WATER RESOURCES RESEARCH, VOL. 43, W09602, doi:10.1029/2006WR005416, 2007

# Reply to comment by J.-P. Renaud et al. on "An assessment of the tracer-based approach to quantifying groundwater contributions to streamflow"

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Received 9 August 2006; revised 11 May 2007; accepted 18 May 2007; published 22 September 2007.

**Citation:** Sudicky, E. A., J. P. Jones, A. E. Brookfield, and Y.-J. Park (2007), Reply to comment by J.-P. Renaud et al. on ''An assessment of the tracer-based approach to quantifying groundwater contributions to streamflow,'' *Water Resour. Res.*, *43*, W09602, doi:10.1029/2006WR005416.

[1] We welcome the comments of *Renaud et al.* [2007] on our recent paper [*Jones et al.*, 2006]. This dialog provides us the opportunity to clarify some of the points we made regarding this important topic.

[2] For the sake of simplicity, a two-component form of the mass balance equations discussed by *Jones et al.* [2006] can be written as

$$Q_t = Q_o + Q_{gw} \tag{1a}$$

$$C_tQ_t = C_oQ_o + C_{gw}Q_{gw} \tag{1b}$$

where Q [$L^3/T$] is discharge, C [$M/L^3$] is concentration and the subscripts t, o and gw refer to the total flow as measured in the stream, the surface runoff component arising directly from the precipitation event, and the pre-event portion from the groundwater system, respectively. As was stated by *Jones et al.* [2006], the Q values in (1a) and (1b) are often interpreted by hydrogeologists and hydrologists to represent a bulk hydraulic gradient–driven flow such as, for example, Darcian-type subsurface flow. *Renaud et al.* [2007] state that, in addition to the hydraulic gradient driving force, dispersive/diffusive processes influence the motion of subsurface water, including isotopically tagged water molecules. We entirely agree with this statement. Indeed, a major point of *Jones et al.* [2006] was to illustrate the influence of mechanical dispersion and molecular diffusion on an interpretation based on (1a) and (1b) that lumps both advective (i.e., hydraulic gradient driven) and dispersive/diffusive processes. Because bulk Darcian subsurface flow is driven by hydraulic gradients, we then demonstrated that the implied lumping of advective and dispersive/diffusive transport processes will lead to an overestimation of the actual Darcian, pre-event contribution to streamflow during a rainfall event.

[3] To further elaborate, let us expand the terms on the right-hand side of (1b) as follows:

$$C_tQ_t = \int_{\Gamma_o} \left[c_o\overline{q}_o - \theta_o\overline{\overline{D}}_o\nabla c_o\right] \bullet \overline{n_o}\, d\Gamma_o + \int_{\Gamma_{gw}} \left[c_{gw}\overline{q}_{gw} - \theta_{gw}\overline{\overline{D}}_{gw}\nabla c_{gw}\right] \bullet \overline{n_{gw}}\, d\Gamma_{gw} \tag{2}$$

where $\overline{q}$ [L/T] is the specific discharge, c [$M/L^3$] is concentration, $\theta$ is porosity [$-$], $\Gamma$ [$L^2$] is the surface-subsurface interface area, $\overline{\overline{D}}$ [$L^2/T$] is the hydrodynamic dispersion tensor, and $\overline{n}$ is the unit vector normal to $\Gamma$. The subscripts *o* and *gw* here denote overland (i.e., event) and groundwater (i.e., pre-event) contributions, respectively, and we have included a "surface" porosity $\theta_o$ to account for rivulet-like overland flow. Note that the hydrodynamic dispersion tensors in (2) combine the effects of mechanical dispersion and molecular diffusion (i.e., the dispersive/diffusive processes), and the values of *c* and $\overline{q}$ appearing in (2) are local values that vary in space and time. Let us consider the second term that appears on the right-hand side of (2) for illustrative purposes:

$$C_{gw}Q_{gw} = \int_{\Gamma_{gw}} \left[c_{gw}\overline{q}_{gw} - \theta_{gw}\overline{\overline{D}}_{gw}\nabla c_{gw}\right] \bullet \overline{n_{gw}}\, d\Gamma_{gw} \tag{3}$$

where $c_{gw}\overline{q}_{gw}$ and $\theta\overline{\overline{D}}_{gw}\nabla c_{gw}$ are the advective and dispersive/diffusive subsurface fluxes, respectively, contributing to the total mass flux $C_{gw}Q_{gw}$. Clearly, the pre-event total mass flux is influenced by hydrodynamic dispersion as driven by concentration gradients that develop at the stream-subsurface interface as well as the magnitude of $\theta_{gw}\overline{\overline{D}}_{gw}$. Values of $Q_{gw}$ calculated from (1a) and the lumped form of (1b) will therefore be inflated from a purely Darcian (hydraulic gradient-driven) flow contribution unless the hydrodynamic dispersion flux is explicitly accounted for. Our inclusion of Figure 2 for the hypothetical cross section for different values of the dispersion parameters was precisely intended to demonstrate this point.

[4] Now consider a hypothetical situation where the dispersive/diffusive flux is negligible ($\overline{\overline{D}}_{gw} = 0$), recogniz-

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0043-1397/07/2006WR005416

ing that at least molecular diffusion will always be present. Equation (3) would reduce to

$$C_{gw}Q_{gw} = \int_{\Gamma_{gw}} \left[c_{gw}\overline{q}_{gw}\right] \bullet \overline{n_{gw}}\, d\Gamma_{gw} \qquad (4)$$

In the absence of hydrodynamic dispersion, the $c_{gw}$ term is constant and would therefore equal $C_{gw}$ in (1b) such that it can be moved outside of the integral. We are then left with

$$Q_{gw} = \int_{\Gamma_{gw}} \left[\overline{q}_{gw}\right] \bullet \overline{n_{gw}}\, d\Gamma_{gw} \qquad (5)$$

which is by definition the total groundwater contribution to streamflow that is solely driven by hydraulic gradients across the stream-subsurface interface. This is why we set the dispersion/diffusion parameters to zero in order to compute the actual hydraulically driven contributions to streamflow in Figures 11 to 15 of *Jones et al.* [2006], and to contrast these values with those obtained from a "lumped" interpretation based on (1a) and (1b) with dispersion included in the model. Our conclusions drawn from these figures therefore remain valid. That is, unless the hydrodynamic dispersion flux is explicitly accounted for in a tracer-based approach to hydrograph separation, the calculated values of $Q_{gw}$ will be inflated. We would also like to point out that, in a given time step in InHM, $\overline{q}$ is calculated from the solution of the mixed form of Richards' equation before being used in the tracer transport computations. Therefore any alteration of the dispersive transport parameters in the model will not affect the value of $\overline{q}$.

[5] Regarding our division of the pre-event waters for the Borden rainfall-runoff experiment into separate unsaturated and saturated components, we would point out that one of our ancillary goals was is to determine the source zones of all of the waters contributing to streamflow generation and that this simply entailed adding an additional unsaturated zone tracer in the model that is used to tag the movement of the vadose zone water that existed prior to the rainfall event. As was shown in Figure 8 of *Jones et al.* [2006], the pre-event water initially residing below the water table (i.e., the saturated zone) did not significantly contribute to the streamflow produced after the onset of the rainfall event, at least on the basis of the hydraulic gradients that developed. Note that dispersive/diffusive processes were included in the simulation results provided in Figure 8 and that the concentration gradients in the saturated zone below the channel are clearly nonnegligible. The primary source of the hydraulically driven pre-event contribution to streamflow came from the unsaturated zone because of the capillary fringe effect, although this quantity was also small compared to the "lumped" pre-event estimate obtained from the direct application of (1a) and (1b) by *Jones et al.* [2006]. We do concede that these findings were not emphasized in the paper.

[6] *Renaud et al.* [2007] also bring up a point concerning the use oxygen isotopes. When isotopically tagged water molecules diffuse (and mechanically disperse) from the subsurface to the surface, this does indeed represent the movement of these molecules; however, this does not necessarily represent the bulk movement of water as described by Darcy's law, and we again point out that the motion of the tagged water molecules comprise both advective (i.e., hydraulically driven) and dispersive/diffusive components. This latter quantity will impact the values of the Q terms inferred from lumped mass balance equations such as (1a) and (1b). That is, a large portion of the water appearing in the stream may appear to be "old" water, but not all of this pre-event water was hydraulically driven into the stream as many hydrologists and hydrogeologists commonly assume.

[7] Finally, we concur with *Renaud et al.* [2007] that tracer-based research has significantly contributed to the advancement of hydrological sciences and will continue to do so in the future. It needs to be strongly emphasized here that we are not questioning the veracity of tracer data itself. Instead, we simply questioned the manner in which the data are commonly interpreted. We remain convinced that the use of lumped mass balance equations such (1a) and (1b) need to be adapted to account for (or at least approximate) dispersive/diffusive processes if they are to produce a direct estimate of the hydraulically driven pre-event contribution, and thus resolve the old water paradox. This is a topic of future work.

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