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REPLY

Reply to Comment on "Automatic estimation of aquifer parameters using long-term water supply pumping and injection records": paper published in *Hydrogeology Journal* (2016) 24: 1443–1461, by Ning Luo and Walter A. Illman

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The author of the Comment is thanked for his interest in the subject article (Luo and Illman 2016), and for providing an opportunity to clarify various issues resulting from applying the Theis (1935) solution to estimate hydraulic parameters using long-term water supply pumping and injection records. In particular, the Comment questions the validity of the presented approach (Luo and Illman 2016) as well as the physical meaning of estimated transmissivity (T) and storativity (S) values. This Reply consists of: (1) additional descriptions of the approach and the rationale in utilizing it to analyze the dataset at hand, (2) a discussion of the physical meaning of estimated T values, and (3) an explanation for the large S values.

For the analyses of drawdowns in a municipal wellfield, Luo and Illman (2016) utilized the Theis (1935) solution modified by applying the superposition principle to account for multiple water-supply boreholes with variable pumping rates as implemented in the WELLS code (Harp and Vesselinov 2011):

$$s_{\mathrm{p}}(t) = \sum_{i=1}^{N}\sum_{j=1}^{Mi}\frac{Q_{i,j}-Q_{i,j-1}}{4\pi T_i}\mathrm{W}\left[\frac{r_i^2 S_i}{4T_i\left(t-t_{Q_{i,j}}\right)}\right] \quad (1)$$

where $s_{\mathrm{p}}(t)$ is the pumping induced drawdown at time t, N is the number of pumping boreholes, M_i is the number of pumping records for borehole i, $Q_{i,j}$ is the pumping rate of the i-th borehole during j-th pumping record, r_i is the distance between the monitoring borehole and the i-th pumping borehole, $t_{Qi,j}$ is the time when borehole i changes its pumping rate to the j-th pumping period, and T_i and S_i are the transmissivity and storativity, respectively.

In deriving Eq. (1), Harp and Vesselinov (2011) stated that:

> T_i and S_i are cross-hole parameters that characterize the influence of the i-th pumping well at the observation location, conceptually similar to parameters that would be estimated from dedicated cross-hole pumping test analysis using the Theis method. As the significance of these parameters is limited by the assumptions of the Theis solution, these parameters are considered as interpreted parameters, and should not be confused with effective parameters (i.e., associated with ensemble averages of state variables) or equivalent parameters (i.e., associated with spatial averages of state variables) (Sanchez-Vila et al. 2006).

The Comment points out that the assumption of homogeneous aquifer implied in the Theis (1935) solution is not retained in Eq. (1) because different T and S estimates are obtained from drawdowns at monitoring boreholes for different water-supply boreholes. In contrast, a uniform set of T and S should be applied in the superposition equation (Eq. 2) to retain the homogenous assumption in the Theis (1935) solution.

$$s_{\mathrm{p}}(t) = \sum_{i=1}^{N}\sum_{j=1}^{Mi}\frac{Q_{i,j}-Q_{i,j-1}}{4\pi T}\mathrm{W}\left[\frac{r_i^2 S}{4T\left(t-t_{Q_{i,j}}\right)}\right] \quad (2)$$

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For the analyses presented in the subject article (Luo and Illman 2016), the aquifer is treated as homogeneous for estimating T and S between each pumping/monitoring borehole pair. Moreover, the total drawdown in a monitoring borehole is decomposed into contribution drawdowns from individual water-supply boreholes (see Fig. 5 in Luo and Illman 2016 as an example). For example, examination of decomposition plots (Fig. 5 in Luo and Illman 2016) reveals valuable information on pumping influences of individual water-supply boreholes at various monitoring boreholes. For each pair of water-supply and monitoring boreholes, the corresponding T and S are estimated based on the associated drawdown contribution using the Theis (1935) solution.

It is important to keep in mind that the estimated T and S values in Luo and Illman (2016) are fitted estimates resulting from utilizing a minimally parameterized analytical model (e.g., the Theis (1935) solution). As such, they are scenario dependent (Wu et al. 2005) and may not yield accurate predictions of drawdowns from pumping tests not used in the calibration effort (e.g., Berg and Illman 2015; Zhao and Illman 2017). However, the analysis still provides fundamental insights into aquifer pressure responses due to variable pumping/injection rates in a large municipal wellfield. Furthermore, the subject article (Luo and Illman 2016) should be considered as a first step toward the development and calibration of a more sophisticated numerical groundwater model (e.g., Berg and Illman 2015; Zhao and Illman 2017) using the same data.

The estimated T values in the subject article exhibit a wide range, from 9 to 55,335 m^2/day with a geometric mean of 1,965 m^2/day. The relatively wide range of estimated T values implies that the investigated aquifer (AFB2) is highly heterogeneous. To examine the reliability of the T values, the physical significance is investigated by converting transmissivity (T) to hydraulic conductivity (K). Since the thickness of AFB2 is assumed to be 20 m for the analysis, K values are calculated to range from 5.21×10^{-4} to 3.20×10^{0} cm/s with a geometric mean of 1.14×10^{-1} cm/s and the variance of the corresponding $\log_{10} K$ values is 0.28. Specific K values are provided in Table S1 of the Electronic Supplementary Material (ESM). Figure 1 illustrates the histogram of the corresponding $\log_{10} K$ values and the fitted normal distribution curve. Within the range of estimated $\log_{10} K$ values, empirical ranges of $\log_{10} K$ values of different materials (Domenico and Schwartz 1990) are also provided at the bottom of Fig. 1. Results indicate that the estimated K values are in the range of silty sand to coarse gravel, which is physically realistic, as AFB2 consists mainly of sand and some gravel, and is consistent with the geological description of AFB2 listed in Table 3 of Luo and Illman (2016). However, as stated earlier, it should be emphasized that the T and S values estimated and presented in the subject article (Luo and Illman 2016) can only be considered as interpreted hydraulic parameters (Harp and Vesselinov 2011) due to the limitation of assumptions implied in the Theis (1935) solution. These estimates cannot be considered as effective parameters that represent the aquifer.

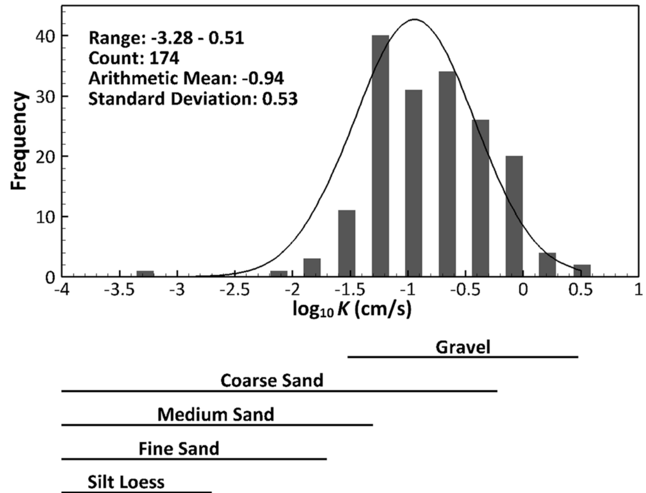

Fig. 1 Histogram of $\log_{10} K$ values; the *curve* indicates the fitted normal distribution. Ranges of $\log_{10} K$ values associated with different aquifer materials are also provided, as reported in Domenico and Schwartz (1990)

The Comment also points out that none of the S estimates reported in the subject article (Luo and Illman 2016) are physically realistic because the S values are significantly larger than those typically estimated for confined aquifers. In this Reply, the estimated storativity (S) values are converted to specific storage (S_s) (Table S2 in ESM) by assuming that the thickness of AFB2 is 20 m. The S_s values range from 1×10^{-6} to 3.68×10^{-4} /cm with a geometric mean of 4.05×10^{-5} /cm and a variance of the corresponding $\log_{10} S_s$ values is 0.15; Fig. 2 shows a histogram. Empirical ranges of $\log_{10} S_s$ values of different materials provided in Fig. 2 are obtained from

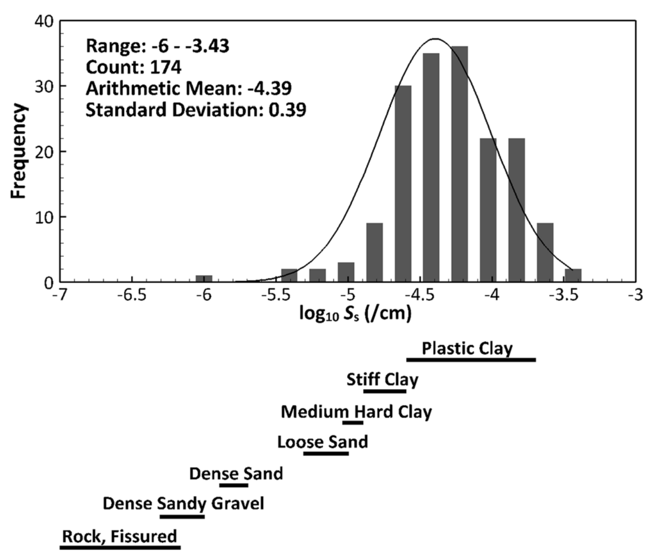

Fig. 2 Histogram of $\log_{10} S_s$ values; the *curve* indicates the fitted normal distribution. Ranges of $\log1_0\ S_s$ values associated with different aquifer materials are also provided as reported in Batu (1998)

Batu (1998). The statistical analysis of $\log_{10} S_s$ values points out that most S estimates obtained in Luo and Illman (2016) are physically realistic in describing hydraulic properties of plastic clay media; however, these estimates cannot be used to represent the storativity of AFB2, which consists mainly of sand and some gravel. The estimated S values in Luo and Illman (2016) are considered to be artificially larger, and potential reasons for this are provided in the following.

First of all, it is worthy to note that large S estimates were also obtained by Harp and Vesselinov (2011) when applying the same approach to characterize aquifer properties at the LANL site, New Mexico, USA. They pointed out that:

> Unrealistic values for storativity are expected due to the utilization of the Theis (1935) solution to characterize the hydraulic response between pumping and monitoring wells. Instead of being actual estimates of storativity, the obtained interpreted storativities may provide indications of point-to-point flow connectivity (i.e., large/small S indicates low/high flow connectivity) (Meier et al. 1998; Sánchez-Vila et al. 1999; Trinchero et al. 2008).

Secondly, the estimated S values in the subject article (Luo and Illman 2016) are found to be comparable to those previously estimated by others (e.g., Dames and Moore 1990; CH2M HILL 2003; CH2M HILL and Papadopulos Associates 2003) through dedicated pumping tests and the use of analytical solutions—e.g., Theis (1935) and Cooper and Jacob (1946). In particular, for each water-supply borehole, the geometric mean of S estimates is quite similar to those previously estimated (see Table 7 in Luo and Illman (2016)).

One potential explanation for these large S estimates is due to the fact that the Theis (1935) solution neglects borehole storage effects in pumping and observation boreholes. Water-supply boreholes at the study site have large diameters (279–406 mm), which may result in significant borehole storage. The influence of a large diameter pumping well with borehole storage on aquifer tests was examined by Papadopulos and Cooper (1967). In particular, they generated a series of type curves that describe drawdown behaviors associated with borehole storage in a confined aquifer in comparison to the Theis (1935) curve. By fitting a drawdown curve affected by borehole storage to the Theis (1935) curve, the T estimate is somewhat lower, while the estimated S value tends to be several orders of magnitude larger. Figure S1 of the ESM illustrates an example of type curve match based on both the Theis (1935) and Papadopulos and Cooper (1967) solutions using drawdown data obtained from a dedicated pumping test conducted at the site (Dames and Moore 1990). This analysis reveals that the estimated T value is somewhat lower, but on the same order of magnitude, while the estimated S value can be several orders of magnitude larger, when the effects of borehole storage are not considered in the analysis.

However, the effect of borehole storage becomes less significant when monitoring boreholes are located at large distances from the pumped borehole, which is the case for most of the borehole pairs examined in this study. Therefore, while borehole storage may be one potential mechanism for the cause of the large S values for observation boreholes located close to the pumped borehole, other mechanisms (e.g., application of a homogeneous solution to a highly heterogeneous aquifer, etc.) are more likely responsible for drawdowns measured at farther monitoring boreholes. The cause of large S values at this site will be investigated in future studies.

The primary purpose of the work of Luo and Illman (2016) was to evaluate whether long-term water-supply pumping/injection records were amenable to aquifer test analysis to estimate hydraulic parameters. Such a study was necessary before utilizing these data in more sophisticated groundwater flow models. Results indicated that the utilization of simple analytical solutions yielded estimates of T and S that are considered to be “interpreted parameters” in representing hydraulic properties of the aquifer due to the limitation of the Theis (1935) solution with its simplifying assumptions. In the subject article (Luo and Illman 2016), this limitation was explicitly acknowledged. While such “interpreted parameters” may not be entirely accurate, the use of analytical solutions for a “first-cut” study provides fundamental insights into aquifer pressure responses, and the estimated results can be used to guide the development of more sophisticated models. In order to obtain the spatial distribution of hydraulic parameters and provide more accurate predictions of groundwater flow, sophisticated numerical models that consider the aquifer as a heterogeneous medium (e.g., Berg and Illman 2015; Zhao and Illman 2017), that consider borehole storage (e.g., Vesselinov et al. 2001) and accurately represent the forcing functions (i.e., initial and boundary conditions, source/sink terms) should be applied to these records to yield more reliable hydraulic parameter estimates.

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