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Reply to comment by H. Lough, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, on the paper "Stream depletion predictions using pumping test data from a heterogeneous stream–aquifer system (a case study from the Great Plains, USA)"

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Letter to the Editor

Reply to comment by H. Lough, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, on the paper "Stream depletion predictions using pumping test data from a heterogeneous stream–aquifer system (a case study from the Great Plains, USA)" By S.J. Kollet and V.A. Zlotnik, 281: 96–114

1. General remark

We thank H. Lough for her interest in our data set and the attempt to re-analyze our results (Kollet and Zlotnik, 2003) using the recent model by Hunt (2003). We welcome others to share our unique data set of the pumping test from the Prairie Creek site, Nebraska, USA. Nevertheless, we believe that this particular attempt was unsuccessful, because H. Lough selected a model of semi-confined aquifer conditions for the interpretation of the pumping test data, which was collected in an unconfined aquifer.

H. Lough based her selection on the three distinct drawdown segments observed during the test. It is well known that geologically distinct aquifers can yield a three-segment drawdown response under pumping conditions (e.g. Streltsova, 1988). Examples include unconfined aquifers (e.g. Neuman, 1972; Moench, 1997), aquifers with double porosity or fractures (e.g. Barenblatt et al., 1960; Boulton and Streltsova-Adams, 1978), and (semi-) confined aquifers in contact with aquitards (e.g. Cooley and Case, 1973; Moench, 1985). At the Prairie Creek site, the aquifer is unconfined. The interpretation of the pumping test data collected at the site using type curves that are valid for an aquifer–aquitard system is inadequate. In fact, this approach illustrates a typical problem associated with inverse modeling: drastically different models can closely reproduce a system response and yield some parameter estimates, although the models do not represent the real system adequately. Here, the improper model yields some parameter estimates for an aquitard, although the aquitard does not exist at the Prairie Creek test site.

We must also unequivocally state that the model by Hunt (2003) is clearly formulated and correct for stream–aquifer–aquitard systems within the stated limitations (pumping wells screened only in the lowest stratigraphic layer, etc.). However, the Hunt (1999) or BZT (Butler et al., 2001) models should be used for interpreting pumping tests near streams in non-leaky aquifers as outlined in our study (Kollet and Zlotnik, 2003).

The purpose of the comment by H. Lough is to examine three drawdown segments and results from Kollet and Zlotnik (2003) using a newer analytical model of stream–aquifer interactions by Hunt (2003). We will address the key issues of this comment in the following sections.

2. The study by Kollet and Zlotnik (2003)

In our study, we evaluated the impact of major assumptions inherent in analytical models of stream–aquifer interactions under pumping conditions on stream depletion predictions. Emphasis was placed on the examination of the streambed conductance concept applied in these models that presumes a thin, semi-pervious layer separating the stream from the underlying aquifer.

We performed a 144 h pumping test using a partially penetrating pumping well at a distance of about 57 m from the stream, an almost fully penetrating observation well and eight-piezometer clusters at

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both stream banks. Each cluster contains three piezometers that are screened at shallow, intermediate, and deep aquifer depths. The sand-gravelly aquifer consists of paleoalluvium of the Platte River that is associated with the braided river depositional environment and is unconfined. In addition, our study showed the presence of aquifer heterogeneity in the form of preferential flow path features at intermediate aquifer depth that are characteristic for braided river deposits.

The time–drawdown curves monitored in all observation points during the experiment exhibit three distinct drawdown segments that are representative for unconfined aquifers and are consistent with the hydrostratigraphy of an unconfined aquifer found at the site and in the region (e.g. Chen and Ayers, 1998). This drawdown behavior is well documented and explained in the literature (e.g. Neuman, 1972, 1975; Moench, 1994).

The model by Hunt (1999) does not consider partial well penetration and is based on the Dupuit assumptions. Data from the three piezometers at each cluster were used to obtain depth-averaged drawdown using the scheme by Kollet and Zlotnik (2003) for inverse modeling.

The study concluded that stream depletion estimates are inherently fraught with uncertainties, because major assumptions in the applied analytical models are commonly violated in real stream–aquifer systems, such as aquifer homogeneity, straight stream, horizontal flow, etc. This was reflected in the quality of the fit between the theoretical curves and field data, and also in spatial trends in parameter estimates from the cut bank to the point bar. An additional finding was that the streambed conductance coefficient cannot be reconciled with upscaled in situ measurements of the hydraulic properties of the stream–aquifer interface by Cardenas and Zlotnik (2003). We believe that these are general conclusions that are applicable to other natural stream–aquifer systems.

3. Remark on the explanation of the drawdown behavior

H. Lough's explanation of the second segment of the time–drawdown curves, the leveling of drawdown at intermediate times, is based on the wrong assumption of a semi-confined aquifer at the site with leakage occurring from the overlying layers. As mentioned above, the aquifer at the site is unconfined as follows from drilling logs, hydraulic testing, geophysical data, and other studies in that region. An observed increase in drawdown with aquifer depth, is a not a result of leakage, but a result of the test geometry (i.e. partially penetrating pumping well, depth-differentiated piezometers), anisotropy in the hydraulic conductivity, and aquifer heterogeneity. This is classic material (Neuman, 1972, 1975; Moench, 1997) that has been extensively cited and discussed by Kollet and Zlotnik (2003, 2005).

The third segment of the time–drawdown curve with predominantly horizontal flow in the aquifer (negligible vertical velocity of the free water table) yields parameters for a larger aquifer volume. This has been shown in many studies, and is one of the major reasons for performing long-term pumping tests. Leveling of the drawdown as predicted by the theory (when the stream depletion rate approaches the pumping rate) could not be observed, because of unfeasible requirements for the pumping duration at the site. Inspection of Fig. 3 reveals that pumping times have to be on the order of 10^1–10^2 days to achieve such conditions. Yet, it is true that, because of the stream depletion's dependence on the conductance coefficient, large pumping times and a leveling of the drawdown curves is necessary for an accurate identification of stream depletion. This has been shown before by Christensen (2000).

4. Remark on the re-analysis of the data from piezometer C2d

H. Lough goes on to present the characteristics of the Hunt (2003) model, which is based on the assumption of a well screened only in the lowest stratigraphic layer. This assumption is also violating the test conditions at the Prairie Creek site, where the well is screened over about 80% of the saturated aquifer thickness under non-pumping conditions. Therefore, the results in Table 1 must be treated with caution.

Additionally, the comment displays confusion over the storativity concept. In unconfined aquifers, the specific storage, which is representative for the compressible properties of the aquifer material and water, is used for the first segment and the specific yield, which is representative for the effective porosity, is used for the third segment (e.g. Neuman, 1972, 1975). In our case, applying Hunt (1999) only to late time–drawdown data implies automatically that the storativity S is representative for the specific yield.

Although the Hunt (2003) model is inappropriate for our site, it has similar type curves and twice more parameters than the Hunt (1999) model. Thus, reasonable fits with the field data using the model by Hunt (2003) are not unexpected. But does the new model reflect the real system at the site better? We doubt it. Both analyses arrive at a similar value for T; however, there is a large discrepancy in the λ estimates. This is due to the misuse of the Hunt (2003) model, as we believe. A comparison of the S estimates is not possible, because they represent different properties as outlined above. We remind the reader that if Hunt (1999) is applied to late time-drawdown data, as we did in our study, the obtained S value is representative for the specific yield. H. Lough suggests to compare S from our analysis with σ (porosity of the overlying aquitard). This is not appropriate, because the aquitard does not exist at the Prairie Creek site.

It is not clear what H. Lough means by the statement that we were able to "…achieve tolerable estimates using only the data recorded after 1.25 days, because the gradient of the drawdown curve at late time was similar to that at early time…". Christensen (2000) presented a comprehensive sensitivity analysis of Hunt (1999) that showed that the streambed conductance has the most significant effect at later times, and the initial portion of the test is immaterial.

It is also interesting that H. Lough compares λ directly with K' without a meaningful definition of B'' and B'. What is B' and B''? Can these parameters be measured in the field? These questions must be answered before comparison and some physical meaning can be attributed to them. Cardenas and Zlotnik (2003) and our study showed that finding effective K'' values from in situ measurements in combination with K''/B'' values from pumping test data analysis resulted in B'' values that could not be reconciled with B'' estimates from ground penetrating radar surveys of the streambed at the site. We concluded that λ appears to be a lumped fitting parameter in our case.

We also feel that Table 1, Figs. 4 and 5 are misleading in that they compare results obtained from our analysis of vertically averaged data from the cluster C2 with individual data from C2d and corresponding analysis results using the Hunt (2003) model. The applied models are for vertically averaged aquifer response only. The response of the deepest piezometer is not representative of this average response.

It is important to note that $T = 5184\ \mathrm{m^2/day}$ obtained with the Hunt (2003) model is even larger than the value $T = 4692\ \mathrm{m^2/day}$ obtained with the Hunt (1999) model using depth averaged drawdown. In our study, we showed a spatial trend in the estimates of T and λ from the cut bank to the point bar where C2 is located. Generally, larger values of T and smaller values of λ were observed at the point bar compared to the cut bank. This has been attributed to large-scale aquifer heterogeneity and the violation of the assumption of a straight stream in the applied model. H. Lough only briefly mentioned that the analysis of the data from C5d arrived at parameter estimates that compared well with estimates from C2d. It is unfortunate that the actual estimates from C5d were not provided, which could give additional insight into the quality of the re-analysis and the existence of spatial trends in the estimates. If all data from all piezometers would be re-analyzed using the Hunt (2003) model, we expect a large range of parameter estimates, because of the violation of major assumptions inherent in the Hunt (2003) model by the real stream–aquifer system and the pumping test geometry.

5. Summary

The aquifer at the Prairie Creek test site is unconfined. This is not an assumption but an observation supported by site characterization and regional data. However, H. Lough used a model of stream depletion for semi-confined aquifer conditions by Hunt (2003). The obtained fit of the type curve to the measured data in a single piezometer C2d over the entire test period is not surprising, because the applied model utilizes a larger number of fitting parameters than the previous one (Hunt, 1999) and produces type curves that are similar to the response of an unconfined aquifer.

The T estimate obtained by H. Lough does not drastically differ from our estimate. However, the streambed conductance estimate is much smaller than our estimate using Hunt (1999), because of the misuse of the Hunt (2003) model (ignoring the unconfined conditions and the test geometry) and shortcomings in the re-analysis (using only a single piezometer response instead of vertically averaged data). The S estimate from the re-analysis cannot be compared to our estimate, which is representative for the specific yield of the unconfined aquifer. The estimate of σ of the aquitard cannot be assessed, because an aquitard does not exist at the Prairie Creek site.

The presented reanalysis does not improve our understanding of the real stream–aquifer system at the Prairie Creek site. It does not change major findings of our study, such as the spatial trends in parameter estimates from the cut bank to the point bar, the influence of aquifer heterogeneity, and the operating mode of the streambed conductance coefficient. We repeat out notion of the streambed conductance coefficient being mainly a fitting parameter that accounts for aquifer heterogeneity, the stream geometry, and the anisotropy in the hydraulic conductivity.

In conclusion, we believe that the Hunt (2003) model may be useful in the case of stream–aquifer–aquitard systems and that the Hunt (1999) or BZT (Butler et al., 2001) models should be used in the case of unconfined aquifers in combination with late time-drawdown data, when the vertical velocity of the free water table is negligible.

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