Evaluation of a pumping test with skin effect and wellbore storage on a confined aquifer in the Bela Crkva, Serbia

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Abstract: Pumping test is a fundamental method to determinate aquifer hydraulic parameters. The main evaluated hydraulic parameters are the transmissivity and the aquifer storage coefficient. For estimation of these parameters a semi-logarithmic straight line method is commonly used, which is based on the assumptions of the Theis mathematical model. Nevertheless, there are other parameters corresponding to real conditions during the pumping test, such as the skin effect and the wellbore storage. The evaluation of pumping test data is usually carried out by estimation through curve matching a straight line to drawdown data plotted on a semi-log graph. Neglecting the skin effect and the wellbore storage can lead to false analysis of the time-drawdown variation in the pumping well. Here an evaluation method is developed to estimate the transmissivity, the aquifer storage coefficient, skin effect and wellbore storage from the pumping test data showing this characteristic curve shape.

Keywords: pumping test; skin effect; wellbore storage; pumping test analysis.

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1 Introduction

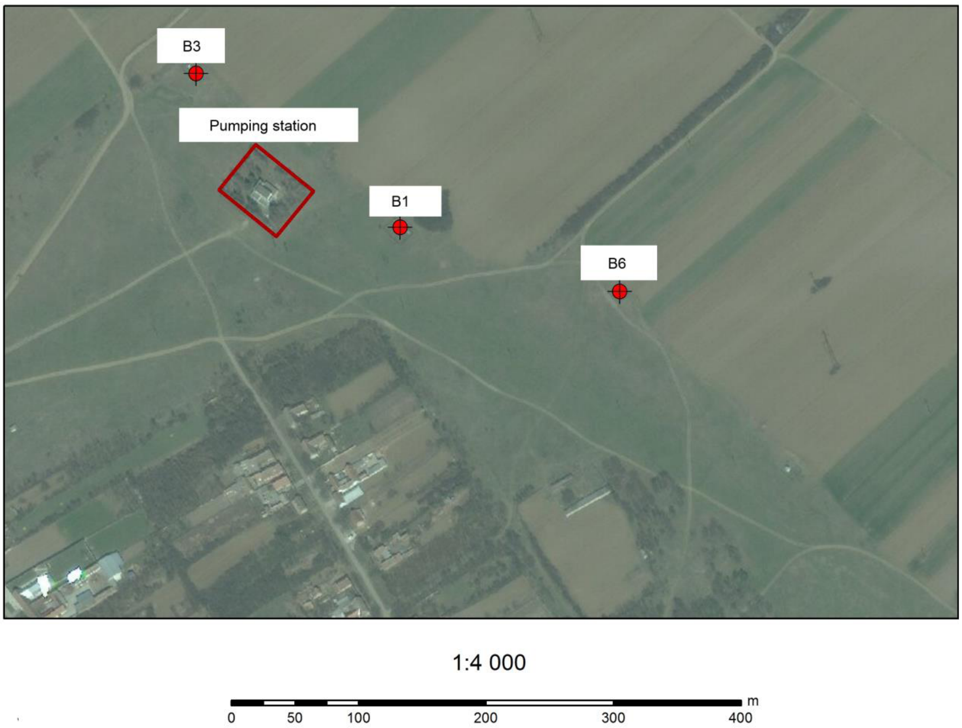
The pumping test is the most used well testing method of aquifer hydraulic parameters evaluation. The estimation technique is based on the Theis model (1935). This model was derived by ‘ideal’ pumping well assumptions, such as that, e.g., the well is fully penetrating, the well has zero radius, wellbore storage does not exist, the head loss over the well screen is negligible, which is not corresponding to the real field situation, where even skin effect and wellbore storage may occur. At an early time of the pumping test, withdrawn mass of water does not come from the surrounding aquifer but from water volume originally stored in the well casing (Papadopulos and Cooper, 1967). For the early-time section of drawdown data $s_w(t)$ is characteristic of a 45 degree straight line on a logarithmic plot (Papadopulos and Cooper, 1967; Garcia-Rivera and Raghavan, 1979; Streltsova, 1988). Although wellbore storage in pumping well occurred only at early time, neglecting this could result in overestimation of storage coefficient (Black and Kipp, 1977). The skin effect was firstly introduced by van Everdingen (1953). Since then many authors of groundwater hydraulics have published articles devoting their attention to the problem of the influence of skin effect and wellbore storage on the measured value of the real drawdown at a well (Taib, 1995; Kabala, 2001; Pech, 2003). The approaches of quantifying the skin effect in the well hydraulic modelling may be grouped into two categories; one assumes the skin to be infinitesimally thin while the other one considers it to be of finite thickness. Here infinitesimal skin thickness is assumed. The published articles assuming the skin to be infinitesimal are, for example, Moench (1997), Park and Zhan (2002) and Chen and Chang (2003). In 1970, Agarwal et al. (1970) introduced the idea of a log-log type curve matching to analysed pressure data at a well dominated by wellbore storage and skin effect. The drawdown solution of the observation well with wellbore storage and skin effect was presented by Moench (1997).

2 Material and methods

2.1 Field description and data collection

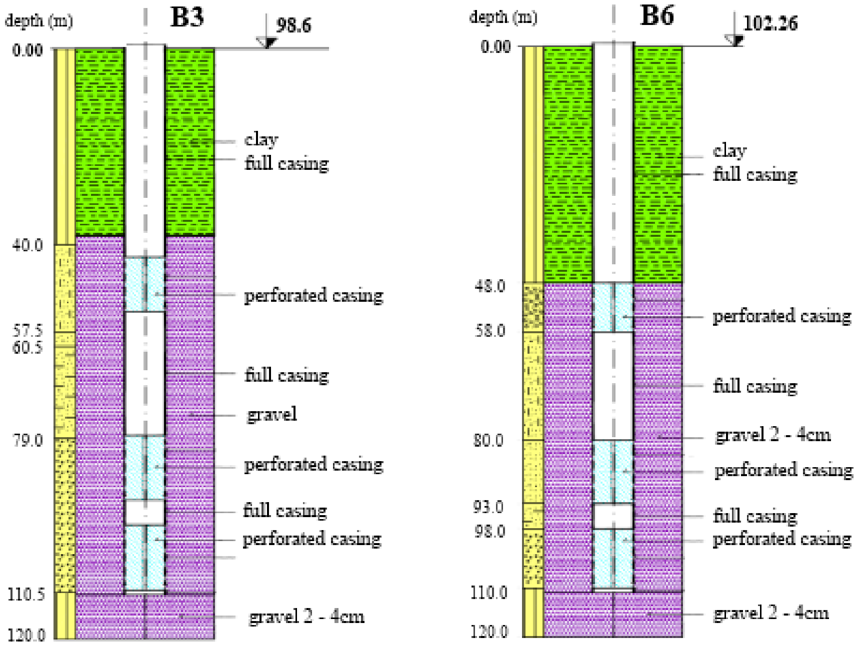
A constant-rate pumping test was conducted in a confined aquifer the location Strza nearby Bela Crkva in the Republic of Serbia, in the eastern part of Vojvodina Province. Figure 1 shows the location of wells B1, B3 and B6 with the pump. The evaluation of hydraulic parameters was performed, however, only for B3 and B6 wells.

Figure 1 Well location with pumping station nearby Strza, Bela Crkva in the Republic of Serbia (see online version for colours)



The depth of the wells B3 and B6 is 120 m. Both the pumping wells fully penetrate the aquifer with uniform radius 0.32 m. The pumping rate was constant 0.14×10^{-3} m^3/s for both B3 and B6. The data of drawdown was recorded at the very beginning of the pumping test for reasons of wellbore storage influence. Moreover, another important fact is to set suitable time step of record for this part of the pumping test, for reasons analysing the early-time section of drawdown.

Figure 2 Hydrogeological conditions of wells B3 and B6 with geological layers detail (see online version for colours)



Depth (m)	Hydrogeological layers
40.00	loam
53.00	sandy loam
57.50	sandy loam with gravel
60.50	sand
79.00	sandy clay
110.50	sand
120.00	loam

Depth (m)	Hydrogeological layers
48.00	loam
58.00	sandy gravel
80.00	sandy loam with gravel
93.00	sand
98.00	sandy clay
110.00	sand
120.00	loam

2.2 *General description of groundwater flow*

The pumping test is commonly composed of the pumping well and at least one observation well. On the pumping well, the time-drawdown during pumping of the groundwater body is recorded while the observation well is for the measurement of variation of drawdown in response to pumping. Subsequently, hydraulic characteristics of the surveyed area should be obtained from analysis of time-drawdown on pumping well and observation well with an appropriate hydraulic model. The Theis model (1935) is normally used to estimate the important or key parameters, such as transmissivity and aquifer storage coefficient, which determines time-drawdown $s(r, t)$ in the distance level between the pumping well and the observation well, and is defined as:

$$s(r,t) = \frac{Q}{4\pi T} W\left(\frac{r^2 S}{4Tt}\right) \tag{1}$$

where $W()$ is the well-known well function (Theis, 1935), T is the transmissivity [L/T^2], S is the storage coefficient, r is the distance [L], t is the time [T] and Q is the constant pumping rate [L^3/T].

The above equation (1) has been defined for assumptions that the radius of pumping well is assumed to be infinitesimally small and the additional losses are neglected. Therefore, the Theis solution based on equation (1) is not suitable to estimate skin effect and wellbore storage, although the skin effect and the wellbore storage can occur.

2.3 Wellbore storage

If the pumping well is a finite-diameter and wellbore storage is appreciable, the discharge rate is the sum of the aquifer flow rate and the rate of wellbore storage depletion. The aquifer flow rate increases exponentially with time towards the discharge rate and the wellbore storage depletion rate decreases in a similar manner to zero (Streltsova, 1988; Walton, 2006). Well storage is influenced only at an early time of the pumping test and decreases with time (Fenske, 1977). Neglecting the wellbore storage could lead to an overestimation of storage coefficient if the Theis model is used in data analysis (Black and Kipp, 1977).

2.4 Skin effect

A thin wellbore skin can be present at the interface between the pumped well screen and the aquifer (Moench, 1985). Part of the phenomenon causing skin effect is already formatted during drilling of a borehole; a drilling process can create a damage zone which induces an extra loss to groundwater flow. Pumping of groundwater can also lead to skin effect formation. The damage zone around the borehole brings changes of hydraulic properties surrounding the borehole and subsequent influence on the time-drawdown record of the pumping test. Additional skin effect occurring on the screen of the well causes additional loss. The head loss represents turbulent flow, partial penetration well and the other phenomena. Owing to the difficulty in determining, the appropriate value of skin effect is usually neglected. However, it exhibits the extra head loss on the wellbore surface. Zero skin indicates no drilling damage or fractures near the wellbore, and partial penetration is negligible.

The approach of quantifying the skin effect in the modelling of well hydraulics may be grouped into two categories; one assumes the skin to be infinitesimally thin while the other considers it to be of finite thickness. The presented solutions here account for wellbore storage and an infinitesimally thin skin in pumping well. As such, the skin factor is introduced to represent the lumped properties of the skin and is used as an energy loss term at the wellbore for mathematical convenience.

The appropriate skin effect value is defined as the difference between the actual drawdown on the pumping well and drawdown based on the Theis model, for large times it can be defined as (van Everdingen, 1953):

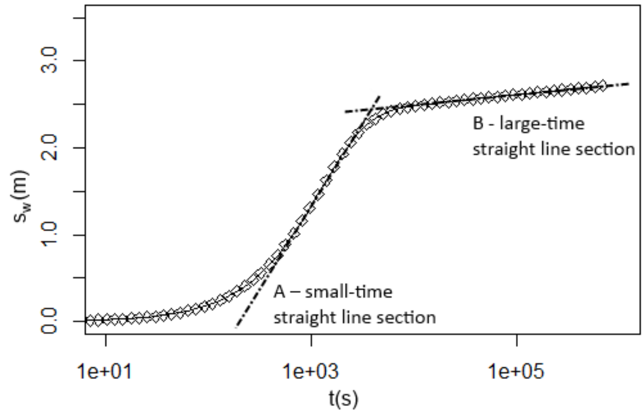
$$s_w = s_{skin} + s_t \tag{2}$$

where s_w is the pumping well drawdown, s_{skin} is the drawdown caused by the skin and s_t is the drawdown based on the Theis model.

2.5 Influence of skin effect and wellbore storage on drawdown data and analytic solution

In the pumping test data two straight lines on a semi-logarithmic graph $s_w(t)$ can occur. This shape indicates the influence of wellbore storage during the pumping test with potential skin effect. Slope and shape, i.e., the first straight line (Figure 3) curve $s_w(t)$ determines occurrence of wellbore storage on the start of the pumping test and skin effect (Garcia-Rivera and Raghavan, 1979; Taib, 1995; Pech, 2003).Valid estimation of hydraulic parameters, specifically the transmissivity and the aquifer storage coefficient based on semi-logarithmic Cooper-Jacob (1946) method is executed for B (Figure 3) large-time straight correct line of drawdown-time variable, which did not affect the wellbore storage (Agarwal et al., 1970; Ramey, 1976). The small-time straight line section A is characterised by a greater slope than in the case of the second straight line segment B on semi-logarithmic graph as shown in Figure 3.

Figure 3 Two straight lines section on the semi-logarithmic drawdown time graph



Note: The data source was used only for illustration purposes.

Both the skin effect and the wellbore storage can occur in a pumping well. Such combined effects may influence drawdown variation in a nearby observation well (Agarwal et al., 1970; Novotny and Pech, 2005; Pech and Novotny, 2005), and neglecting it could lead to serious overestimation of the storativity and underestimation of the transmissivity (Agarwal et al., 1970; Jargon, 1976). For a confined, homogeneous and isotropic aquifer, the dimensionless drawdown s_{wd} in dimensionless time t_d solution of a fully penetrating pumping well subject to both wellbore storage and well skin, can be defined as follows (Agarwal et al., 1970; Kabala, 2001):

$$s_{wd}\left(t_d\right) = L^{-1}\left\langle \frac{K_0\left(\sqrt{p}\right) + S_k\sqrt{p}K_1\left(\sqrt{p}\right)}{p\left(\sqrt{p}K_1\left(\sqrt{p}\right) + C_d\left(K_0\left(\sqrt{p}\right) + S_k\sqrt{p}K_1\left(\sqrt{p}\right)\right)\right)} \right\rangle \tag{3}$$

where $p = i(ln2/t_d)$ is the Laplace transform parameter, K_0 and K_1 are the modified Bessel function of the second kind and order zero and unit respectively, S_k is a dimensionless parameter of the skin effect, C_d is the dimensionless wellbore storage in pumping well and L^{-1} denotes the Laplace inversion, which can be numerically treated by the use of the Stehfest (1970) method.

The Stehfest algorithm pumping test mathematical models are based on Laplace transforms of groundwater function that can be calculated at any dimensional time $t_d > 0$ (Moench and Ogata, 1984). Inversion Laplace transformation has been carried out by use Stehfest algorithm (Stehfest, 1970):

$$s_{wd}\left(t_d\right) \approx \left[\frac{ln2}{t_d}\right] \sum_{i=1}^{N} V_i F(p) \tag{4}$$

where N is the number of Stehfest terms (2, 4, 6, 8, etc.), i is the actual value of the Stehfest terms, used value of V_i are presented by Walton (1996) and $F(p)$ is the Laplace transforms of groundwater function $s_{wd}(t_d)$.

The equation (3) of dimensionless drawdown vs. dimensionless time in the pumping well involves four unknown parameters, T, S, S_k and C_d. In the case where the dimensionless drawdown is calculated with equation (3) using the conventional trial-error procedure for an estimation of these four parameters, when the individual parameters are set in order to achieve the match, is not easily applicable. This data analysis process can be very time-consuming. The estimation of the transmissivity T can be realised using semi-logarithmic Cooper-Jacob (1946) method on the second straight line curve $s_w(t)$. The drawdown variation response measurement in observation well is necessary in order to determine the aquifer storage coefficient S. The evaluation of pumping tests data with observation well using semi-logarithmic straight-line method is used to estimate the parameters T and S. The curve-matching techniques based on equation (3) to determine the parameters S_k and C_d based on the knowledge of the transmissivity value and the aquifer storage coefficient are presented here.

3 Results and discussion

The pumping test evaluation of the transmissivity and the aquifer storage coefficient prevents control whether the late-time data drawdown data of $s_w(t)$ are not influenced by leakage or recharge from the possible hydrogeological boundary. In case of confirmation that the pumping test was influenced by leakage or recharge, the obtained data cannot be evaluated by the method presented here. As is shown in Figure 4 initial time variation $s_w(t)$ exhibits a characteristic slope 45 degree straight line indicating the occurrence of wellbore storage in the pumping well. This fact confirms the occurrence of two straight lines on $s_w(t)$ plot where small-time straight line has to be identified as the line of maximum slope.

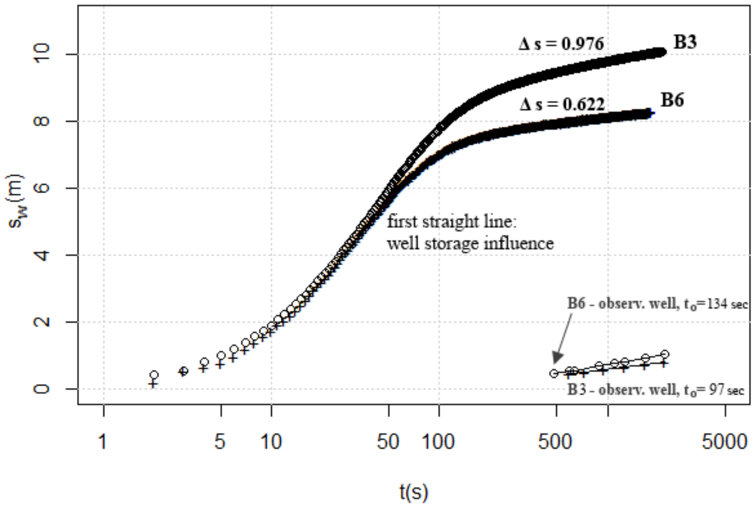
Hydraulic parameters, transmissivity and aquifer storage coefficient as main parameters of aquifers are estimated using the well-known Cooper-Jacob (1946) semi-logarithmic method from large-time straight line section. The slope of late-time straight function $s_w(t)$ defines value $\Delta s = 0.976$ for B3 and 0.622 for B6 pumping well, pumping rate was $Q = 14 \times 10^{-3}$ m^3/s for both and parameter T is determined as:

$$T = \frac{0.183Q}{\Delta s} \tag{5}$$

The transmissivity of the borehole was determined from wells B3 and B6 as 0.00263 m^2/s and 0.00412 m^2/s, respectively. Hydraulic conductivity value is obtained from the formula

$K = T/b$, where b is the thickness of the collector (the result shows under Table 1). Value corresponds to sandy aquifer, which is characteristic for the area where the data were measured.

Figure 4 Drawdown in pumping wells (B3 and B6) with observation well data plotted on semi-logarithmic paper, first straight line indicated well storage effect in the pumping well



The determination of storage coefficient requires the knowledge of value transmissivity, extrapolation straight-line portion to the time intercept t_0 and the distance between the pumping well and the observation well r. Storage coefficient is determined as:

$$S = \frac{2.25 T t_0}{r^2} \tag{6}$$

Both the transmissivity and the aquifer storage coefficient are required to compile evaluations of the skin effect S_k and the wellbore storage C_d from a pumping test data. Equation (3) is governing the equation for the estimation of skin and storage wellbore. Plotting the data $s_{wd}(t_d)$ is preceded by the necessity to convert the data from the hydrodynamic test result to dimensionless units, where the dimensionless drawdown is:

$$s_{wd} = \frac{2\pi T}{Q} s_w \tag{7}$$

and the dimensionless time:

$$t_d = \frac{Tt}{r_w^2 S}$$

where r_w is radius of well screen (L).

Plotting function $s_{wd}(t_d)$ on semi-logarithmic paper obtains characteristic sigmoid curve of pumping test data with skin effect and storage coefficient.

Figure 5 Curve matching, drawdown data plotted on semi-logarithmic paper vs. modelling data based on equation (3)

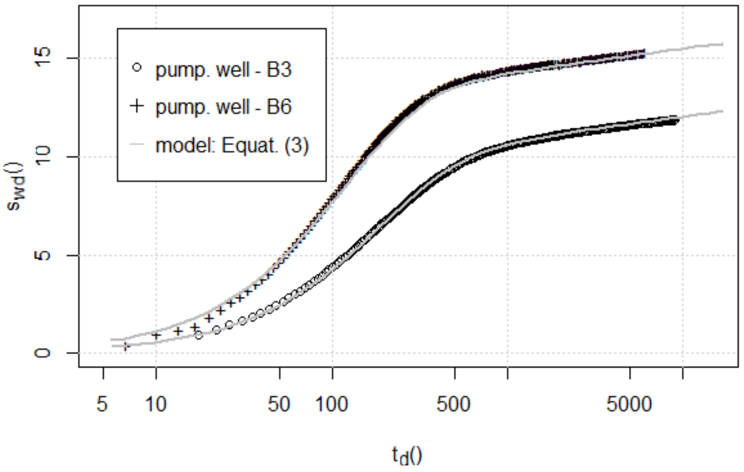


Table 1 Table of estimation hydraulic parameters from constant-rate pumping test located in nearby Strza, Bela Crkva, Serbia

Pumping well	*Parameters*	*Well – B3*	*Well – B6*
	b [m]	57	35
	T [m^2/s]	0.00263	0.00412
	K [m/s]	4.61×10^{-5}	1.17×10^{-5}
	r [m]	5	5
	t_0 [sec]	97	134
	S	0.023	0.0496
	r_w [m]	0.161	0.157
	S_k	7.05	10.5
	C_d	17.5	8.5
	E_{ns}	0.996	0.992

Note: Nash-Sutcliffe coefficient (E_{ns}) reflect value of coefficient getting from model as the result of matching technique [equation (3)].

Evaluation of the skin effect S_k and the wellbore storage C_d was performed using the matching technique drawdown pumping tests data in dimensionless unit $s_{wd}(t_d)$ with the function describing the dimensionless drawdown s_{wd} in dimensionless time t_d [equation (3)]. The agreement of the desired matching curves (Figure 5) was reached through optimisation of values C_d and S_k. The calculated parameters were evaluated as $S_k = 7.05$ and $C_d = 17.5$ for B3 well and $S_k = 10.5$ and $C_d = 8.5$ for B6. The resulting values were read at Nash-Sutcliffe coefficient value = 0.996 and 0.992, respectively which reflects an excellent agreement.

4 Conclusions

This paper presented the evaluation method of the pumping test with an observation well. Transmissivity and storage coefficient as the main hydraulic parameters of the aquifer were determined as well as skin effect and wellbore storage. Time-drawdown pumping test data characterised sigmoid shape, S-shaped drawdown-time curve typical of pumping tests with the influence of skin effect and wellbore storage. The estimation of transmissivity and storage coefficient was carried out through the Cooper-Jacob semi-logarithmic method from large-time straight line section. These parameters were input to the model used to estimate the skin effect and wellbore storage. The evaluation parameters were conducted through matching technique. The parameters were achieved in the value of statistical indicators Nash-Sutcliffe. The result can be regarded as entirely relevant due to the value of statistical indicator. These parameters are not involved in the Theis model which is commonly used to evaluate the pumping test data. However, these parameters influence the pumping test itself and it is not desirable to ignore these parameters. If they are neglected, it may lead to overestimation of the output pumping test data and subsequently devalue the pumping test. The value of skin effect is essential in determining the permeability in conditions of steady flow and can be conducted as basic evaluative criteria of regeneration pumping well with respect to changes in the hydraulic parameters before and after the regeneration process.

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