Stream-upland connections and the effects of stream discharge on transient storage processes

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INTRODUCTION

Stream–catchment connections and the linkages between stream discharge and transient storage processes remain poorly understood. We seek to investiagte stream catchment connections and the impact of discharge magnitude on transient storage dynamics. Previous studies of transient storage in streams have suggested that hyporheic exchange should dominate transient storage as discharge decreases because of reduced stream cross-sectional area relative to the cross-sectional area of the hyporheic zone. However, no direct relationships have been developed between stream discharge and transient storage influences on solute transport. **We tested the hypothesis that the influence of transient storage on solute transport increases with decreasing stream discharge.**

1) Three separate conservative tracer stream additions with LiBr during baseflow recession (over 12 days) in a 16.9 ha headwater catchment, at Maimai New Zealand.
2) Breakthrough of bromide was measured and simulated with OTIS for 2 sub-reaches within the 580 m study reach (145 m, 290 m, 425 m, and 580 m from the injection).
3) Discharge decreased from 1.11 to 0.14 l s-1 at the injection point, and from 4.5 to 1.5 l s-1 at 580 m over the course of the three tracer tests.
4) Terrain analysis was used to quantify stream morphology and local inflow area along the stream.
5) Synoptic sampling during the two steady-state tracer was used to measure variability in later inflow quantity, $\delta^{18}O$, and silica concentrations.

STUDY SITE

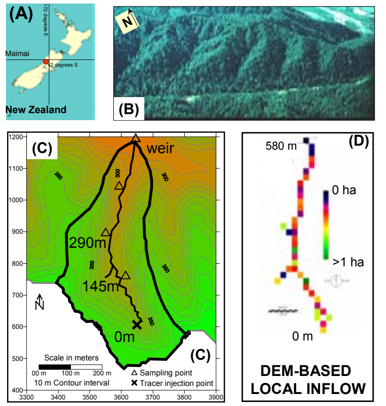


Figure 1.

(A-B) The Maimai catchments are located in NW New Zealand, on the South Island.

(C) The locations of the 4 study reaches are indicated on the topographic map of the 16.9 ha K catchment.

(D) The upland area draining into each 20 meter stream cell was calculated based on topographic analysis of the catchment DEM and a 0.5 ha stream threshold. Note the variability in local inflows to the stream.

MODELLING METHODS

Stream Tracer Solute Transport Modeling

Three LiBr salt stream tracer experiments along a 290 m stream reach. Br addition rate was 105.5 meq L^{-1} for each experiment. Electrical conductance (EC) data was collected on a 120s interval at 145m and 290m. Grab samples for Br analysis were collected periodically throughout the experiments, based on EC. An EC-Br relationship was determined, and the Br breakthrough curves were simulated using the transient storage model OTIS:

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + \alpha(C_S - C) + q_L(C_L - C) \quad \textbf{[Eq. 1]}$$

$$\frac{dC_S}{dt} = \alpha\frac{A}{A_S}(C - C_S) \quad \textbf{[Eq. 2]}$$

where, C is the solute concentration in the stream (meq L^{-1}), C_S is the storage zone solute concentration (meq L^{-1}), C_L is the local inflow solute concentration (set to 0), Q is the stream discharge ($m^3\ s^{-1}$), q_L is the local inflow ($m^3\ s^{-1}\ m^{-1}$), D is the longitudinal dispersion ($m^2\ s^{-1}$), α is the storage zone exchange rate (s^{-1}), A is the cross-sectional area of the stream (m^2), A_S is the cross-sectional area of the storage zone (m^2), t is time, and x is the downstream distance (m) (Runkel, 1998).

Because discharge is changing throughout the tracer experiment (decreasing baseflow), the following relationship was developed from Manning's Equation:

$$A = cQ^{0.6} \quad \textbf{[Eq. 3]}$$

and, c is a coefficient representing a relationship among channel roughness, slope and wetted perimeter.

Optimal values of A_S, D, α, c, and q_L were obtained using UCODE, a universal computer code for model optimization (Poeter and Hill, 1998)

PART I MODELING RESULTS

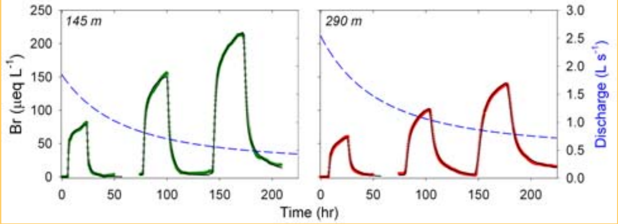


Figure 2. Br observed (points) and simulated (black line) breakthrough curves and hydrographs at 145m and 290m from injection point. During the three experiments, discharge decreased from 1.11 to 0.14 L s^{-1} at the injection point, and from 2.52 to 0.72 L s^{-1} at 290m. Br concentration plateaus were increasing due to a decrease in discharge.

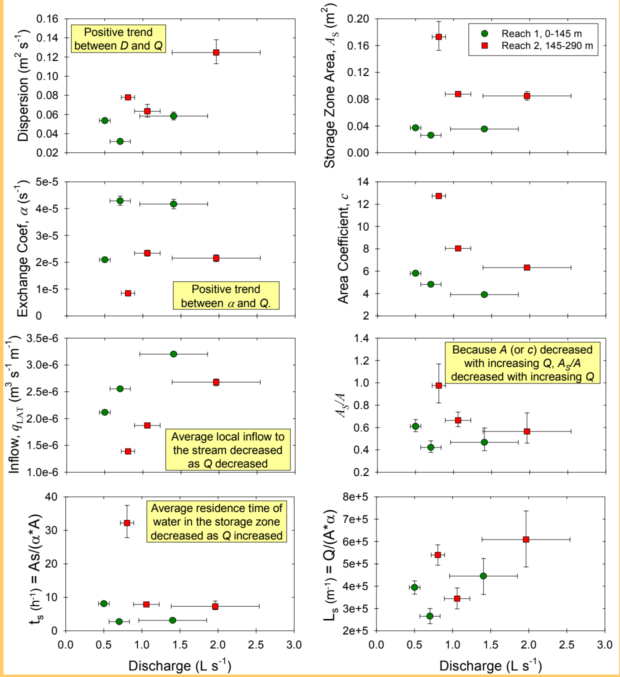


Figure 3. OTIS parameter and discharge (*Q*) relationships for both reaches. Symbols represent best-fit parameter estimate and mean *Q*, bars represent parameter 95% confidence intervals and the range of *Q* for a particular experiment.

- CSS values generally increase for each parameter at lower *Q* (except $A_{S,1}$ and c_2).
- CSS values are highest for q_{LAT}, and lowest for *D* in all experiments.
- α CSS values are higher than A_S CSS values for all experiments.

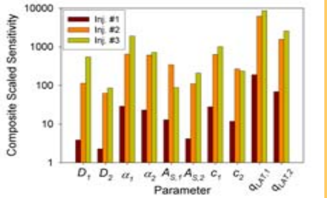


Figure 4. OTIS parameter composite scaled sensitivities (CSS) for each experiment. CSSs represent the potential to confidently optimize a parameter from a particular data set.

RESULTS AND DISCUSSION

FIELD/DEM ANALYSIS RESULTS/DISCUSSION

Streambed slope and cumulative elevation demonstrate the variability in stream gradient for each reach. The average slope ranges from 9% to 6.5% from reach to reach, but more importantly, the range of variability for each 10 meters of stream section is 4% to 14%. Stream morphology is hypothesized to be a strong driver of stream hyporheic exchange.

Local inflow of area to the stream channel was computed from the catchment digital elevation model by calculating the incremental increase in catchment area from stream cell-to-stream cell in a downstream direction. The range of local inflow is greatest in the headwaters where the catchment exhibits the greatest topographic convergence and decreases toward the catchment outlet. The pattern of local inflow area reflects the highly dissected nature of the catchment topography. The catchments at Maimai are comprised of regularly alternating spur-hollow sequences with greatest topographic convergence in the headwaters.

Local inflow of water to the stream channel was computed from synoptic stream samples collected every 10-20 meters during the first two steady state Br^- tracer injections. The following equation was used to calculate discharge at each synoptic sampling point.

$$Q_{\text{stream}} = \frac{(Q_{\text{injectate}})(Br^-_{\text{injectate}})}{Br^-_{\text{stream}}}$$

Local inflow was then calculated for each reach by subtracting the upstream discharge from the downstream discharge.

$$Q_{\text{local inflow}} = Q_{\text{upstream}} - Q_{\text{downstream}}$$

Local $\delta^{18}O$ and SiO_2 inflow to the stream channel

Local inflow solute and $\delta^{18}O$ concentrations were calculated based on synoptic stream samples and calculated local inflow of water (incremental increases in discharge). This approach allows for calculation of the mass and concentration of solutes entering the stream between each sampling point.

$$C_{\text{local inflow}} = \frac{\dfrac{(Q_{\text{upstream}})(C_{\text{upstream}})}{(Q_{\text{downstream}})(C_{\text{downstream}})}}{Q_{\text{local inflow}}}$$

In some instances 10 meter sampling intervals were too short for accurate calculation of local inflow concentrations because the precision of the Br^- analysis and the precision of the solute and isotopic data. Uncertainty analysis such as that used in hydrograph separation studies will be necessary to quantify significance from reach to reach. Despite this caveat, the data suggests that local inflows solute and $\delta^{18}O$ concentrations are highly variable from stream reach to stream reach. We suggest that combined with transient storage modeling during multiple discharge magnitudes, synoptic sampling can elucidate stream catchment connections. More specifically, this approach can provide insight into the relationship between topographic variables such as local inflow and incremental inflows of water and solutes to stream channels.

DISCUSSION OF MODELLING RESULTS:

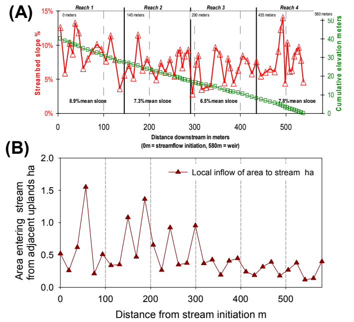
These results support previous assertions that **hyporheic exchange potential increases at lower discharge, as evidenced by 1) positive relationships between *a* and *Q* and 2) increasing CSS values for *a* in each sequential (lower *Q*) experiment**. However, the uncertainty associated with A_S parameterization in Reach 2, and the negative relationship between A_S and *Q* in Reach 2, but a generally positive relationship between A_S and *Q* in Reach 1, **suggests that greater relative storage zone area at lower discharge is an equivocal conclusion**.

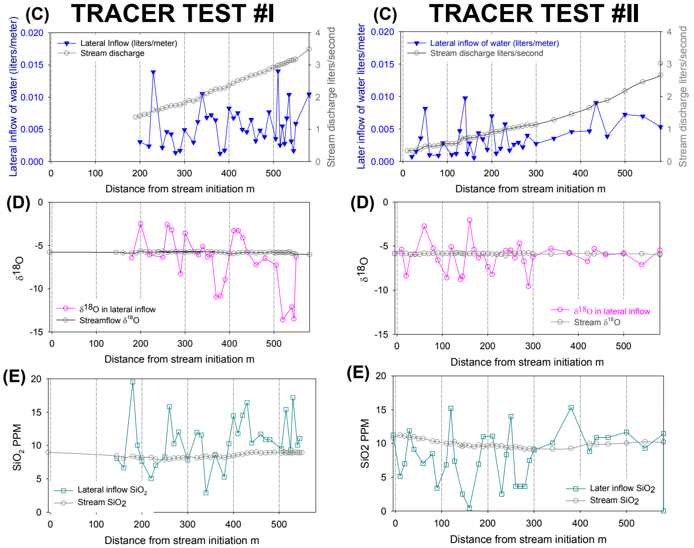
Using UCODE to obtain 95% confidence intervals for parameter estimates and CSS values allowed us to evaluate the relative confidence in the OTIS model parameterization. Our results suggest that in general, at lower discharges, there is greater information available within data sets for *D*, *a*, *A* (or *c*), and q_{LAT}. Estimates of A_S were not as robust, as evidenced by the CSS value trend and the larger 95% confidence intervals obtained. **This suggests that comparisons of A_S/A should be made with great caution when comparing different reaches, particularly in different streams**.

PART II STEADY STATE SYNOPTIC SAMPLING

Figure 5A-E. We synoptically sampled the stream every 10 meters from the tracer injection point to the catchment outlet during the first and second steady-state tracer tests. We surveyed the stream channel elevation at each sampling point and calculated streambed slope. In addition, we calculated the incremental increase in catchment area for each stream cell (20 meters) along the stream. (A) Streambed slope and cumulative stream elevation, (B) Local inflow of area along the stream, (C) Computed later inflow of water along the stream network, (D) $\delta^{18}O$ in streamwater and local inflow, and (E) SiO_2 in streamwater and local inflow.

STREAM MORPHOLOGY





CONCLUSIONS

- **The storage zone area to stream area ratio (A_S/A) increased with decreasing stream discharge and average local inflows to the stream decreased as stream discharge decreased. This effect was more pronounced in the headwaters where baseflow decreased at a higher rate than in reaches closer to the catchment outlet.**
- **We also tested the linkage between local subsurface water inflow to the stream channel and local upland accumulated area. We found suggestion of a linkage between topography and incremental changes in discharge. We plan to more fully assess the significance of this relationship.**
- **We found pronounced variability in $\delta^{18}O$ and of SiO2 concentrations in local inflow of water to each stream reach. Uncertainty analysis is required for quantitative assessment, however our results suggest local inflows can be highly variable. This information is masked in synoptic stream sampling results that do not include high resolution quantification of incremental changes in stream discharge.**

A more enhanced understanding of transient storage within particular reaches is possible with analysis of stream–upland connections and repeated solute tracer experiments at varying discharge. One test at one discharge does not provide adequate comparison to either the same reach at another discharge, or another stream system.

References:
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Runkel, R. L. 1998. One-dimensional transport with inflow and storage (OTIS): A solute transport model for streams and rivers. U.S. Geological Survey. Water Resources Investigations Report 98-4018. [http://co.water.usgs.gov/otis/]

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