Evaluation of automated groundwater level measurements for transmissivity and storativity calculation

M. C. Kirlas and K. L. Katsifarakis

ABSTRACT

In this paper, we discuss the accuracy of aquifer transmissivity (T) and storativity (S) values, obtained through the processing of hourly and 5-min groundwater level data, regularly and accurately recorded by automated stations. In particular, we discuss the role of the selection of (a) the initial undisturbed hydraulic head level, which might be influenced by prior pumping cycles, and (b) the exact time of start or shutdown of the pump, which might not be exactly recorded. Furthermore, the accuracy of T and S values based on sparse measurements is also examined. The Cooper–Jacob method and the recovery test method have been applied to obtain both T and S, and T values, respectively. Groundwater level measurements at Moudania aquifer, Chalkidiki, Greece, are used as an illustrative example. Our main conclusions are (a) assuming that pumping starts earlier than it actually does, leads to the underestimation of T and the overestimation of S, (b) transmissivity might be overestimated if the residual drawdown, due to previous pumping cycles, is substantial, (c) in recovery tests, the deviation of the straight line that fits the experimental points from the point (1,0) is an indication of residual drawdown, and (d) sparse measurements can offer reasonable estimates.

Key words | automated groundwater level measuring, Cooper–Jacob method, Moudania aquifer Greece, recovery test method, storativity, transmissivity

M. C. Kirlas
K. L. Katsifarakis (corresponding author)
Department of Civil Engineering,
Aristotle University of Thessaloniki,
University Campus, 54124 Thessaloniki,
Greece
E-mail: *klkats@civil.auth.gr*

INTRODUCTION

Fresh water availability is a basic prerequisite for the development of human activities. Population growth, uneven distribution of demand (both in time and space) and adverse effects of climate change call for the optimal management of all available water resources (Bostan *et al.* 2016). Well-planned management, though, requires the simulation of the response of water systems to development scenarios, which, in turn, requires adequate knowledge (or reasonable estimate) of the respective physical parameters. Obtaining this knowledge might be a difficult exercise, in particular with groundwater resources. Actually, the determination of basic aquifer features such as transmissivity (or hydraulic conductivity) and storativity constitutes the inverse problem of groundwater hydraulics (Karpouzos *et al.* 2001; Carrera *et al.* 2005).

The most common problem regarding the determination of aquifer features is the scarcity of accurate and adequate groundwater level measurements. In many cases, it is attributed to financial restrictions; therefore, the introduction of cost-efficient measurement procedures would alleviate the problem (Tizro *et al.* 2014). The use of sophisticated or complex simulation models is not a substitute to field data and may even lead to a false sense of accuracy of the obtained results.

The interpretation of field data, in order to arrive at accurate T and S estimates, is an important task as well (Wu *et al.* 2005; Halford *et al.* 2006; Renard *et al.* 2009). While use of the

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classical Theis and Cooper–Jacob methods is still predominant, additional techniques, involving numerical evaluation (Tumlinson *et al.* 2006; Calvache *et al.* 2016) and metaheuristic search methods (Lin *et al.* 2010), have been introduced.

In this paper, we investigate the accuracy of aquifer transmissivity and storativity values, obtained through the processing of groundwater level data, regularly and accurately recorded by automated stations, during both pumping and recovery periods. In such cases of seemingly good quality data, result inaccuracies may be due to: (a) the exact time of start or shutdown of the pump, which might not be accurately recorded, (b) the initial undisturbed hydraulic head level, which might be influenced by prior pumping cycles, and (c) the sparsity of measurements. In our investigation, data sets from the aquifer of Moudania, Greece, are used as an example. Our results contribute to the evaluation of field measurements and to the selection of T and S values on the safe side.

THE STUDY AREA AND THE MONITORING NETWORK

The watershed of Moudania (Figure 1) is located in the Region of Central Macedonia, Greece, and more specifically in the south-western part of Chalkidiki peninsula. It covers a total area of 127.22 km^2, belonging, administratively, to the municipalities of Nea Propontida and Polygyros. The study area is characterized by low altitude (with a mean value close to 210 m) and mild slopes, and constitutes a major agricultural land of the peninsula. The climate is characterized as semi-arid to humid, while the average annual precipitation for the flat and the hilly area is approximately 420 and 505 mm, respectively (Siarkos & Latinopoulos 2016a). More than 81% of the total area is intensively cultivated and irrigated (Panteli & Theodossiou 2016). Along the coast, touristic and urban development is significant. Data from the 2011 national census show that the permanent population exceeds 16,000 people, whereas the maximum population can be higher than 40,000 people (Kirlas 2017). Therefore, regional water demand for irrigation and domestic use is high, especially during summer time. Moreover, there is a severe lack of surface water, while precipitation is rather low. Nevertheless, the groundwater resources can satisfy the water needs through a basic network of privately owned wells, in principle supervised by the pertinent authority (Latinopoulos *et al.* 2003).

According to its hydrogeological behavior, the watershed of Moudania is separated in two major geological formations. The first one in the north (mountainous area) consists of rocky formations (mostly clay schists, gneiss and ophiolite) and the second in the south (lowlands) of Neogene and Quaternary deposits. In general, the rocky formations are characterized as impermeable; hence, hydrogeological interest is mainly concentrated on the recent deposits (Kirlas 2017). The water system that is shaped inside these recent deposits is complex and is characterized by intense heterogeneity as well. It consists of an alternation of permeable and impermeable layers, without standard geometric development (Siarkos & Latinopoulos 2016b). The hydraulic conductivity of the study area is rather low, and its values range from 1×10^{-6} to 2×10^{-5} m/s (Latinopoulos *et al.* 2003). In addition, it is important to notice that even around boreholes close to each other, the value of the hydraulic conductivity can vary remarkably, because of the intense heterogeneity of the aquifer's geological formations and tectonic structure (Panteli & Theodossiou 2016).

Since September 2013, a monitoring network has been installed in the study area, consisting of two meteorological stations and eight automatic groundwater monitoring stations, namely eight municipal water supply boreholes, equipped with a piezometer and sensors that measure many important groundwater parameters such as groundwater level, salinity and temperature (Panteli & Theodossiou 2016). The sensors are placed into cables at depths larger than 100 m below the pumping level. The aforementioned parameters are regularly recorded every 60 min. Then, they are published on the network's website (https://meteoview2.gr). Generally, access to the real-time data is restricted.

In this paper, we have used hourly data from one well, located at Karya, shown as a red circle on the map in Figure 1. Moreover, we have used data collected every 5 min for a period of 3 days (from 13 April 2018 to 15 April 2018), specifically for our study. They include successive periods of well operation (at a rate of 30 m^3/h) and shutdown, and they are equivalent to data collected from pumping tests. The aforementioned data can be obtained from the corresponding author.

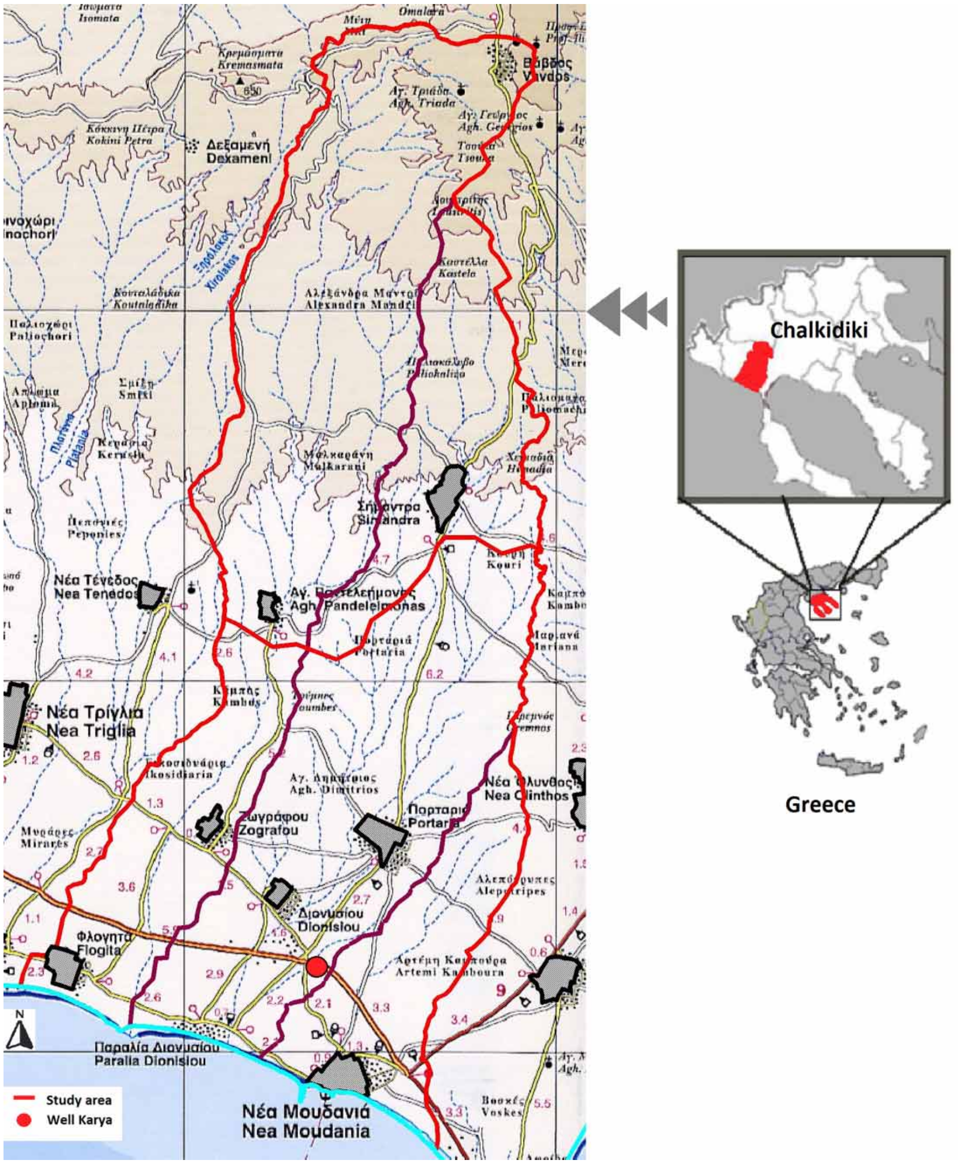

Figure 1 | The study area (watershed of Moudania) in Central Macedonia, Greece (Latinopoulos *et al.* 2003). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/aqua.2020.100.

A sketch of the well is shown in Figure 2. It penetrates successive gravel, clay with gravel and clay layers.

METHODS

Most pumping test methods are based on measurements of the hydraulic head level drawdown during transient groundwater flows towards a well, usually pumping at a constant rate. The drawdown cone dimensions, which increase with time at a diminishing rate, depend on the aquifer's transmissivity and storativity. While, in our case, water is pumped from a multilayer aquifer system (Figure 2), we have drawdown measurements at the pumping well only. For this reason, we could not apply more sophisticated conceptual models (Hemker & Maas 1987; Hemker 1999; Chang & Chen 2003). Therefore, we have sought average T and S values, namely we assumed flow through a homogeneous and isotropic

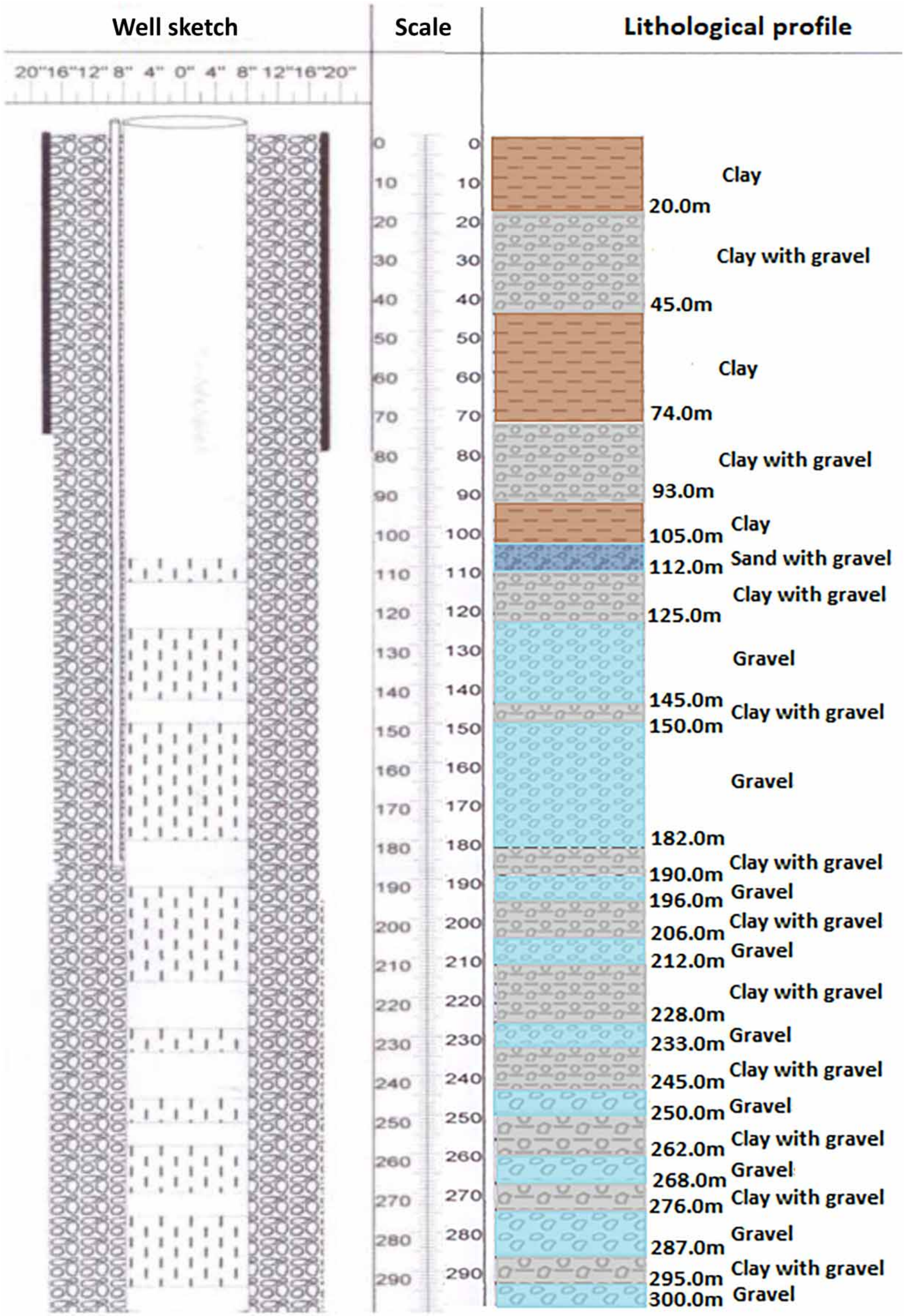

Figure 2 | Sketch of the investigated well and the soil layers that it encounters.

confined aquifer, where the following equation holds:

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{T}\frac{\partial s}{\partial t} \tag{1}$$

In the above-mentioned equation, s is the drawdown, r is the distance between the pumped and the observation well, and t is the time since the initiation of pumping, while S and T stand for aquifer's storativity and transmissivity, respectively.

Theis (1935) derived a solution to Equation (1) based on the parallelism between heat conduction and groundwater flow (Todd & Mays 2005). Theis assumed that the well could be replaced by a sink of constant strength and applied the initial condition $h = h_0$ for every r for $t = 0$ and the boundary condition $h \to h_0$ as $r \to \infty$ for $t \geq 0$. The solution to Equation (1) is:

$$\begin{aligned} s &= \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}}{u}du = \frac{Q}{4\pi T}W(u) \\ &= \frac{Q}{4\pi T}\left[-0.57722 - \ln u + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} + \ldots\right] \end{aligned} \tag{2}$$

where Q is the constant well flow rate and u is given as follows:

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

Graphical methods were very popular before the development of computers, since they facilitate calculations. In this framework, a graphical procedure was developed based on the Theis solution, to calculate T and S. Their values are obtained through the comparison of the curve that best fits field data with a typical curve, both drawn on logarithmic graph paper.

Cooper & Jacob (1946) noticed that if u is small, the series terms in Equation (2) are negligible and the drawdown is given by the following equation:

$$s = \frac{Q}{4\pi T}\left(-0.5772 - \ln\frac{r^2 S}{4Tt}\right) \tag{4}$$

Cooper & Jacob (1946) suggest a maximum allowable value of $u_{\max} < 0.01$ and most authors, such as Freeze & Cherry (1979), Schwartz & Zhang (2003), Todd & Mays (2005), follow their recommendation, while Fetter (2001) affirms that a maximum value of $u_{\max} = 0.05$ is acceptable. Nevertheless, Alexander & Saar (2011) suggest a significantly higher value of $u_{\max} = 0.2$, to avoid the omission of valuable data measured in monitoring wells that are placed at longer distances r from the pumping well, while avoiding the inclusion of potentially poor data very close to the pumping well that can consequently lead to unrealistic poor regression lines in Cooper and Jacob analysis.

Taking into account that $0.5772 \sim \ln(4/2.25)$ and substituting Napierian by decimal logarithm, Equation (4) can be transformed to:

$$s = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2 S} \tag{5}$$

According to the above-mentioned equation, the relation between s and log $(2.25\,Tt/(r^2S))$ is linear. Then, it is represented as a straight line on a semi-logarithmic paper, with s on the linear axis and $(2.25\,Tt/r^2S)$ on the logarithmic one. The graphical Cooper–Jacob method is based on marking field measurement data on such a semi-logarithmic paper and plotting the straight line that best fits them. The transmissivity T is calculated first, based on the straight line slope; then, the point of its intersection with the logarithmic axis is used to calculate storativity S.

When the distance between the observation point and the well is constant, one can use time t only on the logarithmic axis. The respective formulas are

$$T = \frac{2.3Q}{4\pi\Delta s/\Delta\log t} \tag{6}$$

$$S = \frac{2.25Tt_0}{r^2} \tag{7}$$

where t_0 corresponds to the point of intersection of the straight line with the logarithmic t-axis. We have used this version of the Cooper–Jacob method in this paper, considering that $r = 0.30$ m.

Moreover, we have used measurements during well shutdown periods to calculate the aquifer transmissivity. Assuming again that the u values are small, the formula describing residual drawdown s with time reads:

$$s = \frac{2.3Q}{4\pi T}\log\frac{t}{t - t_1} \tag{8}$$

where t is the time from the initiation of pumping, while t_1 is the time of well shutdown. Equation (8) results from Equation (5), using the superposition principle. As the relationship between s and $\log(t/(t-t_1))$ is linear, it is represented as a straight line on a semi-logarithmic paper, with s on the linear axis and $t/(t-t_1)$ on the logarithmic one. In theory, this line should pass from point (1, 0), since s tends to zero for very large times (when $t/(t-t_1)$ tends to 1 and the respective logarithm tends to 0). Transmissivity T is calculated based on the slope of the straight line by means of the following formula:

$$T = \frac{2.3Q}{4\pi\Delta s/\Delta\log(t/(t-t_1))} \quad (9)$$

Recovery tests are considered more accurate when s measurements are conducted at the pumped well, as in our case (Willmann *et al.* 2007).

COMPUTATIONAL TOOLS

The application of the graphical Cooper–Jacob and recovery test methods has been facilitated by means of computer programs. In our study, we have initially used the specialized software package AquiferTest, which offers a choice of pumping test methods and the presentation of the results as diagrams, such as the plot of Figure 3. In this diagram, s appears on the linear axis and t on the logarithmic one, while the origin of the axis is on the upper left corner of the graph.

Then, we opted to use MS Excel to produce the diagrams in a form that is more conventional and convenient for the purposes of our study. Based on the graphs, we calculated T and S values, using Equations (6) and (7), or T values by means of Equation (9). Such a diagram is shown in Figure 4. It is produced with the same field data as that of Figure 3, while the origin of the axis is at its lower left corner.

Before the final adoption of MS Excel, we compared the T and S values obtained by the two computational tools. Typical comparison results are summarized in Table 1. The deviations between the two methods are negligible.

RESULTS

Application of the Cooper–Jacob method

First, we applied the Cooper–Jacob method to hourly data recorded during one pumping cycle on 11 April 2018, following a period of zero well flow rate Q. During the whole cycle Q was constant and equal to 30 m^3/h. We considered that pumping started at the moment of the last measurement with $Q = 0$. Then, the initial 'undisturbed' hydraulic head

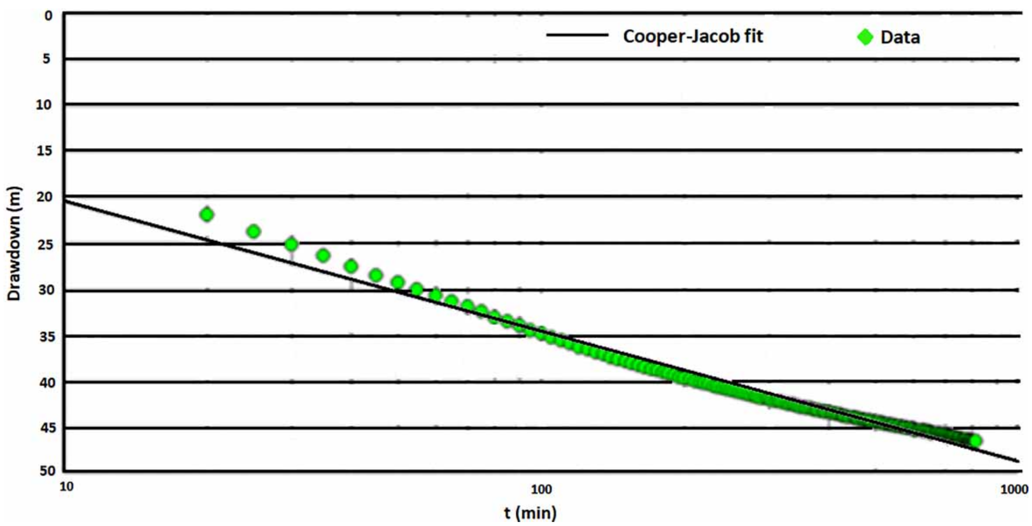

Figure 3 | Scatter plot from the AquiferTest showing the Cooper–Jacob model fit on drawdown data.

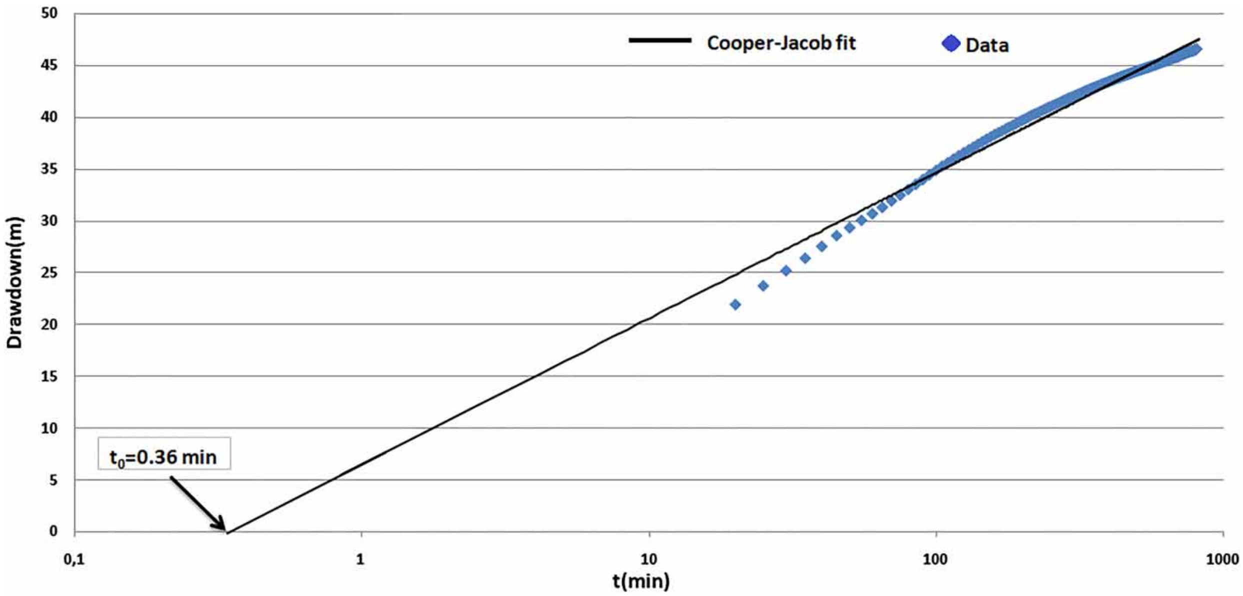

Figure 4 | Scatter plot from MS Excel 2007 showing the Cooper–Jacob model fit on drawdown data.

Table 1 | Comparison of *T* and *S* between AquiferTest and MS Excel 2007 results

Cooper and Jacob analysis

Aquifer parameters	AquiferTest	MS Excel 2007	Deviation (%)
T (m^2/min)	6.45×10^{-3}	6.53×10^{-3}	1.22
S	5.90×10^{-2}	5.87×10^{-2}	0.51

level was 75.66 m and the duration of pumping was 1,380 min. The application of the method is shown in the diagram of Figure 5.

We ended up with transmissivity and storativity values $T = 6.12 \times 10^{-3}$ and $S = 0.084$, respectively. While drawdown data can be considered as accurate, the validity of the results could be compromised due to the following reasons: (a) the time of the initiation of pumping, (b) the value of the initial undisturbed hydraulic head level and (c) the sparsity of data, although they fit very well to a straight line. First, we investigated the effect of the selection of the pumping initiation time. We varied the time difference Δt_0 between the pumping initiation time and the time of the first recorded positive Q value from 60 to 30 min, and we came up with the results appearing in Table 2.

It can be seen that reduction of Δt_0 results in an increase of T values and a decrease of S values. The influence is much more pronounced on S, though.

Then, we applied the Cooper–Jacob method to hydraulic head level data that were collected every 5 min during two pumping cycles from the same well on 14 and 15 April 2018. During both cycles, Q was constant and equal to 30 m^3/h. Again, we considered that pumping started at the moment of the last measurement with $Q = 0$. For the first cycle, the initial undisturbed hydraulic head level was 78.74 m below the well head level (the preceding shutdown period was 580 min) and the duration of pumping was 990 min. The application of the method is shown in the graph of Figure 6. For the second cycle, the initial undisturbed hydraulic head level was 80.67 m (the preceding shutdown period was 420 min), and the duration of pumping was 810 min. The application of the method is shown in the graph of Figure 4.

To further investigate the effect of the selection of the pumping initiation time, we varied the time difference Δt_0 between the pumping initiation time and the time of the first recorded positive Q value from 5 to 2 min. We came up with the results appearing in Table 3. The trend for both T and S is similar as with hourly data, but the discrepancies are much smaller, as expected. Differences

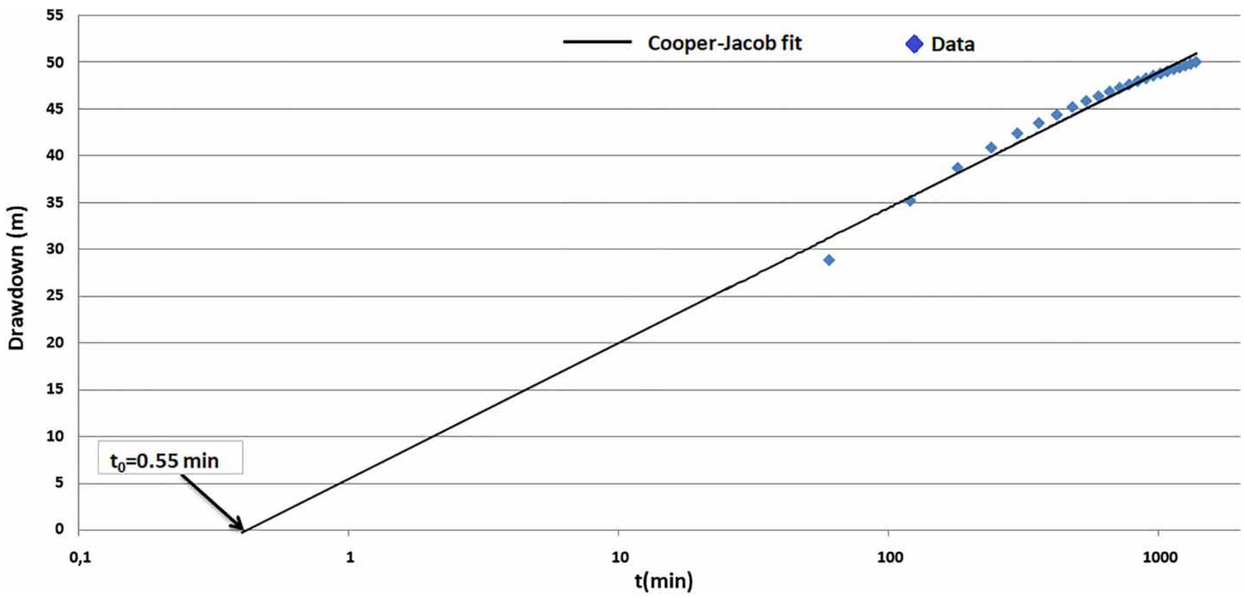

Figure 5 | Scatter plot showing the Cooper–Jacob model fit on drawdown data on 11 April 2018.

Table 2 | Variations of T and S with Δt_0

Cooper and Jacob analysis

Δt_0 (min)	T (m²/min)	S
60	6.12×10^{-3}	8.41×10^{-2}
50	6.58×10^{-3}	6.25×10^{-2}
40	6.88×10^{-3}	3.78×10^{-2}
30	7.2×10^{-3}	2.7×10^{-2}

between the T and S values obtained from the two 5-min data sets are small. They are probably due to different initial hydraulic head levels, namely to different influence of previous pumping cycles.

It should be mentioned that the first three measurements (for $t = 5$, 10 and 15 min) were excluded from the calculations in all cases. Their exclusion, which was initially decided based on visual inspection, was justified ex-post by calculating the respective u values, which are larger than 0.01, which is the limit, proposed by most researchers.

To investigate the role of data sparsity, we have recalculated the T and S values, using only hourly hydraulic head data from the above two data sets. We came up with the following results:

For cycle 1: $T = 6.55 \times 10^{-3}$ m^2/min, $S = 4.67 \times 10^{-2}$

For cycle 2: $T = 6.71 \times 10^{-3}$ m^2/min, $S = 4.62 \times 10^{-2}$

It can be seen that the sparsity of data has a small effect on transmissivity values, provided that inaccuracy in pumping initiation time is small. Nevertheless, differences in storativity values are more pronounced (of the order of 20%).

Application of the recovery test method

We have applied the recovery test method to the shutdown periods that followed the three aforementioned pumping periods. We have used hourly data for the first one and 5-min data for the other two. The duration of the recovery periods was 360, 420 and 440 min, respectively, considering that shutdown occurred at the moment of the last measurement with $Q > 0$. The respective plots are shown in Figures 7–9, while the resulting T values are summarized in Table 4. The difference between the T values obtained from the two 5-min data sets is less than 3%, while the T value obtained from the hourly data is 15% smaller.

To further investigate the effect of the selection of the pump shutdown time, we varied the time difference Δt_0 between the pumping initiation time and the time of the first recorded zero Q value from 5 to 2 min. We came up with the results appearing in Table 5. Transmissivity T

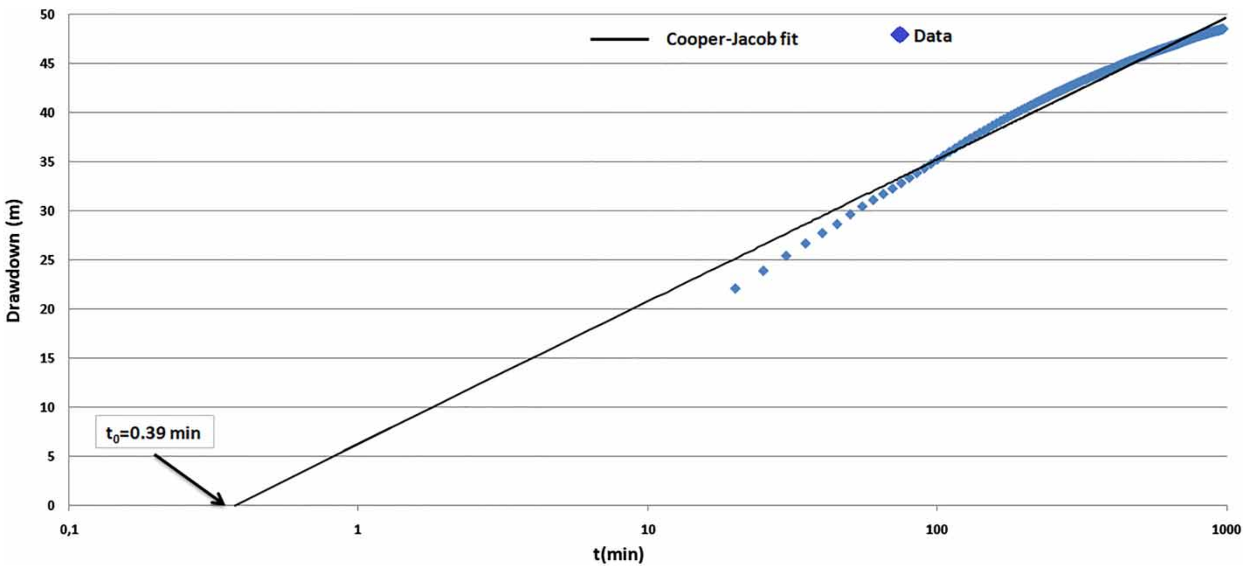

Figure 6 | Scatter plot showing the Cooper–Jacob model fit on drawdown data on 14 April 2018.

Table 3 | Variation of T and S with Δt_0

Cooper and Jacob analysis				
	14 April 2018		**15 April 2018**	
	Initial hydraulic head level (m)			
	78.74		**80.67**	
Δt_0 (min)	**T (m²/min)**	**S**	**T (m²/min)**	**S**
5	6.35×10^{-3}	5.76×10^{-2}	6.53×10^{-3}	5.66×10^{-2}
4	6.40×10^{-3}	5.55×10^{-2}	6.58×10^{-3}	5.42×10^{-2}
3	6.45×10^{-3}	5.33×10^{-2}	6.63×10^{-3}	5.19×10^{-2}
2	6.49×10^{-3}	5.11×10^{-2}	6.68×10^{-3}	4.94×10^{-2}

increases as Δt_0 decreases, namely it exhibits a similar trend in recovery and Cooper–Jacob methods.

DISCUSSION

The role of the selection of pumping initiation and shutdown time

Results of the illustrative example show clearly that the precise recording of pumping initiation and shutdown time is very important for the quality of the results. If it is assumed that pumping started earlier than it actually did, the calculated T values will be smaller and the calculated S values larger than the actual ones.

Mathematically, the effect on T values is due to their dependence on $\Delta\log t$ (as shown in Equation (6)): for a given Δt, $\Delta\log t$ decreases as the t values increase. The effect on storativity values is due to their dependence on the t_0 value (as shown in Equation (7)): the shift in t values, caused by changing Δt_0, has, percentagewise, a more pronounced effect on the respective t_0 value than on the value of T.

From the physical point of view, the decrease of S with Δt_0 can be explained in the following way: reduction of Δt_0 means that measured hydraulic head level drawdown values s occur in a shorter period of time, namely less water is extracted from an aquifer volume, with the same reduction in pressure. The effect of Δt_0 on T values can be explained as follows: assuming that pumping started earlier than it actually did, affects the drawdown rate for the first time interval only, which is actually ignored in the calculations. From then on, it shifts slower drawdown towards later times.

The role of initial 'undisturbed' water level

The drawdown at the time of the initiation of the pumping test may be affected by previous pumping cycles. This, in

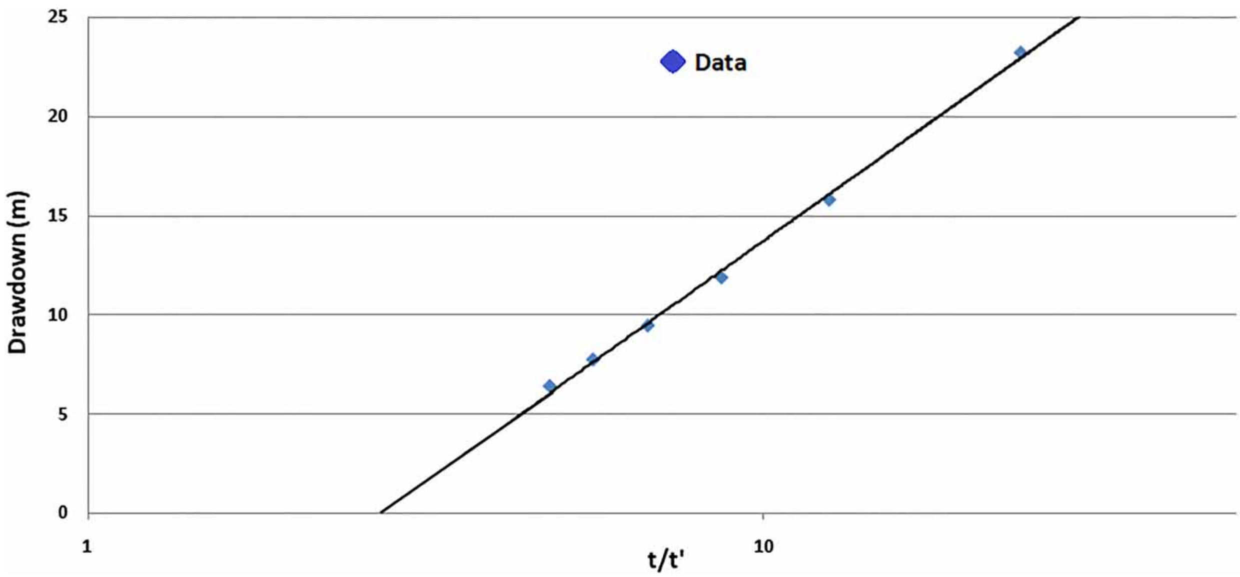

Figure 7 | Application of the recovery method on hourly residual drawdown data on 13 April 2018.

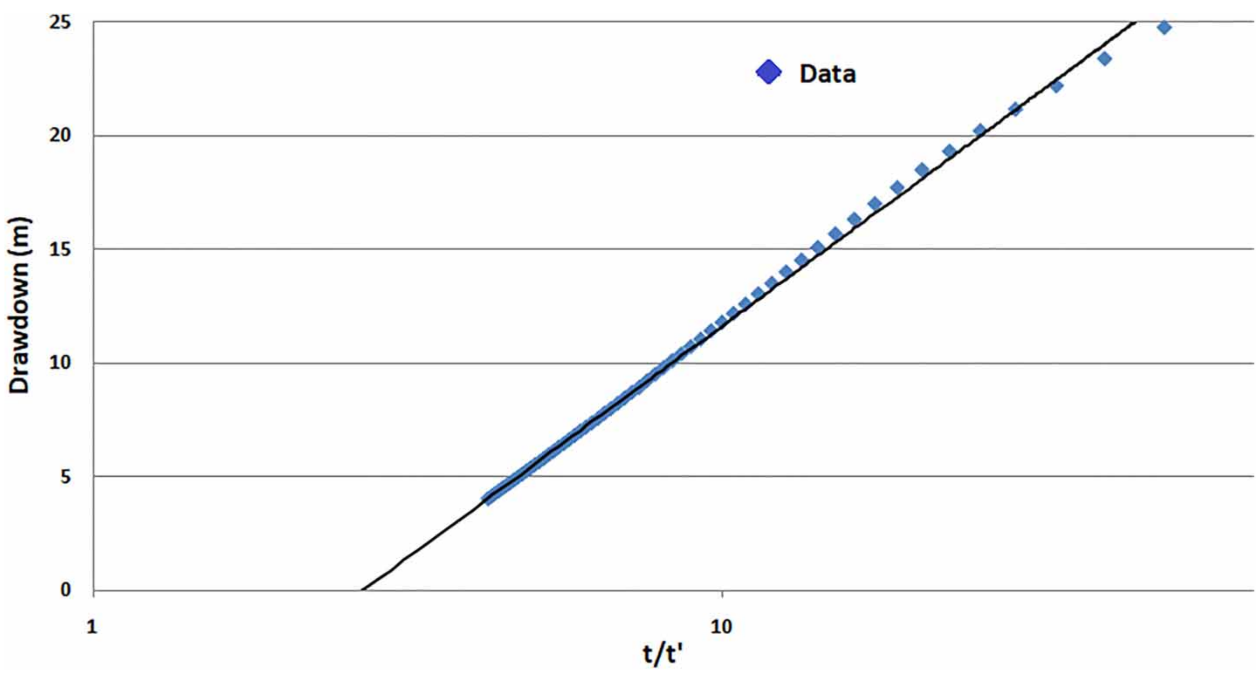

Figure 8 | Application of the recovery method on the first set of 5-min residual drawdown data on 15 April 2018.

turn, may affect the resulting transmissivity and storativity values. Results presented in Table 3 for two successive pumping cycles with initial hydraulic head levels of 78.74 and 80.67 m below the well head level, respectively, show that the differences are rather small. Results regarding S are inconclusive, as Δt_0 could be different and further research is needed to arrive at quantitative conclusions. On the other hand, calculated T values are larger in

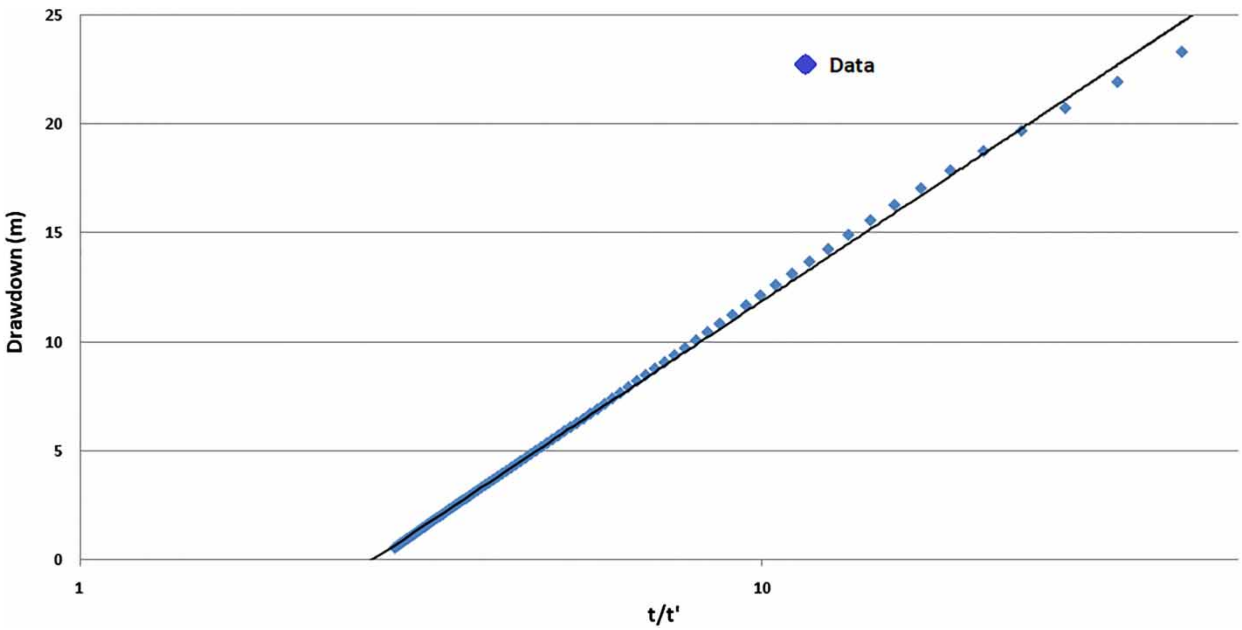

Figure 9 | Application of the recovery method on the second set of 5-min residual drawdown data on 15 April 2018.

Table 4 | Results of *T* for different data sets

Recovery method

Data (min)	*T* (m^2/min)
60	3.78×10^{-3}
5	4.51×10^{-3}
5	4.38×10^{-3}

Table 5 | Variations of *T* with Δt_0 for the first set of 5-min measurements

Recovery method

Δt_0 (min)	*T* (m^2/min)
5	4.51×10^{-3}
4	4.55×10^{-3}
3	4.60×10^{-3}
2	4.69×10^{-3}

the second case. This can be explained in the following way: by ignoring the residual drawdown, one ignores the groundwater flow which is associated with it. For this reason, the calculated transmissivity value is larger than the actual one.

In our opinion, an indication of the magnitude of residual drawdown due to previous pumping cycles can be offered by recovery tests. As mentioned in previous sections, the straight line that best fits the experimental points should pass from the point (1,0). Intersecting the logarithmic axis at a t/t' value substantially larger than 1 could be attributed to residual drawdown. In all the recovery tests, presented in this paper, the influence of previous pumping cycles is well documented. As it can be seen in Figures 7–9, the fitting line intersects the logarithmic axis at a point between 2.5 and 3.

The above comments are independent of the groundwater level measurement procedure and can be used in the evaluation of any pumping or recovery test.

Validity of sparse measurements

Transmissivity values obtained from hourly data are rather close to those obtained from 5-min data both for pumping and recovery tests. This is an indication that hourly data are dependable, as long as the time of pumping initiation (or pump shutdown) is accurately known.

CONCLUSIONS

The conclusions drawn from our paper are the following:

- The accuracy of T and S values calculation, based on regular automated groundwater level measurements, is compromised if the pumping initiation time is not accurately known. Assuming that pumping starts earlier than it actually does leads to the underestimation of T and the overestimation of S.
- Transmissivity might be overestimated if the residual drawdown, due to previous pumping cycles, is substantial.
- In recovery tests, the deviation of the straight line that fits the experimental points from the point (1,0) is an indication of residual drawdown due to previous pumping cycles.
- Sparse measurements can offer reasonable estimates, provided that the pumping initiation time is accurately known.

Finally, the general conclusion of this paper is that in order to arrive at the accurate evaluation of T and S values, the critical interpretation of field data is required, even if groundwater level measurements can be considered as accurate.

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CONFLICT OF INTEREST

The authors do not have any conflicts of interest or financial disclosures to report.

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