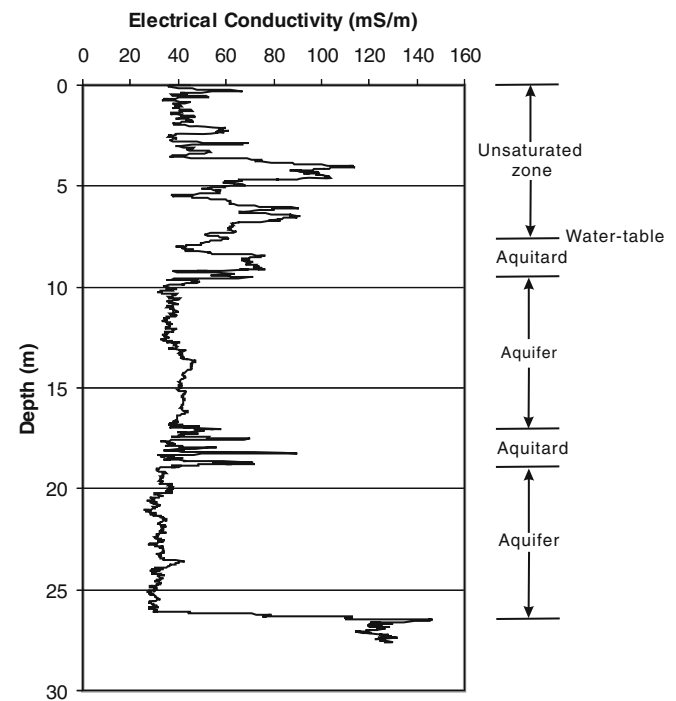


Fig. 2 The electrical conductivity (EC) log showing the multiple-layer aquifer–aquitard system at the Chapman South site

also recorded in 10-min intervals for about 35 h. The pumped water was dispersed by a center-pivot and was unlikely to be returned to the water table through infiltration during the pumping-recovery period because the water table was 7.6 m below the ground surface. Figure 3 shows the time-drawdown and recovery data of the three observation wells used in the pumping-recovery test.

During the drilling for the construction of observation well 1, sediment samples were taken for every 1.5-m interval and grain-size analyses were performed. Near observation well 2, the direct-push technique using a Geoprobe system was used to collect sediment cores into a plastic liner of 1.5-m in length and 4 cm in diameter, on which permeameter tests were performed in the laboratory.

Methods

Inverse analysis of the hypothetical examples

The inverse numerical modeling using MODFLOW (McDonald and Harbaugh 1988) and PEST (Doherty 2004) determines the hydraulic parameters in aquifer-aquitard systems from pumping tests. Here, the inverse numerical analysis is performed using Visual MODFLOW. During inverse parameter estimation, PEST runs the MODFLOW model many times, thereby comparing the measured and simulated observations. After each iteration, PEST evaluates the new parameters to determine whether the parameters have been improved. Iteration continues until the changes of weighted, least-squared differences between the measured and simulated observations reach the convergence criteria. After the parameter estimation converges, the optimal parameters and the composite sensitivities for each parameter are produced by PEST. The composite sensitivities identify which parameters contribute more information on the parameter estimation with relatively larger sensitivities and which parameters contribute less information with relatively smaller sensitivities. The coefficients of correlation be-

tween the estimated parameters are also calculated by PEST, which are in the range of -1 and 1 . The closer the correlations are to -1 or 1 , the more the parameters are correlated. For any set of parameters, absolute correlation coefficients larger than 0.95 may indicate that two or more parameters cannot be estimated uniquely (Hill 1998).

In order to identify the feasibility of the inverse numerical solution in determining the hydraulic properties in aquifer-aquitard systems, several hypothetical models are developed to perform sensitivity analyses and to evaluate possible effects of model-design and the placement of the pumping well screen on the parameter optimization. In this study, a hypothetical aquifer-aquitard system of an 8-m deep aquitard overlying a 10-m deep aquifer is assumed. A river is located at the north of the pumping well with 60 m in width, and it is in the distance of 100 m to the pumping well. The river stage is 0.1 m higher than the water table in this system. The vertical hydraulic conductivity of the streambed is 3 m/day, and the thickness of the streambed is 1.5 m. Two different pumping wells are simulated in the system. For one testing case, a pumping well fully penetrates the aquifer with a 10-m screen, and for the other testing case, the well partially penetrates the aquifer with a 5-m screen. Three observation wells (1-1, 1-2, 1-3), placed at different depths, are in the distance of 25 m to the pumping well, and the other three wells (2-1, 2-2, 2-3), also at different depths, are 40 m to the pumping well. Figure 3 shows the locations of the six observation wells. The pumping lasts for 3,000 min with a constant rate of 3,270 m³/day. The hypothetical K_h (horizontal hydraulic conductivity in the aquifer, L/T) and K_v (vertical hydraulic conductivity in the aquifer, L/T) are 100 and 5 m/day, respectively, and the k_h (horizontal hydraulic conductivity in the aquitard, L/T) and k_v (vertical hydraulic conductivity in the aquitard, L/T) are 5 and 0.5 m/day, respectively. The S_s (specific storage, L^{-1}) and S_y (specific yield) are $1.0 \times 10^{-5} \text{ m}^{-1}$ and 0.05, respectively.

A three-dimensional groundwater flow model is constructed for the two testing cases. In general, the size of the model domain should be large enough to prevent the effects of the boundary condition, which must be imposed, on the parameter estimation. The dimension of the model is 2,000 m in length, 2,000 m in width, and 18 m in depth. The model is discretized into 68 columns and 65 rows in x , y directions, and 4 layers in z direction, and the grid spacing is smaller near the pumping well and observation wells. The screens of observation wells 1-1 and 2-1 are in layer 2, the screens of observation wells 1-2 and 2-2 are in layer 3, and the screens of observation wells 1-3 and 2-3 are in layer 4 (Fig. 4). Two model zones of hydraulic properties representing the aquitard and aquifer are specified. Layers 1 and 2 are grouped into the aquitard, and layers 3 and 4 are categorized into the aquifer (Fig. 4). The initial head of the model is 18 m with an unconfined condition in the aquitard. A constant-head boundary is imposed in the model for each layer and the head is equal to the initial head. MODFLOW calculates the drawdown of the six observation wells at different time intervals.

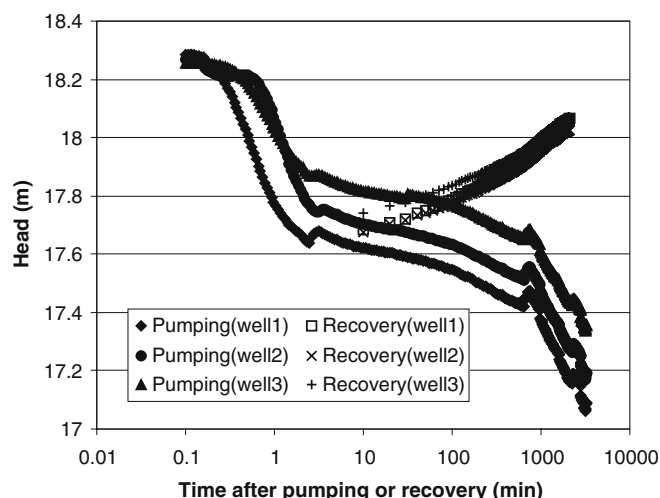


Fig. 3 The time-drawdown and recovery curves of the observation wells used in the pumping-recovery test at the Chapman South site

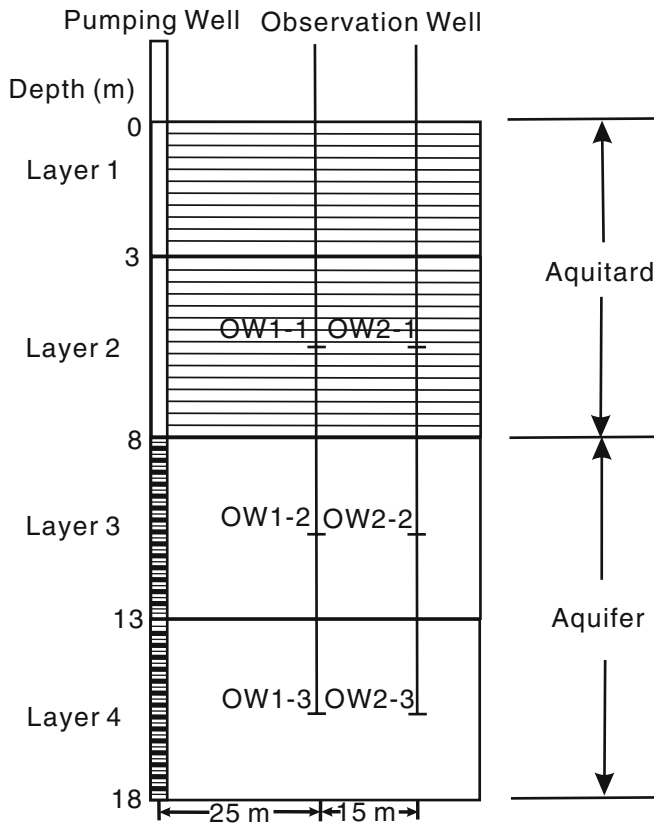


Fig. 4 Schematic diagram showing the model layers and the observation wells for the full penetration pumping well of the hypothetical examples

Then, the time-drawdown data are assigned to the corresponding observation wells and PEST is used inversely to estimate the hydraulic parameters.

The vertical groundwater flow around the partial penetration pumping well may be significant. Therefore, in order to evaluate the effects of some analytical solutions in determining the hydraulic conductivities which assume an isotropic condition, a groundwater flow model is constructed which assumes the aquifer and aquitard as isotropic for the partial penetration pumping well of the original model. Furthermore, another groundwater flow model is constructed with the river being removed from the model, which is used to determine the effects of the river on the parameter estimation. The original drawdown data at the observation wells are still used in these models. PEST calculates the new hydraulic parameters which are compared with those obtained from the original model.

Inverse analysis of the pumping-recovery test at the Chapman South site

At the Chapman South site, a three-dimensional groundwater flow model is constructed to determine the hydraulic parameters in the aquitard and aquifer from the pumping-recovery test data. The dimension of the model is 6,000 m in length, 6,000 m in width, and 18.3 m in depth. The modeling area is discretized into 140 columns

and 135 rows in the x and y directions, and 8 layers in the z direction (Fig. 5). The pumping well is placed at the center of the model with the 10.1-m screen through the layers 5, 6, 7, and 8. Three observation wells are placed in their corresponding distances to the pumping well. The screens of observation wells 1 and 2 occur in layer 6, and the screen of observation well 3 occurs in layer 3 (Fig. 5). Two different model zones representing the aquitard and aquifer are assigned, and each model zone is homogeneous and anisotropic. Layers 1, 6, and 7 are grouped into the aquitard, and layers 2, 3, 4, 5, and 8 belong to the aquifer (Fig. 5). Similarly to the hypothetical examples, a constant-head boundary is assumed for each layer, and the constant-head is equal to the initial head of 18.3 m.

Furthermore, the Platte River is included in the model domain; thus it is simulated by using the river package of MODFLOW. The Platte River is placed in the first layer with 6,000 m in length and 200 m in width, and its south bank is 400 m to the pumping well. The river stage is assumed to be 0.1 m higher than the initial water table, and the thickness of the streambed is half of the thickness of the first layer. The vertical hydraulic conductivity of the streambed is estimated to be 1 m/day from the nearby streambed permeameter tests. In order to reduce the number of to-be-estimated parameters, the lower and upper aquifers are assumed to have the same hydraulic properties, and the same approach applies to the lower and upper aquitards.

Permeameter tests in the laboratory

The sediment columns produced by the direct-push technique at the study site preserve sedimentary structures and are tested for vertical hydraulic conductivity in the

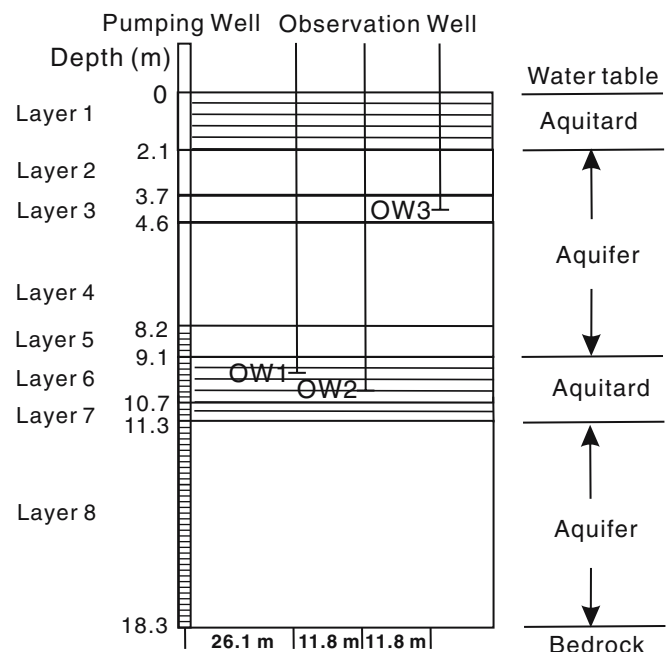
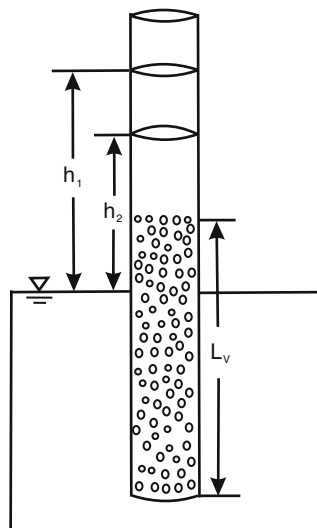


Fig. 5 Schematic diagram showing the model layers and the observation wells at the Chapman South site

Fig. 6 Schematic diagram showing a permeameter test in the laboratory



laboratory. Figure 6 is a schematic diagram showing a permeameter test in the laboratory. The plastic tube filled with the sediments is laid vertically in a tank full of water. The bottom end of the tube is covered by several layers of fine plastic screen. Water is added into the tube and the hydraulic head in the tank remains constant. The hydraulic head inside the tube begins to fall and the rate of the falling head depends on the hydraulic properties of the sediment in the tube and the hydraulic head differences between the tube and the tank. According to Darcy's Law, the vertical hydraulic conductivity is calculated by

$$K_v = \frac{L_v}{(t_2 - t_1)} \ln(h_1/h_2) \quad (1)$$

where K_v is the vertical hydraulic conductivity of the sediment (L/T), L_v is the length of the sediment column in the tube (L), and h_1 and h_2 (L) are the hydraulic head differences between the tube and the tank at time t_1 and t_2 (T) since the beginning of a permeameter test. Equation 1 has been used to calculate the K_v values of streambed sediments based on permeameter tests in river channels (Chen 2004).

Grain-size analysis

Empirical methods are used to determine the hydraulic conductivities of the porous medium materials from the grain-size analysis (Ayers et al. 1998). Vukovic and Soro

(1992) summarized several empirical methods from former studies and presented a general formula

$$K = \frac{g}{\nu} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad (2)$$

where K is the hydraulic conductivity (L/T), g is the acceleration of gravity (L/T^2), ν is the kinematic coefficient of viscosity (L^2/T), C is a dimensionless coefficient, $\varphi(n)$ is the porosity function, and d_e is the effective grain diameter (L). The values of C , $\varphi(n)$, and d_e are dependent on the different methods used in the grain-size analysis. In addition, porosity may be derived from the empirical relationship between porosity and the coefficient of grain uniformity (Vukovic and Soro 1992)

$$n = 0.255(1 + 0.83^\eta) \quad (3)$$

where η is the coefficient of grain uniformity and is given by (Vukovic and Soro 1992)

$$\eta = \frac{d_{60}}{d_{10}} \quad (4)$$

Here, d_{60} and d_{10} are the grain diameters with 60 and 10% cumulative weight of the sample from the grain-size distribution curve.

Vukovic and Soro (1992) noted that the applications of different empirical methods to the same porous medium material can yield different values of hydraulic conductivity, which may differ by a factor of 10 or even 20. Generally, the hydraulic conductivities derived from the empirical methods are lower than those estimated by pumping test analysis.

The sediment samples were sieved by Geotechnical Services, Inc. (Omaha, Nebraska, USA) for grain size distribution. The finest sieve size is 0.074 mm. There are nine sieves for particles between 0.074 and 2 mm. In this study, particle size <0.074 mm is grouped into silt and clay, particle size of 0.074–2 mm is categorized into sand, and particle size >2 mm is classified into gravel. Five empirical methods (Table 1) are utilized to determine the hydraulic conductivities in the aquifer and aquitard. While analysis of pumping tests can provide the horizontal and vertical hydraulic conductivities, analysis of grain-size distribution does not provide directional hydraulic conductivity because the sedimentary structures were destroyed during sampling.

Table 1 Five empirical methods of grain-size analysis and their domains of applicability

Method	Value of coefficient (C)	Porosity function $\varphi(n)$	Effective grain diameter (d_e)	Domain of applicability
Hazen	6×10^{-4}	$1 + 10(n - 0.26)$	d_{10}	$0.1 \text{ mm} < d_e < 3 \text{ mm}$ $\eta < 5$
Slichter	1×10^{-2}	$n^{3.287}$	d_{10}	$0.01 \text{ mm} < d_e < 5 \text{ mm}$
Terzaghi	$6.1 \times 10^{-3} < C < 10.7 \times 10^{-3}$	$\left(\frac{n-0.13}{\sqrt{1-n}}\right)^2$	d_{10}	Large-grain sand
Beyer	$6 \times 10^{-4} \log \frac{500}{\eta}$	1	d_{10}	$0.06 \text{ mm} < d_e < 0.6 \text{ mm}$ $1 < \eta < 20$
USBR	$4.8 \times 10^{-4} \cdot d_{20}^{0.3}$	1	d_{20}	Medium-grain sand $\eta < 5$

Table 2 The estimated hydraulic parameters under different circumstances for both full and partial penetration pumping wells of the hypothetical examples

		k_h (m/day)	k_v (m/day)	K_h (m/day)	K_v (m/day)	S_s (10^{-5}) (m^{-1})	S_y
True value		5	0.5	100	5	1.0	0.05
Original model	Fully	5.19	0.49	100.52	4.58	1.00	0.049
	Partially	4.87	0.49	100.45	5.01	1.00	0.049
No river in the model	Fully	5.97	0.48	104.29	6.50	0.93	0.051
	Partially	4.82	0.39	111.52	4.89	0.85	0.043
Isotropic aquifer–aquitard	Partially	0.30		111.22		0.894	0.062

Results

Hypothetical examples

The six hydraulic parameters of the hypothetical examples are determined using composite observation wells (Table 2). For both full and partial penetration pumping wells, the estimated values of k_v , K_h , S_s , and S_y are close to their hypothetical true values. Furthermore, for the partial penetration pumping well, the estimated K_v is 5.01 m/day, which is very close to the original value of 5 m/day and thus suggests that a vertical flow component is much stronger around a partial penetration pumping well. Therefore, the accuracy of K_v can be ameliorated by using a partial penetration pumping well compared with that using a full penetration pumping well. Compared to the other five parameters, k_h is the least sensitive parameter in the inverse modeling for both fully and partially penetrating cases.

All of the correlations between the estimated parameters are less than 0.95 for both full and partial penetration pumping wells. The sensitivity analyses show that K_h has the highest composite sensitivity, which indicates it is the most certain and reliable parameter (Fig. 7). The important information that k_v has higher composite sensitivity than k_h (Fig. 7) indicates that vertical groundwater flow has more influence on the parameter estimation than horizontal groundwater flow in the aquitard, which is consistent with the flow hydraulics that groundwater flow in the aquitard is mainly vertical during pumping. On the other hand, K_v has lower composite sensitivity than K_h , which is consistent with the flow hydraulics that groundwater flow in the aquifer is mainly horizontal during pumping.

Furthermore, the effects of the size of the model domain, the anisotropy of the hydraulic conductivities in the aquifer and aquitard, and the river on the parameter estimation are evaluated. The drawdown around the boundary area at the end of pumping is zero from the original forward model, which indicates that the current domain size of the hypothetical models has no effects on the parameter estimation. For the partial penetration pumping well, when the aquifer and aquitard are assumed to be isotropic, the K value in the aquifer is overestimated compared to K_h and the k value in the aquitard is underestimated compared to k_v (Table 2). A strong vertical groundwater flow exists around the partial penetration pumping well, the magnitude of which can be related to the vertical hydraulic conduc-

tivity. Neglecting the anisotropic hydraulic conductivity also leads to inaccurate estimation of storage coefficient and specific yield (Table 2). All of these inaccuracies in the estimated parameters result from the fact that the isotropic model does not reflect the “true” hydrologic condition. It is apparent that use of analytical solutions such as by Hunt (2003) in parameter estimation, which does not take into account the anisotropic hydraulic conductivity and partial penetration wells, may give inaccurate results.

When the river is not included in the model, the most certain parameter, K_h , is larger than that with the river in the model for both pumping wells (Table 2). This is reasonable because there is recharge from the river to the pumping well, which may decrease the transmissivity value to produce the needed drawdown. On the other hand, S_y estimated with the river in the model is larger than that without the river, and this is because the correlation between K_h and S_y is negative by using inverse parameter optimization. The differences of K_h are about 11% and 4% for full and partial penetration case, respectively, and the model including the river provides more precise results.

Pumping-recovery test at the Chapman South site

At this site, the screen of the pumping well fully penetrates the lower aquifer and aquitard, and also partially penetrates the upper aquifer. As suggested by the results of the hypothetical examples, the aquifer and aquitard are necessary to be assumed as anisotropic. The six hydraulic parameters at this site are estimated

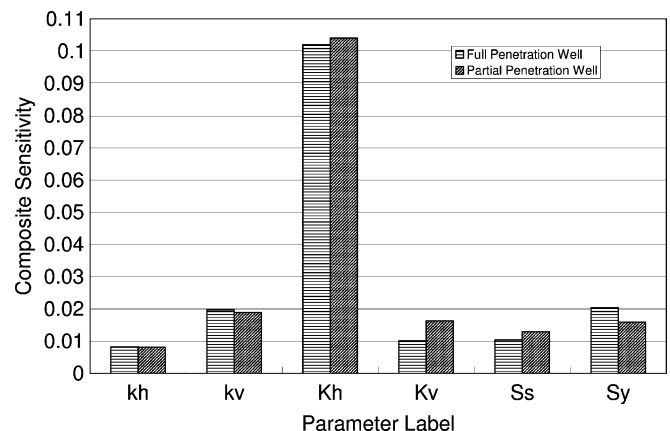
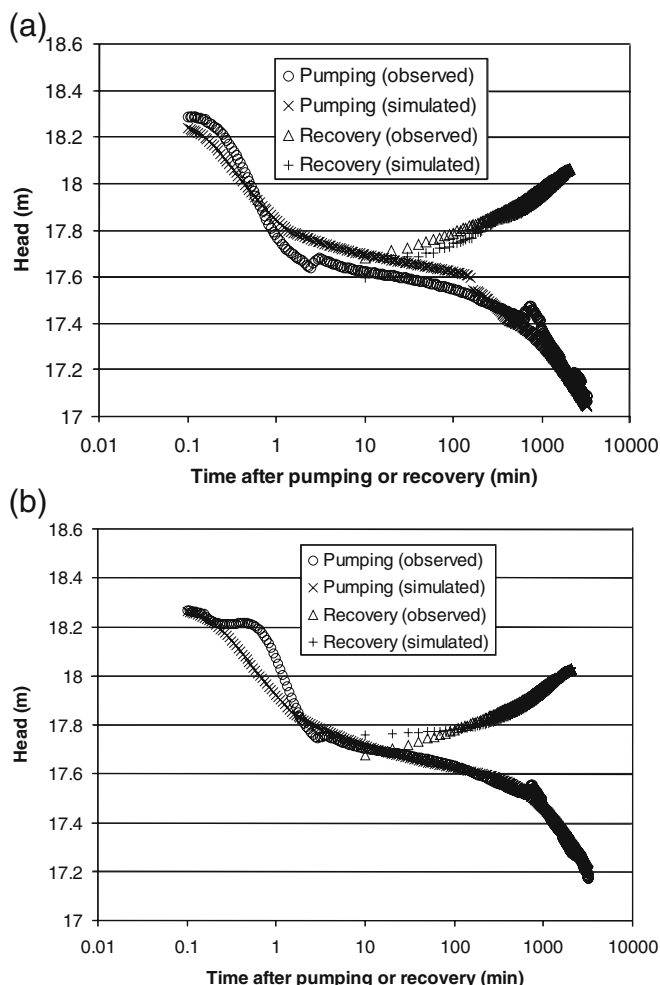
**Fig. 7** The composite sensitivities for both full and partial penetration pumping wells of the hypothetical examples

Table 3 The estimated hydraulic parameters and composite sensitivities for each parameter at the Chapman South site

	k_h (m/day)	k_v (m/day)	K_h (m/day)	K_v (m/day)	S_s (m ⁻¹)	S_y
Parameter	7.55	0.49	113.11	7.10	2.29×10^{-5}	0.033
Sensitivity (10^{-3})	3.55	7.43	33.63	2.98	3.50	7.14

by using composite observation wells and their values are summarized in Table 3. The anisotropic ratios of the hydraulic conductivities are about 15 for the aquifer and aquitard. The correlations between the estimated parameters are all less than 0.95, thus these parameters can be used to represent the hydraulic parameters at the study site.

Similar to the situation of the hypothetical examples, the parameter with the largest composite sensitivity is K_h , and k_v has higher composite sensitivity than k_h (Table 3). The time-drawdown curves for observation wells 1 and 2 (Fig. 8a and b) show good fits between observed and simulated heads during the pumping-recovery period. The size of the model domain has no effect on the parameter optimization, because the drawdown around the boundary area is nearly zero at the end of the pumping.

**Fig. 8** The observed and simulated heads of the observation wells 1 (a) and 2 (b) during the pumping-recovery periods at the Chapman South site

Determination of vertical K values from permeameter tests

At the study site, sixteen sediment columns were generated by the direct-push technique near observation well 2. However, the sediment columns with a part or full tube of clay or silt are hardly suitable for permeameter tests because these aquitard materials have a very low hydraulic conductivity which can not be determined effectively using laboratory permeameter tests. In this study, only one sediment column of the aquitard materials for the interval of 16.5–18.0 m and seven sediment columns of the aquifer materials were used for permeameter tests. The vertical hydraulic conductivities of these sediment columns are calculated by Eq. 1 and are summarized in Table 4. Results show that the lower aquifer has higher K_v values than the upper aquifer. The K_v values of the aquifer materials range from 0.51 to 11.52 m/day with an average of 5.14 m/day, which is compatible to that (7.10 m/day) obtained from the pumping-recovery test. On the other hand, the k_v value of the aquitard materials for the interval of 16.5–18.0 m is 0.01 m/day, which is much smaller than that (0.49 m/day) determined by the pumping-recovery test.

Determination of K values from grain-size analysis

At the study site, nine sediment samples were sieved. The diameters of sediment particles at 10 and 20% cumulative weight (for d_c), the coefficients of uniformity, and the porosity values are determined from the cumulative distribution curves of the sediment and these values are shown in Table 5. Since the kinematic coefficient of viscosity value is necessary for the estimation of hydraulic conductivity, it is derived for a water temperature of 15°C in this study. The hydraulic conductivities, calculated by the five empirical methods shown in Table 1, are summarized in Table 5. The hydraulic conductivities of the silt and clay materials are not available for the Terzaghi and USBR methods

Table 4 The vertical hydraulic conductivities of the aquitard and aquifer materials obtained from laboratory permeameter tests at the Chapman South site

Characteristics of sediment	Interval (m)	L_v (cm)	K_v (m/day)
Sand/gravel	12.0–13.5	101.92	2.43
	13.5–15.0	112.71	2.29
	15.0–16.5	59.69	0.51
Silt/clay	16.5–18.0	106.36	0.01
Sand/gravel	18.0–19.5	120.33	11.52
	19.5–21.0	112.08	5.05
	21.0–22.5	96.52	4.69
	22.5–24.0	82.23	9.51

Table 5 The hydraulic conductivities of the aquitard and aquifer materials determined by grain-size analysis at the Chapman South site. *NA* not available

Characteristics of sediment	Interval (m)	d_{10} (mm)	d_{20} (mm)	Coefficient of uniformity	Porosity	Hazen (m/day)	Slichter (m/day)	Terzaghi (m/day)	Beyer (m/day)	USBR (m/day)
Silt/clay	1.5–3.0	0.04	0.05	2.17	0.43	1.89	0.72	NA	NA	NA
	4.5–6.0	0.04	0.05	2.30	0.42	1.86	0.69	NA	NA	NA
	7.5–9.0	0.04	0.05	1.64	0.44	2.02	0.82	NA	NA	NA
Sand/gravel	15.0–16.5	0.16	0.17	1.72	0.44	31.95	12.80	28.80	28.10	6.42
Silt/clay	16.5–18.0	0.06	0.11	8.81	0.30	NA	0.54	NA	NA	NA
Sand/gravel	18.0–19.5	0.09	0.17	4.96	0.36	7.08	2.02	4.42	7.23	6.39
	19.5–21.0	0.12	0.20	3.69	0.38	14.32	4.57	10.13	13.68	8.34
	21.0–22.5	0.08	0.19	5.61	0.35	NA	1.43	3.11	5.56	NA
	22.5–24.0	0.16	0.22	2.97	0.40	27.57	9.48	21.14	25.40	10.84

because these methods are only applicable to sand. Some of the hydraulic conductivities are not available for the Hazen, Beyer and USBR methods because the Hazen and USBR methods require that $\eta < 5$ and the Beyer method requires that $d_c > 0.06$ mm, which are not satisfied in this study.

Results show that the hydraulic conductivities calculated by the Slichter and USBR methods are lower than those by the other three methods, which is consistent with the conclusion by Vukovic and Soro (1992). These two methods are considered inaccurate compared to the other three methods (Vukovic and Soro 1992). The hydraulic conductivities calculated by the Hazen, Terzaghi, and Beyer methods are of little difference. The hydraulic conductivities of the aquitard materials calculated by the Hazen method are from 1.86 to 2.02 m/day with the average value of 1.92 m/day, and the hydraulic conductivities of aquifer materials calculated by the Hazen, Terzaghi, and Beyer methods are from 3.11 to 31.95 m/day with the average value of 16.32 m/day. The average hydraulic conductivities of the aquitard and aquifer materials determined by grain-size analysis are smaller than the horizontal hydraulic conductivities but larger than the vertical hydraulic conductivities in the aquifer and aquitard estimated by the pumping-recovery test.

Summary and conclusions

Inverse numerical modeling of pumping tests using MODFLOW-PEST provides the hydraulic properties of aquifer–aquitard systems which are hydrologically connected to a river. MODFLOW-PEST can take into account the geological heterogeneity, surface-water systems, and the screen positions of pumping wells more appropriately than inverse analytical solutions. Hypothetical pumping tests suggest that K_h has the highest composite sensitivity, which indicates that it is the most certain and reliable parameter. k_v has higher composite sensitivity than k_h , which is consistent with the flow hydraulics around a pumping well that groundwater flow is mainly vertical in the aquitard and horizontal in the aquifer during pumping. The

results of the inverse numerical analysis suggest that using a partial penetration pumping well can improve the quality of estimated hydraulic conductivity values. Additionally, vertical hydraulic conductivity influences groundwater flow near the partial penetration pumping well. Use of a model assuming isotropic condition for parameter estimation of an anisotropic aquifer–aquitard system can give a large inaccuracy in the results. Furthermore, K_h could be overestimated if the river is neglected in the model. Although these findings are based on a single-layer aquifer–aquitard system, they still can provide suggestions for analyzing multiple-layer aquifer–aquitard systems.

The field site in this study, the Chapman South site, is a multiple-layer aquifer–aquitard system. The results of grain-size analyses of the sediment samples show that the average hydraulic conductivity in the aquitard is 1.92 m/day and the average hydraulic conductivity in the aquifer is 16.32 m/day. These values are smaller than the horizontal hydraulic conductivity but larger than the vertical hydraulic conductivity determined by the pumping-recovery test. Although these values are derived from only nine sediment samples, they are reasonable because the sediment structure has been destroyed during sampling and thus they are neither horizontal nor vertical. Therefore, grain-size analysis cannot provide the evaluation of the anisotropy of the hydraulic conductivities in the aquitard and aquifer. Laboratory permeameter tests of sediment columns obtained from the direct-push technique show that the average K_v value of the aquifer materials is 5.14 m/day, which is compatible to that estimated by the pumping-recovery test. Consequently, the combination of direct push technique and permeameter tests gives a less expensive method for determination of vertical hydraulic conductivity in the aquifer than a pumping test.

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References

- Ayers JF, Chen XH, Gosselin DC (1998) Behavior of nitrate-nitrogen movement around a pumping high-capacity well: a field example. *Ground Water* 36:325–337
- Boulton NS, Strelsova TD (1975) New equation for determining the formation constant of an aquifer from pumping test data. *Water Resour Res* 11:148–153
- Chen XH (2004) Streambed hydraulic conductivity for rivers in south-central Nebraska. *J Am Water Resour Assoc* 40:561–574
- Chen XH, Ayers JF (1997) Utilization of the Hantush solution for the simultaneous determination of aquifer parameters. *Ground Water* 35:751–756
- Chen XH, Goeke J, Summerside S (1999) Hydraulic properties and uncertainty analysis for an unconfined alluvial aquifer. *Ground Water* 37:845–854
- Chen XH, Yin Y, Goeke J, Diffendal R Jr (2005) Vertical movement of water in a high plains aquifer induced by a pumping well. *Environ Geol* 47:931–941
- Cooley RL, Case CM (1973) Effect of a water table aquitard on drawdown in an underlying pumped aquifer. *Water Resour Res* 9:434–447
- Doherty J (2004) PEST model-independent parameter estimation users manual. Watermark Numerical Computing, Brisbane, Australia
- Halford KJ, Yobbi D (2006) Estimating hydraulic properties using a moving-model approach and multiple aquifer tests. *Ground Water* 44:284–291
- Hill MC (1992) A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional groundwater flow model using nonlinear regression. US Geol Surv Open-File Rep 91–484
- Hill MC (1998) Methods and guidelines for effective model calibration. US Geol Surv Water Resour Invest Rep 98–4005
- Hunt B (2003) Unsteady stream depletion when pumping from semiconfined aquifer. *J Hydrol Eng* 8(1):12–19
- Hunt B, Scott D (2005) Extension of Hantush and Boulton solutions. *J Hydrol Eng* 10(3):223–236
- Hvilshøj S, Jensen KH, Barlebo HC (1999) Analysis of pumping tests of partially penetrating wells in an unconfined aquifer using inverse numerical optimization. *Hydrogeol J* 7:365–379
- Lebbe L, Breuck WD (1995) Validation of an inverse numerical model for interpretation of pumping tests and a study of factors influencing accuracy of results. *J Hydrol* 172:61–85
- McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite difference groundwater flow model. US Geol Surv Open-file Rep 83–875, book 6, chapter A1
- Neuman SP, Witherspoon PA (1972) Field determination of the hydraulic conductivity of leaky multiple aquifer systems. *Water Resour Res* 8:1284–1298
- Poeter EP, Hill MC (1998) Documentation of UCODE, a computer code for universal inverse modeling. US Geol Surv Water Resour Invest Rep 98–4080
- Vukovic M, Soro A (1992) Determination of hydraulic conductivity of porous media from grain-size composition. Water Resources Publications, Littleton, Colorado