DISCUSSIONS AND CLOSURES

Discussion of “Stream Depletion by Groundwater Pumping in Leaky Aquifers” by Vitaly A. Zlotnik and Daniel M. Tartakovsky


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The authors’ solution assumes that a pumped leaky aquifer is underlain by a source bed that has zero drawdown for all time. However, an actual source bed always has finite drawdown values after relatively long periods of time, and this means that the authors’ solution is valid only for a relatively short period of time after pumping starts. Since stream depletion solutions are almost always used to predict stream depletion values after long periods of time, this means that the solution obtained by the authors is of very limited use. In particular, steady-flow stream-depletion values predicted after an infinite period of pumping in the authors’ solution will always underestimate the actual stream depletion. Unfortunately, this means that their solution is in danger of being misapplied by anyone who wants to justify excessive well abstractions when applying for water right permits.

In closing, it is worth pointing out that the equations solved by the authors are identical with Eqs. (18)–(21) in Hunt (2003) if S and σ in Hunt are replaced with the pumped aquifer specific yield and infinity, respectively. In other words, an appropriate choice of variables allows the Hunt (2003) solution to reproduce the solution obtained by the authors. It would be a misuse of this solution to do so, however, for the reason given above.

Discussion of “Stream Depletion by Groundwater Pumping in Leaky Aquifers” by Vitaly A. Zlotnik and Daniel M. Tartakovsky


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The authors address an important issue. Leaky aquifer conditions are common and the possibility that leakage may mitigate the stream depletion effect of pumping is of interest to water resource managers and water resource users.

The authors show that maximum stream depletion will be less than the pumping rate if the pumped aquifer is underlain by an aquifer in which changes in hydraulic head can be assumed to be negligible. They describe two necessary conditions for that assumption to be reasonable:

1. The lower aquifer must have a very large transmissivity, and
2. The pumping location must be close to a recharge source for the lower aquifer.

They also suggest that observations of drawdown in the upper and lower aquifers could be used to evaluate whether these conditions have been met for a specific case.

I have evaluated these propositions using the MODFLOW model (McDonald and Harbaugh 1988) to represent conditions illustrated in the authors’ Fig. 1. Simulations have been undertaken by adding a river to the upper aquifer in the three-layer aquifer system described by Hunt and Scott (2007) to represent an isotropic and homogeneous area of 50 × 50 km using a 185 row × 185 column grid with 8 model layers configured as follows:

- The upper two model layers represent an unconfined aquifer (transmissivity (T)=720 m²/d, specific yield=0.1), with a fully penetrating river through the center column of the grid (width=10 m, bed thickness=1 m, bed hydraulic conductivity =0.144 m/d) and a pumped well (100 m from the river, pumping rate 4,320 m³/d, pumping duration=10,000 days).
- The middle four model layers represent an aquitard (thickness=5 m, hydraulic conductivity=0.0144 m/d, zero storativity).
- The lower two layers represent a confined aquifer (T =1,440 m²/d, storativity=0.0001) with general-head boundaries in columns 1 and 185. Except for these general-head boundaries no-flow boundary conditions apply to all model boundaries.

I have used this model to simulate stream depletion rates (Fig. 1), drawdown (Fig. 2) and inter-aquifer flows (Fig. 3) for the following cases:

- Case A: no proximal recharge source;
- Case B: initial head condition held constant in a single column of the lower aquifer, 4,984 m from the pumped well (i.e., 5,084 m from the river);
- Case C: initial head condition held constant in a single column of the lower aquifer, 1080 m from the pumped well (i.e., 1,180 m from the river);
- Case D: initial head condition held constant in a single column of the lower aquifer, 300 m from the pumped well (i.e., 400 m from the river); and
- Case E: initial head condition held constant for all cells in the lower aquifer.

Case A approximates an idealized extensive aquifer system with a semiconfined aquifer underlying an unconfined aquifer. Case E approximates the situation represented in the schematic representation in the authors’ Fig. 1 (i.e., negligible change of head in the lower aquifer). The remaining cases (B, C, and D) represent the condition, postulated by the authors, with a recharge zone for the lower aquifer in proximity to the pumping. For all five cases the MODFLOW simulations were completed with zero mass balance error and with maximum simulated inflow rates from the specified general head boundaries being less than 0.3% of the pumping rate even after 10,000 days pumping. This indicates that the model domain is sufficiently extensive for ex-
ternal boundary conditions to have minimal effect on the solution.

For Case A the pumping-induced flow from the lower aquifer is negligible over the entire simulation period as shown in Fig. 3. At late times the simulated stream depletion rate approaches the Hunt (1999) analytical solution for a river with a clogging layer in an unconfined aquifer (Fig. 1). Rerunning this case with an order of magnitude higher transmissivity in the underlying aquifer results in little change in stream depletion rates for early time (<30 days) and at late time the rate approaches the pumping rate.

For Case B the lower aquifer recharge source (~5 km from the well) results in a negligible reduction in stream depletion rate over the first 1,000 days pumping with an equilibrium rate of approximately 75% of the pumping rate (Fig. 1). For this case drawdown in the lower aquifer is indistinguishable from that in Case A (Fig. 2). Inter-aquifer flow develops after approximately 100 days and tends toward an equilibrium rate of approximately 25% of the pumping rate (Fig. 3).

The closer lower aquifer recharge sources represented in Cases C and D (~1 km and 300 m from the well, respectively) result in progressively reduced long-term stream depletion rates (Fig. 1). Drawdown in the lower aquifer is also progressively reduced but the differences between all four cases are so small that they would be difficult to discriminate in a limited duration aquifer test (less than 10 days).

For Case E, which is equivalent to the case considered by the authors, the stream depletion rate is further reduced, reaching a maximum approximately 20% of the pumping rate (Fig. 1). Drawdown in the lower aquifer is zero (hence is not shown in

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**Fig. 1.** Stream depletion rate as a percentage of the pumping rate for a range of lower aquifer settings

**Fig. 2.** Drawdown in lower aquifer immediately beneath pumped well
Fig. 2 and interaquifer flow reaches an equilibrium rate equivalent to 80% of the pumping rate after about 100 days pumping (Fig. 3).

Several conclusions can be drawn from these simulation results:

1. The late-time stream depletion rate for Case E is the rate that would occur only if there was an unlimited recharge source in the lower aquifer. The authors refer to that rate as the “maximum stream depletion rate” (MSDR), presumably because the solution approaches that value at late time, but it would be more appropriately described as the minimum late-time stream depletion rate since in reality the rate will always be higher.

2. A lower aquifer recharge source would have to be in close proximity to the pumped well to provide any effective mitigation of stream depletion. It is difficult to imagine the circumstances under which this condition would occur. The authors refer to a case in the High Plains aquifer (Zlotnik 2004). That reference includes no evidence of a recharge source in close proximity to the pumping but instead appears to rely on a presumption that lower aquifer drawdown will be negligible because of its high transmissivity and stable water levels.

3. Drawdown observations in a lower aquifer may not reliably demonstrate the presence or absence of a lower aquifer recharge source. For example, a 10-day pumping test would not be long enough to detect the influence of a constant head boundary at a distance of 1,080 m (Case C) even though the late-time stream depletion rate would be less than 50% of that in the absence of a recharge source. The authors’ view that analysis of drawdown provides a straightforward approach to validate this concept seems to be overly optimistic.

4. The assumption of constant head, while reasonable for conventional leaky aquifer analysis where overlying water-table aquifer storage results in a delayed yield response, is not valid for confined aquifer conditions or for long times.

The authors’ solution is at risk of being misused to seriously underestimate actual stream depletion rates. In their discussion on the implications for streams in leaky aquifers some of the limitations of the solution are acknowledged. Nevertheless, the terminology used (maximum stream depletion rate) is potentially very misleading because the solution actually describes a lower bound. Water resource managers should be cautious of stream depletion assessments that invoke the assumptions that the authors’ solution depends upon.

References


Closure to “Stream Depletion by Groundwater Pumping in Leaky Aquifers” by Vitaly A. Zlotnik and Daniel M. Tartakovsky


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We thank Dr. Scott and Dr. Hunt for their interest in our analysis. Their separate comments present us with an opportunity to discuss several important aspects of the stream depletion phenomen-
enon. The comments raise two major issues, both of which were addressed by Zlotnik and Tartakovsky (2008). The first issue is potential misuses and misinterpretations of our model and definitions. The second issue, which is closely related to the first, is a clarification of conditions for the applicability of our model.

Many regions of the world face a challenging task of balancing the use of ground and surface water. Early in the twentieth century, water management studies focused largely on surface water use, while ignoring the effects of groundwater use on surface runoff. Proliferation of large-capacity wells by the end of the twentieth century made a conjunctive management of groundwater-surface water resources imperative. The classical results from aquifer hydraulics by Theis and Glover and Balmer became a widespread tool to assess stream depletion rate (SDR).

These classical results and their more recent analytical and semianalytical counterparts (Zlotnik et al. 1999; Hunt 1999; Butler et al. 2001) disregard leakage into the exploited aquifer from the adjacent aquifers. This may overestimate SDR. The objective of our study was to provide more accurate bounds of stream depletion by considering leakage of aquifers (Zlotnik 2004; Butler et al. 2007, 2008; Zlotnik and Tartakovsky 2008). For the reader interested in applications, we explicitly state (section “Implications for Streams in Leaky Aquifers,” p. 49):

“We must emphasize that these equations represent the lowest bound on an estimate of depletion for the adjacent stream in the aquifer-aquitard-aquifer system. The actual SDR might fall into the range between those described by Eq. (22) and the equations developed by Hunt (1999) (see Sec. 5.2). In practical assessment of the SDR, information on hydrostratigraphy and aquifer recharge zone must be emphasized. When data are scarce, an assessment of the SDR must include both the lower bound from Eq. (22) and the upper bound from Eq. (35).”

This point is emphasized further in the section “Summary and Conclusions” (p. 49): “The SDR for an adjacent stream induced by a given well can be assessed only with full consideration of hydrogeological conditions that include the hydraulic properties of the aquifer and streambed, geometry of recharge and discharge zones of the upper and lower aquifers, and location of the pumping well. In general this would require numerical modeling. The obtained solutions may be used for preliminary assessment of the SDR and will complement detailed numerical techniques that are applied for evaluation of stream-aquifer water budgets, when necessary parameters are available a priori.”

Dr. Scott followed the latter advice by presenting a series of synthetic examples, which demonstrate that the ultimate stream depletion may be used for preliminary assessment of the adjacent well. In general this would require numerical modeling. The obtained solutions may be used for preliminary assessment of the SDR and will complement detailed numerical techniques that are applied for evaluation of stream-aquifer water budgets, when necessary parameters are available a priori. Also, solutions can be used for designing the aquifer testing programs similar to these by Sophocleous et al. (1988), Hunt et al. (2001), Nyholm et al. (2002, 2003), and Kollet and Zlotnik (2003, 2005). The pretesting designs can be significantly enhanced by a sensitivity analysis of the on-site conditions (Christensen 2000).

A slow drawdown progression may be a technical impediment in using our model. Therefore, field assessments of SDR and/or MSDR must be designed differently from typical pumping tests. This finding led Dr. Scott to question the use of drawdown observations to validate the source-bed concept introduced by M. Hantush. Our study draws attention to this issue on p. 48: “The time it takes for each SDR curve to reach the corresponding MSDR may differ, and a sensitivity analysis to the stream-aquifer-aquitard parameters would be appropriate.” And again on p. 49: “The obtained solutions may be used for preliminary assessment of the SDR and will complement detailed numerical techniques that are applied for evaluation of stream-aquifer water budgets, when necessary parameters are available a priori. Also, solutions can be used for designing the aquifer testing programs similar to these by Sophocleous et al. (1988), Hunt et al. (2001), Nyholm et al. (2002, 2003), and Kollet and Zlotnik (2003, 2005). The pretesting designs can be significantly enhanced by a sensitivity analysis of the on-site conditions (Christensen 2000).”

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