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Assessment of porous aquifer hydrogeological parameters using automated groundwater level measurements in Greece

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Abstract: In this paper, the hydrogeological parameters of a confined aquifer, such as transmissivity (*T*), storativity (*S*) and radius of influence (*R*), have been assessed using real groundwater level measurements recorded by a monitoring network, consisting of automated municipal water supply boreholes at Nea Moudania aquifer, Chalkidiki, Greece. Particularly, the paper focused on the correlation between the drawdown and the constant flow rate during pumping time. So the Cooper-Jacob and the recovery test method were applied in order to delineate if turbulent head losses occur, as well as the impact of incorrect measurements of the radial distance (*r*) in the accuracy of estimating *S* values. The results show that a) the occurrence of a linear correlation between *s* and *Q* indicates a negligible turbulent head loss in the pumping wells and thus a reasonable flow rate usage, b) the validity of storativity values could be compromised if the *r* value is not accurately measured, and c) recovery test method can be used as an indicator of residual drawdown (*s'*) caused by previous pumping cycles, when the straight line intersecting the logarithmic *t/t'* axis has a value greater than 1.

Keywords: Cooper-Jacob method; Greece; Recovery test method; Storativity; Transmissivity

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Introduction

Groundwater is vital for the development of human activites, such as agriculture, industry and consumption. Nevertheless, in the last few decades, overexploitation of groundwater due to the growing population, rapid urbanization and intensive agricultural activities leaded to the quantitative degradation (Brindha and Elango, 2015). In addition, the improvident use of chemical fertilizers and pesticides alongside abusive farming practices leads to the qualitative deterioration of both surface and groundwater resources (Gardner and Vogel, 2005; Saidi et al. 2011; Ncibi et al. 2020). Integrated groundwater management requires dense and accurately recorded groundwater level measurements to determine the aquifer hydrogeological parameters, such as transmissivity and storativity. Then, importantly, the values of the hydrogeological parameters could be used as inputs in groundwater flow simulation models. Moreover, the estimation of the aquifer parameters is of pivotal importance in designing geotechnical engineering procedures (Ha et al. 2020). The scarcity of reliable groundwater measurements is an ordinary problem that researchers should resolve (Kirlas, 2017).

Pumping tests is a method for hydrogeological parameters evaluation, using the Theis (1935) and the Cooper-Jacob (1946) equations for a transient state flow (Chapuis, 1992; Osiensky et al. 2000; Anomohanran and Iserhien-Emekeme, 2014). Here are the basic restrictive conditions underlying the methods: The aquifer is confined, porous, homogenous, isotropic and pumped at a constant flow rate; a fully penetrated pumping well is used; the piezometric surface is horizontal before pumping; small well diameter and instantaneously discharge of water (Kruseman and de Ridder, 2000).

Further research of pumping tests has been studied using different techniques, such as numerical models (Halford et al. 2006; Weber and

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Chapuis, 2013; Bateni et al. 2015; Chattopadhyay et al. 2015; Calvache et al. 2016; Ha et al. 2020) and electrical resistivity tomography (González et al. 2021; Rao and Prasad, 2021) for aquifer parameters evaluation. Recently, Gomo (2019, 2020) explained that regardless of the maximum *u* value, transmissivity and storativity values could be inaccurately calculated in Cooper-Jacob approximation. Therefore, rather than using *u*, he suggested the Infinite Acting Radial Flow (IARF) condition as an alternative objective criterion to ascertain the applicability of the Cooper-Jacob approach. In addition, Kirlas and Katsifarakis (2020) examined the accuracy of *T* and *S* values, derived from automated sparse groundwater level measurements, and demonstrated that the accurate recording of pumping initiation and shutdown time is essential for good-quality results. For instance, when the pumping starts earlier than it actually does, transmissivity is underestimated whereas storativity is overestimated. Furthermore, they concluded that in case of substantial residual drawdown, transmissivity could be overestimated.

The objective of this paper is to determine the impact of different parameters in analytical solutions of pumping tests, which are often ignored by groundwater practitioners, such as the correlation between the drawdown and the constant flow rate during pumping time, in order to check if turbulent head losses are observed. Moreover, we analyze and emphasize the impact of incorrect measurements of the radial distance on the accuracy of storativity values. For this reason, accurate groundwater level data sets, derived from automatic groundwater monitoring stations at Nea Moudania aquifer in Greece, are used as an illustrative example and obtained by the corresponding author.

1 Study area

The study area of Nea Moudania is located in the south-western part of Chalkidiki peninsula, in northern Greece, and covers a total area of 127 km^2 (Fig. 1). This coastal hydrological basin has a low altitude, with a mean slope altitude of 2%, annual precipitation of approximately 420 mm, annual mean temperature of 16℃, and the climate is characterized as semi-arid to humid (Siarkos and Latinopoulos, 2016). The permanent population is over 16 000; however, during the summer period (May to September), it can exceed 40 000. The largest part of the area is used as agricultural land (almost 80%) and is intensively cultivated and irrigated. In particular, more than 90% of the total water consumption is used for irrigation purposes. Alongside the coastal zone, an essential touristic activity is developed. Geologically, the area mainly consists of Neogene and Quaternary alluvial deposits, which constitutes the main aquifer. Such deposits are sandstones, Pleistocene red to brick bed clays with mica and fine-grained quartz, gravels and sands layers, Due to their significant capacity

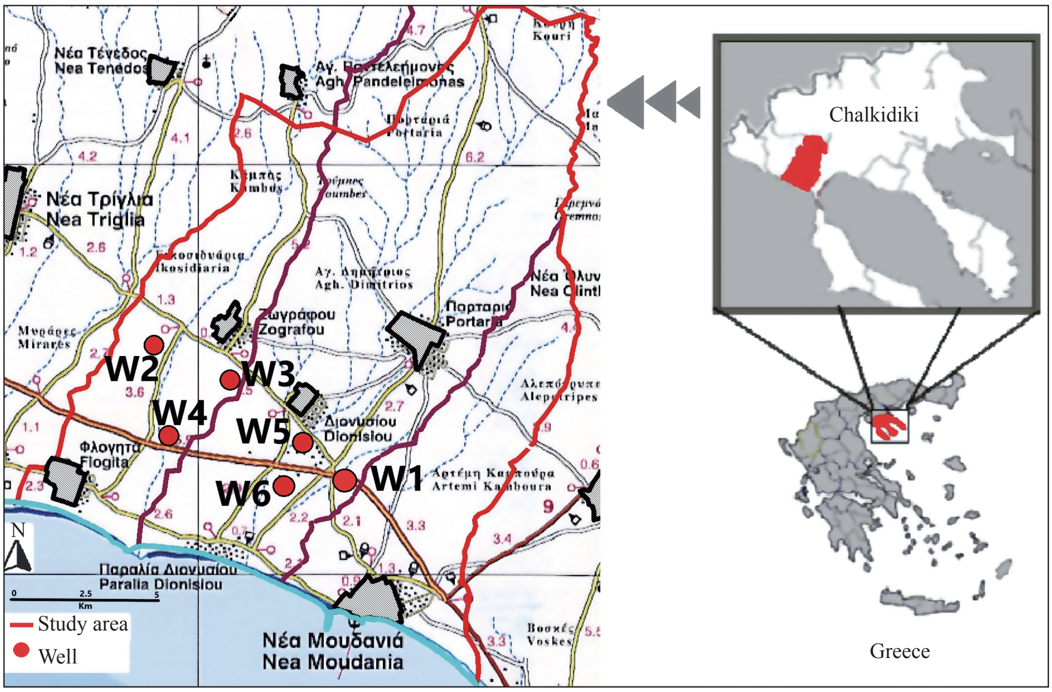

Fig. 1 Study area of Nea Moudania aquifer, Chalkidiki, Greece

Pumping wells are shown with red circle (W1 to W6).

of water storage, they have an extended development, thickness and extension, as well as a significant hydrogeological interest (Fig. 2) (Syridis, 1990; Siarkos and Latinopoulos, 2016; Kirlas, 2017).

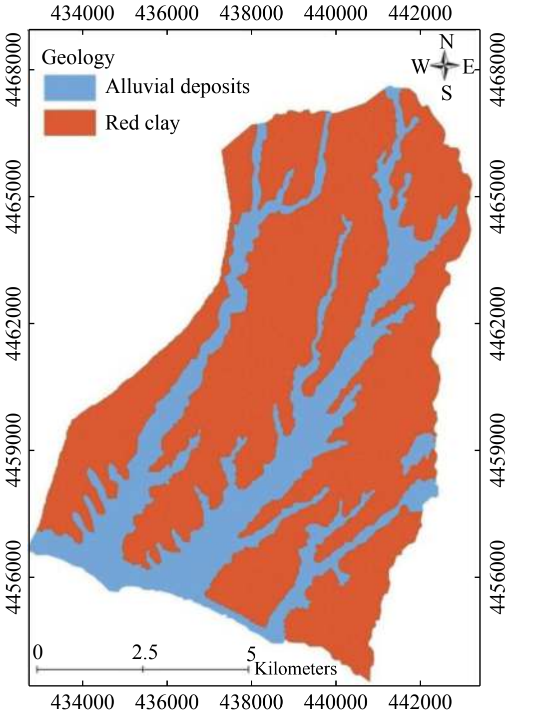

Fig. 2 Geological map of the study area (Syridis, 1990)

The hydrographic network is considered dense, particularly in the hilly area in the northern part, where it drains directly to the sea (Siarkos and Latinopoulos, 2016). The aquifer system is a multi-layered system characterized by heterogeneity, and complexity. It is mainly composed of alternated beds of permeable, semi-permeable and impermeable materials without normal geometric development (Fig. 3). The thickness of the unsaturated zone has a mean value of approximately 45 m and primarily consists of semi-permeable materials (Veranis et al. 2016).

Since there is a severe lack of surface water, groundwater is the only resource that can fulfill the water needs, and thus overexploitation conditions of groundwater resources occur in the area (Latinopoulos et al. 2003). The wells pump the multi-layer confined aquifer system at a constant flow rate. In the last few years, a monitoring network has been installed in the area, consisting of automatic groundwater monitoring stations that measure groundwater level, temperature, and salinity (Panteli and Theodossiou, 2016). A representative sketch of a well and the soil layers (clay, clay with gravel, sand with gravel and gravel) successfully penetrated in the study area is shown in Fig. 4.

2 Methods

Theis (1935) suggested Equation 1 and Equation 2 to calculate the hydraulic drawdown of the water table in confined aquifers, based on the assumption

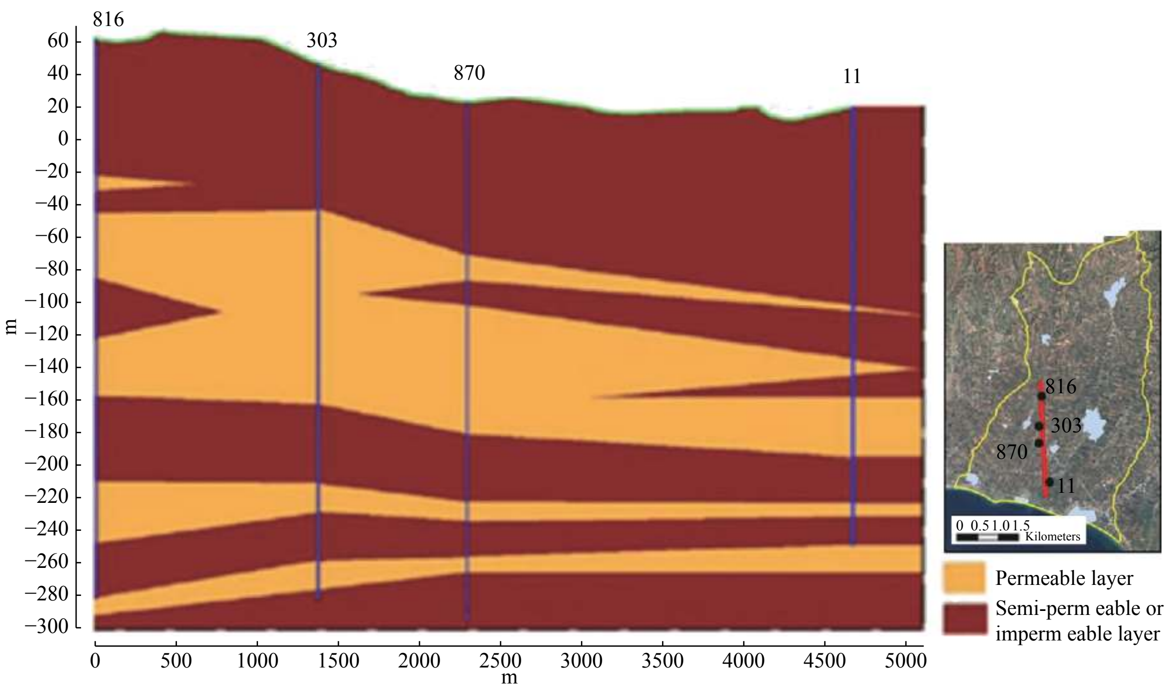

Fig. 3 Schematic geological section across the study area (Adapted from Latinopoulos et al. 2003)

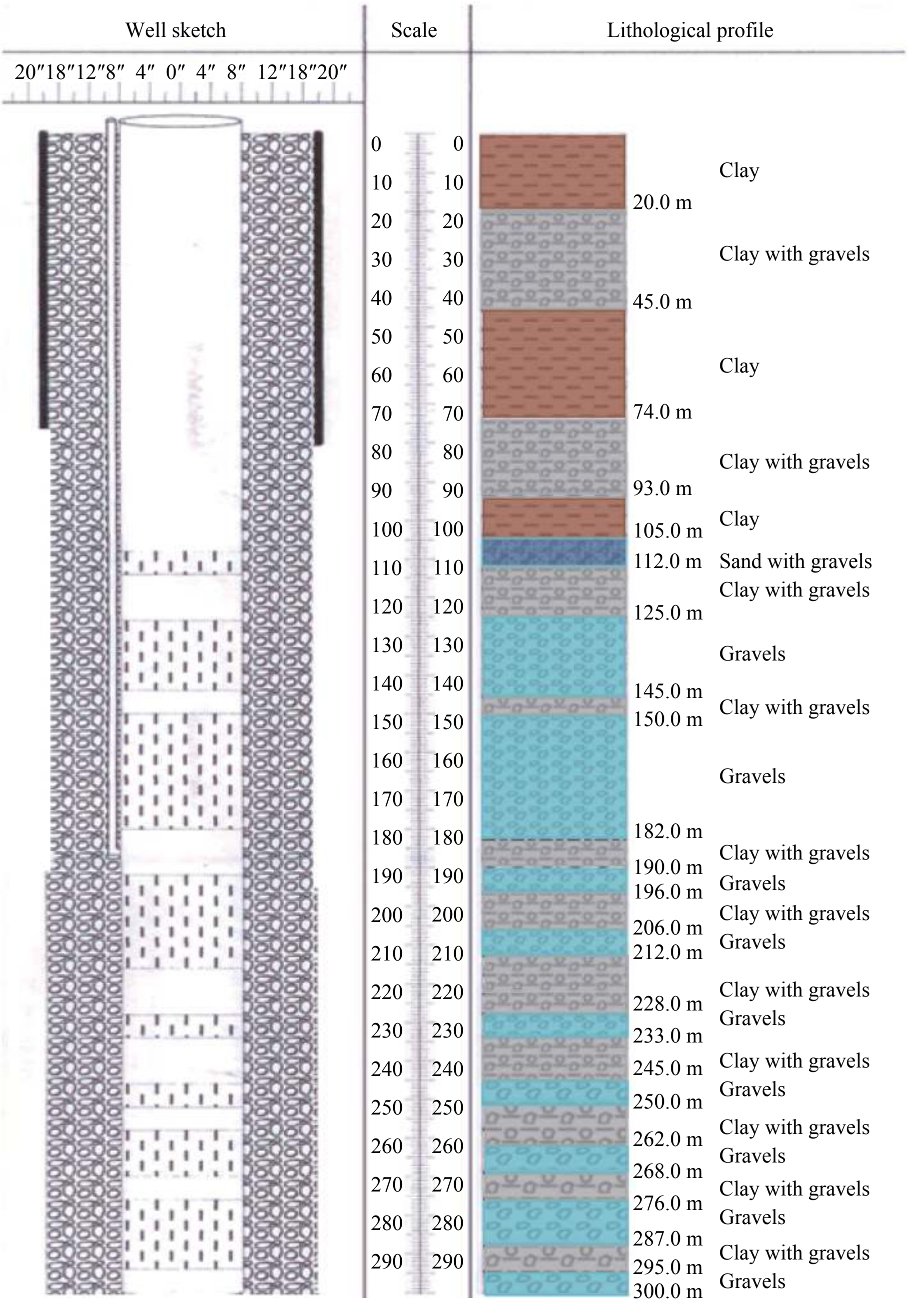

Fig. 4 Representative sketch of a well (W1) and the soil layer encountered in the study area (Kirlas and Katsifarakis, 2020)

of uniform well pumping in a homogeneous and isotropic aquifer of constant thickness. The following equations can be used to unconfined aquifers as well.

$$s = \frac{Q}{4\pi T}\int_u^{\infty}\frac{e^{-u}}{u}du = \frac{Q}{4\pi T}W(u) = \frac{Q}{4\pi T}\left[-0.577\,216 - \ln u + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} + \cdots\right] \quad (1)$$

$$u = \frac{r^2 S}{4Tt} \quad (2)$$

Where: s represents the drawdown, Q is the constant well-pumping flow rate, $W(u)$ is the exponential integral of u, r is the distance between the piezometer and the pumping well, t is the duration of pumping, T and S are aquifer's transmissivity and storativity, respectively. Based on the previously described method, Cooper and Jacob (1946) developed a method that permits an acceptable approximation to the Theis nonequilibrium equation, using a simple graphical approach. More specifically, when $u_{max} \leq 10^{-2}$ (r is small and t is sufficiently long), all series terms in the expansion beyond ln(u) are negligible and can be neglected.

On the one hand, many authors such as Freeze and Cherry (1979), Schwartz and Zhang (2003) and Todd and Mays (2005) follow the recommendation of $u_{\max} \leq 10^{-2}$, on the other hand, other authors suggest a maximum value of u_{max} = 0.05 (Fetter, 2001; Sterrett, 2007). In addition, Alexander and Saar (2011) affirm that a value of u_{max} = 0.2 can be satisfactory. Hence, Cooper and Jacob showed that Equation 1 could be transformed to Equation 3:

$$s = \frac{2.3Q}{4\pi T}\log\left(\frac{2.25Tt}{r^2 S}\right) \quad (3)$$

The graphical Cooper-Jacob method is based on plotting drawdown values against corresponding time on a semi-logarithmic paper and then drawing the best straight line that fits them. The transmissivity is determined based on the straight-line gradient (Equation 4), whilst storativity is based on the straight-line intersection to the zero drawdowns (Equation 5).

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

$$S = \frac{2.25Tt_0}{r^2} \quad (5)$$

Furthermore, since the results from the Cooper-Jacob analysis derived, the radius of influence can be calculated using Equation 6. The radius of influence R is defined as the maximum distance from a pumping well at which the drawdown can be detected and the pumping influence is significant (Dragoni, 1998). According to Knudby and Carrera (2006) the hydraulic diffusivity D_a can be estimated using Equation 7. The transmission velocity v_R of the radius of influence is derived from Equation 8.

$$R = \sqrt{\frac{Tt}{S}} \quad (6)$$

$$D_a = T/S \quad (7)$$

$$v_R = 0.75\sqrt{D_a}\frac{1}{\sqrt{t}} \quad (8)$$

The recovery test method was also used to assess the aquifer transmissivity when the pumping stopped. Residual drawdown s' is calculated according to Equation 9.

$$s' = \frac{2.3Q}{4\pi T}log\frac{t}{t-t_1} \quad (9)$$

Where: t is the pumping time and t_1 is the shutdown time of the well. Transmissivity is calculated using the following formula (Equation 10). This method cannot determine storativity. When the residual drawdown is measured at the pumping well, results might be more accurate (Willmann et al. 2007).

$$T = \frac{2.3Q}{4\pi\Delta s/\Delta log\frac{t}{t-t_1}} \quad (10)$$

3 Results

3.1 Cooper-Jacob method application and radius of influence calculation

Firstly, the Cooper-Jacob time-drawdown method was applied to six groundwater level data sets (hourly drawdown data), derived from six different boreholes accordingly (W1 to W6), in order to determine the aquifer characteristics, such as transmissivity, storativity, radius of influence and u value (Table 1).

Specifically, the following drawdown data, derived from the pumping tests, were used for the calculations. For data set 1 (W1), the pumping duration was 750 minutes, the pumping flow rate was Q_1 = 23 m^3/h, and for the first drawdown value, u was 9.9 × 10^{-3}<0.01. For data set 2 (W2), the pumping duration was 600 minutes, the pumping flow rate was Q_2 = 25 m^3/h, and for the first drawdown value, u was 2.2 × 10^{-3}<0.01. For data set 3 (W3), the pumping duration was 660

Table 1 Results of the Cooper-Jacob method

Data sets	Q (m^3/h)	T (m^2/sec)	S	Pumping duration (min)	R (m)	u
1	23	1.035×10^{-4}	8.543×10^{-2}	750	11.08	9.9×10^{-3}
2	25	9.088×10^{-5}	3.135×10^{-2}	600	15.32	2.2×10^{-3}
3	24	1.457×10^{-4}	7.652×10^{-2}	660	13.03	3.3×10^{-3}
4	20	1.456×10^{-4}	6.117×10^{-2}	900	14.31	2.6×10^{-3}
5	30	1.027×10^{-4}	6.458×10^{-2}	990	14.58	7.9×10^{-3}
6	27	1.063×10^{-4}	2.872×10^{-2}	930	21.56	3.4×10^{-3}

minutes, the pumping flow rate was Q_3 = 24 m^3/h, and for the first drawdown value, u was 3.3 × 10^{-3}<0.01. For data set 4 (W4), the pumping duration was 900 minutes, the pumping flow rate was Q_4 = 20 m^3/h, and for the first drawdown value, u was 2.6 × 10^{-3}<0.01. For data set 5 (W5), the pumping duration was 990 minutes, the pumping flow rate was Q_5 = 30 m^3/h and for the first drawdown value, u was 7.9 × 10^{-3}<0.01. For data set 6 (W6), the pumping duration was 930 minutes, the pumping flow rate was Q_6 = 27 m^3/h, and for the first drawdown value, u was 3.4 × 10^{-3}<0.01 (Fig. 5).

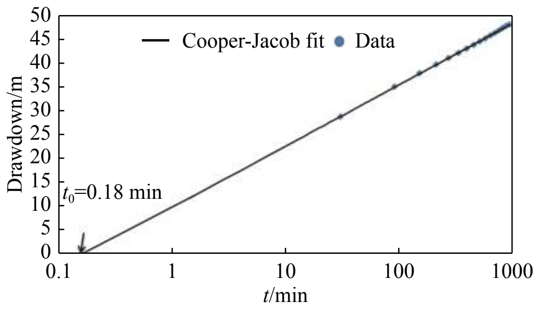

Fig. 5 Scatter plot showing the Cooper-Jacob method for data set 6

Moreover, the radius of influence R (m) was estimated for the total pumping duration of every well using Equation 6. The radius of influence indicates the horizontal effect of head-loss in a pumping well. Table 1 shows the results of the Cooper-Jacob method application (T, S and R). The radius of influence is unaffiliated with the pumping flow rate, and it only depends on the duration of pumping t and the hydraulic diffusivity. The transmissivity values varied from 9.088 × 10^{-5} m^2/sec to 1.457 × 10^{-4} m^2/sec, the storativity varied from 2.872 × 10^{-2} to 8.543 × 10^{-2}, and the radius of influence varied from 11.08 m to 21.56 m.

The transmission velocity v (m/sec) of the radius of influence for every data is shown in Fig. 6. It can be seen that in all cases, an increase of pumping duration results in a reduction of transmission velocity of the radius of influence, which means that after a relatively extended duration of pumping, the radial distance from a pumping well becomes negligible. Its values are practically close to zero ($\Delta s/\Delta t$ = negligible). Also, it should be mentioned that the radius of influence and its transmission velocity only depends on the pumping time t and the ratio of T/S (hydraulic diffusivity). Finally, the correlation between the v and the pumping duration is nonlinear.

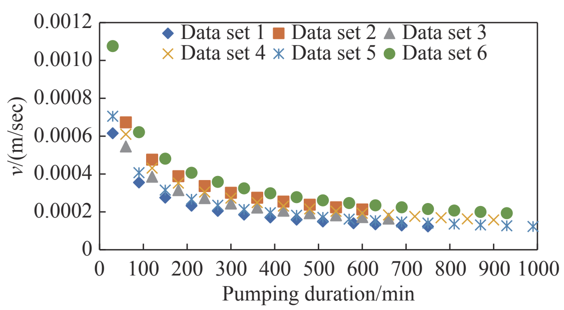

Fig. 6 Scatter plot showing the correlation between transmission speed of the radius of influence and pumping duration

3.2 Correlation between drawdown (s) and flow rate (Q)

Secondly, after the Cooper-Jacob application and the evaluation of T and S, we discuss the correlation between the drawdown and constant flow rate of every data set. From the Cooper-Jacob equation for linear head-loss, it is assumed that A_o= (2.3/4πT) × log (2.25Tt/r^2S) and thus, Equation 4 can be transformed to Equation 11.

$$s = A_o Q \tag{11}$$

It can be seen that there is a linear correlation between s and Q. Furthermore, according to the Cooper-Jacob method, the value of A_o is constant for each different data set, as long as the hydrogeological parameters T and S, the radial distance to the well r, and the pumping time t (as a time step) are constant characteristics of an aquifer. Therefore, using Equation 11, the flow rate was calculated for every drawdown data of all six data sets ($Q = s/A_0$).

Fig. 7 shows that the flow rate values increase linearly as the drawdown increases. Additionally, the linearity indicates that in the case, negligible turbulent (nonlinear) head-loss was observed in all data sets and thus there is no need to redefine the current pumping flow rate schedule (e.g. reduce pumping flow rate). The correlation delineation is essential for pumping well efficiency and is often ignored by groundwater practitioners.

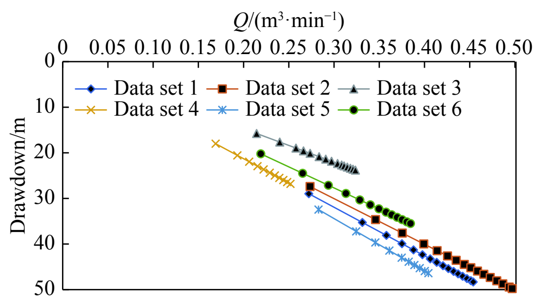

Fig. 7 Scatter plot showing the correlation between flow rate and drawdown

3.3 The impact of incorrect measurements of *r* in the accuracy of *S* values

In Cooper-Jacob method, the distance r between the pumped and observation well plays an important role on calculating u values and is often inaccurately calculated. Generally, in order to minimize u values, r should be small, and t should be rather large. The influence of r is more pronounced as it is squared in Equation 2.

Similarly, according to Equation 5, r influences the storativity values. In this study the Cooper-Jacob method was applied to evaluate T and S, considering r = 0.30 m. Nevertheless, the validity of storativity values could be compromised if the r value is not accurately measured. For this reason, a variation of r values (from 0.25 cm to 0.41 cm) was examined for all data sets in order to recalculate the storativity values (Fig. 8). The values of T and t_0, calculated before with the Cooper-Jacob method (Table 1), are supposed to be constant.

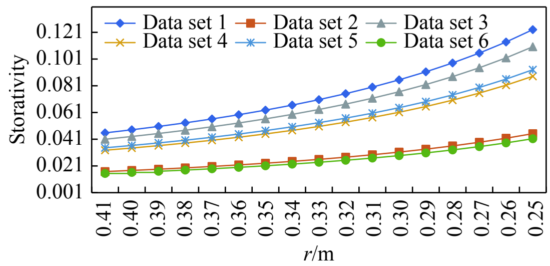

Fig. 8 Scatter plot showing the variability of S values with different r

In addition, a percentage change of storativity values with different r compared with those with r = 0.30 m appears in Fig. 9. Results show that in all data sets, storativity decreases as the radial distance to the pumping well increases. For instance, if the distance r is assumed to increase by only 0.02 m (from 0.3 m to 0.32 m), storativity values decreases by more than 12%, whilst if r decreases by 0.02 m (from 0.3 m to 0.28 m), storativity values increases by nearly 15%. Furthermore, Fig. 9 shows that the percentage change of S values is more pronounced when r decreases. Generally, it should be mentioned that the accurate measurement of r value is sometimes not considered by groundwater practitioners. However, it is crucial for the quality of S values, and even a small inaccuracy might lead to incorrect results.

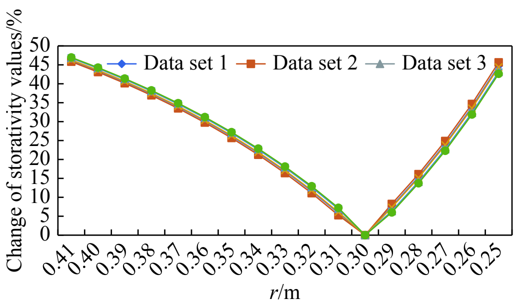

Fig. 9 Scatter plot showing the variability (%) of S values with different r

3.4 Recovery test method application

Finally, the recovery test method was applied to the shutdown periods that followed all the data sets, using hourly residual drawdown data. The recovery duration of the six pumping wells was 900, 900, 840, 900, 540 and 600 min, respectively.

Fig. 10 shows the plot of the application of the recovery test for data set 2, whilst the resulting transmissivity values are summarized in Table 2. The T values vary from 6.788 × 10^{-5} m^2/sec to 1.021 × 10^{-4} m^2/sec and they can be considered accurate. As mentioned before, the storativity values cannot be evaluated with this method.

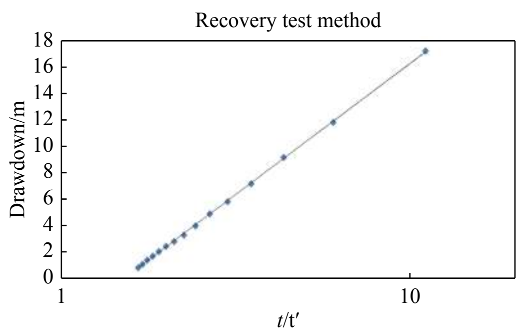

Fig. 10 Application of the recovery test method

Table 2 Results of the recovery test method

Data sets	T (m^2/sec)	Recovery duration (min)
1	6.788 × 10^{-5}	900
2	9.280 × 10^{-5}	900
3	9.150 × 10^{-5}	840
4	1.021 × 10^{-4}	900
5	9.951 × 10^{-5}	540
6	8.833 × 10^{-5}	600

4 Disscussion

Evaluation of hydrogeological parameters, such as transmissivity and storativity, is of great importance for well-planned management of groundwater and an accurate groundwater flow simulation. In this study, the interpretation of the real groundwater level data, recorded from automated stations, was made by applying the Cooper-Jacob time-drawdown method.

Regarding the radius of influence, results show that it increases whilst storativity values decreases. This result is under another reported research in a different study area (Castellazzi et al. 2016). Moreover, results show that the radius of influence constantly increases with time at a diminishing rate during a pumping with steady state flow rate. Nonetheless, the transmission velocity of the radius of influence constantly decreases with pumping duration, so that after some time, this velocity is barely noticeable (Fig. 6).

In this study, results show that in the examined confined aquifer the correlation between the drawdown s and the flow rate Q is linear, whilst the increase of the drawdown results in the increase of the flow rate values (Fig. 7). This means that, in our case, no turbulent head loss occurred in the pumping wells. Notably, the case where the relation between s and Q is nonlinear can indicate turbulent and non-horizontal groundwater flow caused by high pumping rates, which might lead to pumping well efficiency issues. This procedure and understanding are recommended to be applied in the assessment of any pumping test. However, the examination of this correlation is often ignored by groundwater practitioners.

Furthermore, results of this research illustrate clearly that the accurate measurement of radial distance r to the pumping well is of great importance for the validity and quality of storativity values and even a small inaccuracy might lead to incorrect results. Fig. 8 shows that an increase in r results in the decrease of S values, whilst Fig. 9 indicates that, for instance, an increase of 0.02 m for r decreases S by more than 12%.

Finally, the results of the recovery tests show that the T values can be considered accurate, because they are in agreement with the respective values derived from Cooper-Jacob. The recovery test method can offer researchers an indication of the magnitude of residual drawdown caused by previous pumping cycles. Indeed, when there is no influence of previous pumping cycles, the straight line that best fits the plotted points should intersect the time-ratio axis where the residual drawdown $s' = 0$ and the logarithmic axis $t/t' = 1$ (point 1, 0). Otherwise, if the straight line intersects the logarithmic t/t' axis at a value larger than 1, there is an indication of previous pumping cycles. Additionally, the substantial residual drawdown might affect the transmissivity values in a way that can be slightly overestimated. In this study, the influence is well recorded, as the straight line intersects the t/t' axis at the points between 1.1 and 2.1.

5 Conclusions

In this paper, the Cooper-Jacob time-drawdown method and the recovery test method were applied in order to assess the hydrogeological parameters of the Nea Moudania multi-layered confined aquifer system in northern Greece, such as transmissivity, storativity and radius of influence. Particularly, this study emphasized on the delineation of correlation between the drawdown and constant flow rate, the importance of the radial distance to the well in the accuracy of storativity values and the importance of the recovery test method during pumping tests. This procedure and understanding, often ignored by groundwater practitioners, are recommended to be applied in the assessment of any pumping test. The conclusions derived from this paper are the following:

In a confined aquifer, an increase of the radius of influence decreases of storativity values. In particular, the radius of influence is not affiliated with the pumping flow rate, but only depends on the duration of pumping and the hydraulic diffusivity. Its value increases at a diminishing rate with pumping time. An indication of negligible turbulent head losses is the linear correlation between drawdown and flow rate during pumping time. Otherwise, if this relation is nonlinear, then turbulent and non-horizontal groundwater flow is observed alongside the borehole and hence a redefined pumping flow rate schedule is needed for a better well efficiency. The validity and the quality of storativity values could be compromised if the radial distance value is not accurately measured. The recovery test method can be used to indicate residual drawdown caused by previous pumping cycles, if the straight line intersecting the logarithmic t/t' axis has a value greater than 1.

Finally, it should be mentioned that the assessment of aquifer hydrogeological parameters requires accurately recorded groundwater level measurements for an integrated groundwater management.

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