# A combined computational and experimental approach to quantifying habitat complexity in Scottish upland streams

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**Abstract** Stream metabolism studies offer tremendous potential insights into the effects of climate and land-use change on aquatic ecosystems. Both temperature and habitat complexity (i.e. the physical nature of the stream bed and surrounding environs) are thought to be important determinants of stream metabolism. In this paper the authors describe a combined computational and experimental approach for characterising and quantifying relevant features of stream channels using the concept of transient storage. In this the main channel is enveloped by a transient storage zone, which is characterised by the volume of stream bed interstices and other stagnant water regions and the rate at which material is transferred into and out of these regions. By fitting a model of stream solute transport, which incorporates these mechanisms (and parameters), to tracer data obtained from field experiments we can estimate these parameters for the stream in question. In this paper we use a series of tracer studies from two small Scottish streams and focus particularly on how one the transient storage parameters scales with stream discharge.

**Keywords** tracer studies; rivers; MATLAB; numerical method; advection; model fitting

## INTRODUCTION

Stream metabolism studies offer tremendous potential insights into the effects of climate and land-use change on aquatic ecosystems. In-stream habitat complexity (i.e. the physical nature of the stream bed and surrounding environs) is thought to be an important determinant of stream metabolism [Crenshaw & Webster, 2002]. Measuring habitat complexity is rather challenging [Salehin et al, 2003]. The physical stream habitat (e.g. riffles, backwater pools, glides, plunge pools) is shaped by hydrology, geology and vegetation (both live *in situ* plants and dead material, e.g. log jams). Assessing and quantifying the physical stream habitat is usually accomplished by means of a time-consuming and expensive visual survey [Kemp et al., 1999]. But the physical habitat complexity should be strongly related to the quantity and characteristics of stream bed interstices and other stagnant water regions and the spatial heterogeneity of these features [Zarnetske et al., 2007]. Consider, for example, the lack of stream habitat complexity in a smooth concrete channel as an extreme case. The authors have been developing a combined computational and experimental approach for quantifying the nature and size of stream bed interstices and other stagnant water regions that occur in natural channels; this total volume is often referred to as the stream transient storage. We propose that the stream physical habitat complexity might be quantified quickly through correlation with the surrogate parameters that describe the stream transient storage. In this paper we describe recent work on this topic.

Specifically, we describe the combined experimental and computational methodology for quantifying the stream transient storage. The method starts with a tracer study in which we introduce a pulse of conductivity into the freshwater stream in question by adding a small mass of salt (NaCl). We then observe how this conductivity pulse changes as it moves through the stream by measuring conductivity versus time at two locations on the stream. Figure 2 shows a typical pair of measured conductivity versus time profiles. Next we take the observed upstream conductivity versus time profile and predict how it would be altered in shape and translated downstream based on a theoretical model of stream transport processes. Finally we optimise the parameters of the model (main channel velocity and dispersion; transient storage volume and exchange rate) until we find the combination of parameters that gives the best agreement with the observed downstream conductivity versus time profile. By repeating the experimental and modelling exercises for various streams and flow conditions we seek to build up a picture of stream habitat complexity in these streams. Combining results from several streams allows correlations with gross stream parameters to be identified. We demonstrate the application of the approach to small Scottish streams.

Stream solute transport is often modeled using the advection-dispersion equation (ADE). This two-parameter model is characterized by the stream velocity, u, and the dispersion coefficient, D, that represent advective and dispersive transport, respectively. Although these are inherently spatially variable, the model represents the processes in terms of reach average values. However, the ADE does not adequately represent the long and elevated tails found in some observed tracer data, which are caused by transient storage. Transient storage zones include recirculation areas, streambed irregularities and bed sediment interstices. Transient storage zones (the physical manifestation of habitat complexity) are thought to be important for nutrient cycling and stream metabolism [DeAngelis *et al*, 1995], and have long been recognised as playing an important role in the transport of dissolved or suspended materials in rivers [Sabol & Nordin, 1978; Valentine & Wood, 1979; Worman et al, 2002]. In the modeling context, the storage zones are characterized by their size (cross-sectional area, $A_s$), and the rate at which solute mass is transferred into and out of them (exchange rate, $\alpha$). Including transient storage in the ADE model gives an enhanced model that has four characterizing parameters.

The parameters of both the standard and enhanced ADE models may be found by fitting the model to observed solute concentration data, and by identifying the parameter values that minimise an appropriate objective function, defined as the difference between predicted and observed concentrations, we can estimate the optimum model parameters. However, by their very nature, the models are implemented using numerical solutions to governing partial differential equations. When casting models via numerical solutions it is important to use a numerical method that is known to be free of problems such as numerical diffusion and grid scale oscillations. The authors' semi-Lagrangian method DISCUS (Domain of Influence Search for Convective Unconditional Stability) is one such approach that has been successfully applied to a wide range of fluvial scenarios for more than a decade [Wallis *et al*, 1998; Manson & Wallis, 1999; Neelz & Wallis, 2007]. As well as being accurate, numerically robust and computationally efficient the semi-Lagrangian approach is also particularly attractive for optimisation problems because it caters well for the use of large time steps. The method's complexity and its various computational nuances can be a barrier to its use by non-specialists, however, the authors have recently created a user callable function for the popular computational tool, MATLAB, so that users may be shielded from some of the technical details, if they so wish.

## MODEL DESCRIPTION

The enhanced ADE model then, which describes one-dimensional solute transport in steady, non-uniform flows in rivers with transient storage is described by:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} = D\frac{\partial^2 c}{\partial x^2} + \alpha(s - c) \tag{1}$$

$$\frac{\partial s}{\partial t} = -\alpha\frac{A}{A_s}(s - c) \tag{2}$$

where c(x,t) is the concentration of solute in the main channel, s(x,t) is the concentration of solute in the transient storage zone, A is the main channel cross-sectional area, x is the longitudinal spatial co-ordinate and t is time (u, D, $\alpha$ and $A_s$ have been previously defined). The following boundary conditions are frequently used with these equations. At the upstream boundary a concentration versus time curve specifies the solute mass entering the computational domain; at the downstream boundary a zero diffusive flux is assumed which implies that solute is carried out of the domain unhindered.

Equations (1) and (2) were solved using a finite volume approach in space (with space step, $\Delta$x), evaluating the advection term explicitly in time and evaluating the dispersion and transient storage terms implicitly in time. The DISCUS method was used for the advective term in equation (1) [Wallis *et al*, 1998; Manson & Wallis, 1999; Manson & Wallis, 2000; Manson et al, 2001] and the Crank-Nicolson method was used for the dispersion term and the transient storage term in equation (1) and for equation (2) because it is unconditionally stable and robust. It is also superior to the fully implicit method used previously [Manson *et al*, 2001] being second order accurate in time.

When equations (1) and (2) are solved the solution consists of estimates for c and s over some discretised spatial and temporal domain, i.e. $(c_i^n, s_i^n)$ for i=1 to N and n=1 to T where N is the number of cells in the spatial domain and T is the number of computational points in the temporal domain. When the model is fitted to data that has been observed at a downstream location then a fitting parameter may be defined as,

$$R = \sum_{n=1}^{T}\left(Observed_N^n - Model_N^n\right)^2 \tag{3}$$

so that an R value of zero indicates a perfect fit. Only main channel concentration was used for the fitting, because concentrations in the storage zones were not measured.

The current implementation of the model used an existing FORTRAN code which solves equations (1) and (2) using the techniques described earlier. The FORTRAN code consisted of a subroutine that takes the concentration-time curve at an upstream location and predicts the concentration-time curve at a downstream location subject to given parameters (u, D, $\alpha$, $A_s$, N, T, $\Delta t$ and $\Delta x$). The FORTRAN subroutine (discus.f) was combined with the code required by MATLAB and then compiled using the GNU FORTRAN compiler (g77) to create object code (discus.o) and then linked with the "fmexlib*" object libraries to create the final MATLAB callable function (discus.dll). The MATLAB function is available from the first author by email. The new function was employed using MATLAB's fminsearch tool to find the best set of parameter values [u, D, $\alpha$, $A_s$] which would fit the model equations (1) and (2) to the tracer data.

## FIELD SITE AND TRACER STUDIES

The study area was located within the Glensaugh Research Station of the Macaulay Institute in north-east Scotland (Long 2º 33' W, Lat 57º 55' N). The catchment areas of the studied streams (Cairn Burn and Birnie Burn) are < 1 $km^2$ and lie within a 265-450 m altitude range. Annual average precipitation and evapotranspiration are 1040 mm and 300 mm, respectively. The area lies just to the North of the Highland Boundary Fault, and contains soils of the Strichen Association developed on glacial drifts.

**Figure 1:** Photograph showing the streams and the surrounding landscape. Streams are indicated with arrows. Cairn Burn is to the left; Birnie Burn is to the right.

At the top of the catchment the soils are mainly hill peat (2 m deep on average), whilst at lower altitudes freely-drained humus iron podzols predominate. The streams, which are 0.5-1.0 m wide, drain incised valleys of rounded hilltops (see Fig. 2). Small surface water flushes on the main hill-slope feed the main stream. The catchment is used for hill farming: mixed grazing of sheep and cattle. The vegetation cover is predominantly grass and heather with rushes growing in the flushes and bracken on the hill slope along the stream. The management of the land includes the regular heather burning (10-12% of surface area yearly target).

Several tracer (NaCl) releases were undertaken under stable flow conditions in two streams and the eight most reliable data sets were used for analyses. Generally a 50 L carboy was partially filled with stream water and several kg of NaCl. The solution was then injected continuously using a Watson Marlow 504S/RL peristaltic pump. Sometimes, salt (NaCl) was added to stream water in a bucket and a slug injection performed. Conductivity was monitored below the mixing zone, at the top and bottom of the studied stream reaches (50-100 m long) using multiparameter sondes (YSI600XLM, Yellow Springs, Ohio) and a Campbell conductivity sensor and data logger. An independent measurement of discharge was also carried out at the lowest station of the Cairn Burn (using a calibrated flume, sonic sensor and Campbell data logger). Discharge estimates from the salt dilution gauging and the flume were extremely well correlated, with $Q_{flume}$=1.04(±0.01) $Q_{NaCl}$ ($r^2$=0.999; n=6; $P$<0.0001) spanning the whole range of flow conditions presented here.

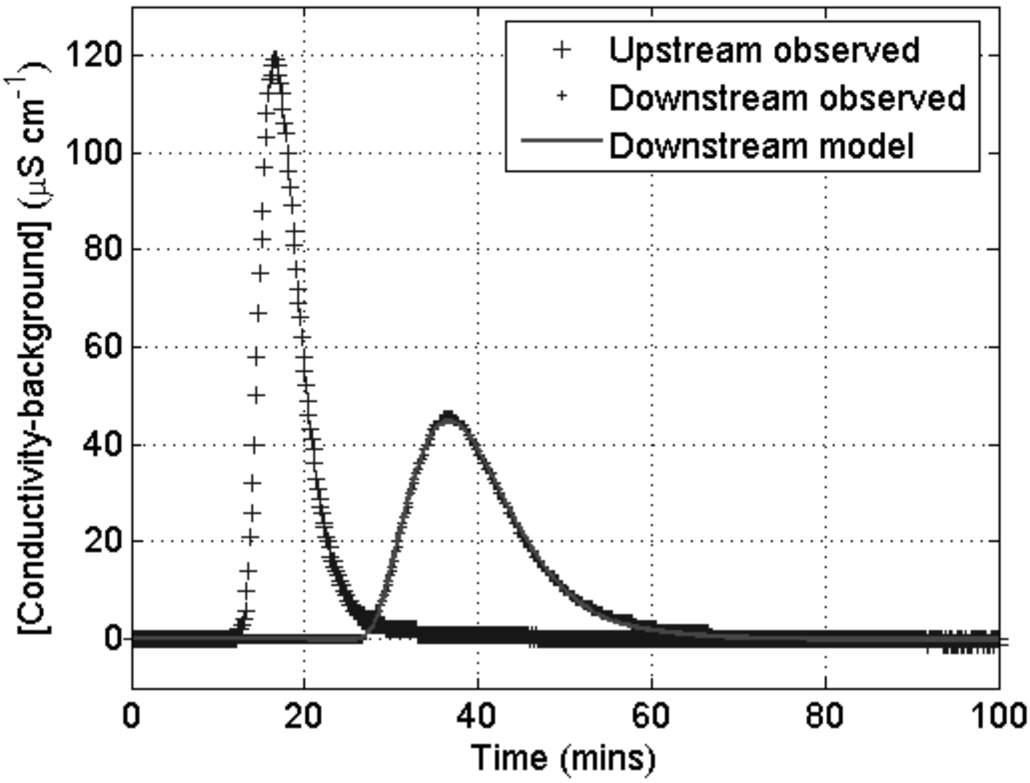


**Figure 2:** A typical tracer study result showing the conductivity (corrected to remove background conductivity) versus time measured at two locations on the Cairn Burn. Also shown is the optimised model output.

## RESULTS AND DISCUSSION

Eight tracer studies from the Birnie Burn and the Cairn Burn were analysed to ascertain the required stream transport parameters (u, D, $\alpha$, $A_s$). Figure 3 shows an how the exchange parameter varies with stream discharge. Results indicate a weak power law relationship between the two variables (r=0.46, n=8). The magnitude of the exchange parameter indicated residence times in the storage zones on the order of minutes (5-25mins) which seems reasonable. This suggests that the exchange parameter scales with stream discharge. This makes sense physically for two reasons: (1) at higher flows and velocities there will be greater turbulent diffusion which will enhance solute exchange between the main channel and the storage zones and (2) at higher velocities there will be a stronger and steeper shear layer with a, therefore, enhanced concentration gradient driving the exchange.

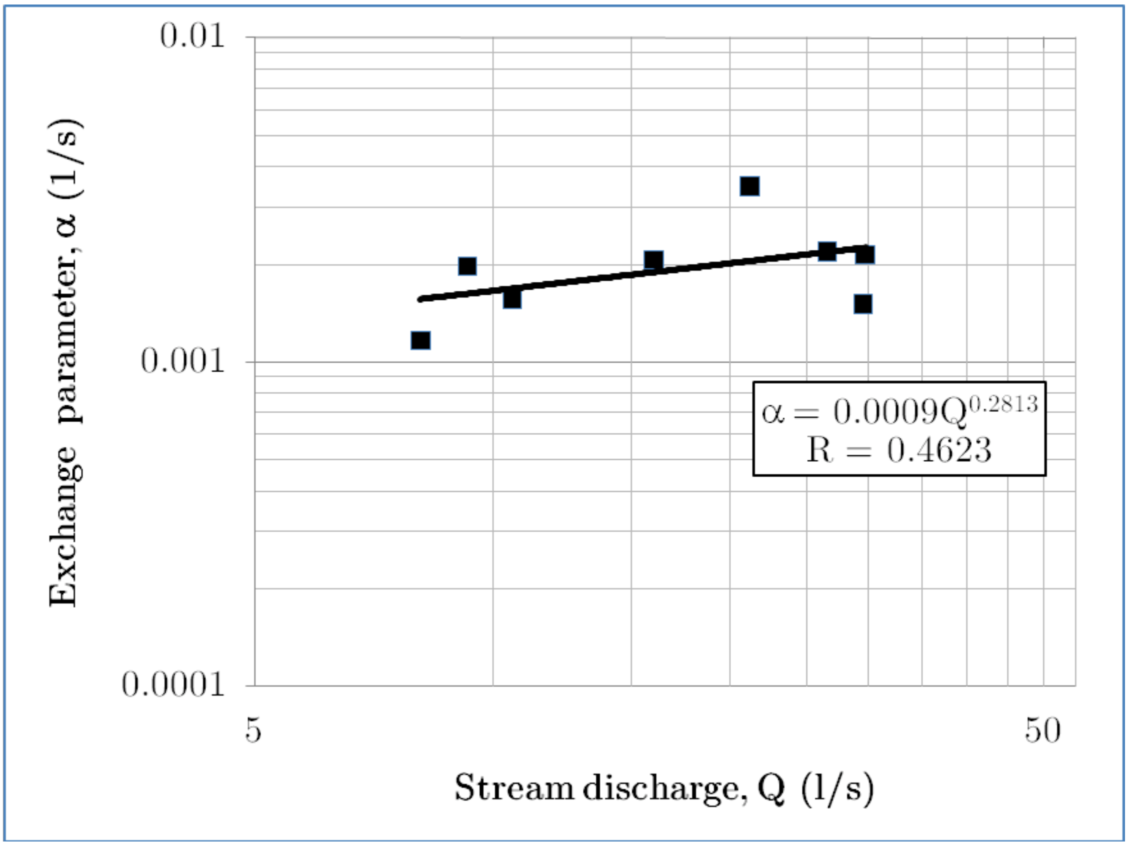


**Figure 3:** Values of the exchange parameter plotted against stream discharge for the two experimental streams.

The storage volume fraction for these streams varied from 20% to 40% of the main channel area and was found to scale inversely with stream discharge (R=0.835, n=8). This also makes sense; at higher flows (and depths) the transient storage zone (which is largely in the bed) becomes a lesser fraction of the total flow area. The actual storage volume is likely to be heavily influenced by geomorphology, geology and other factors independent of flow characteristics [Stofleth et al, 2007].

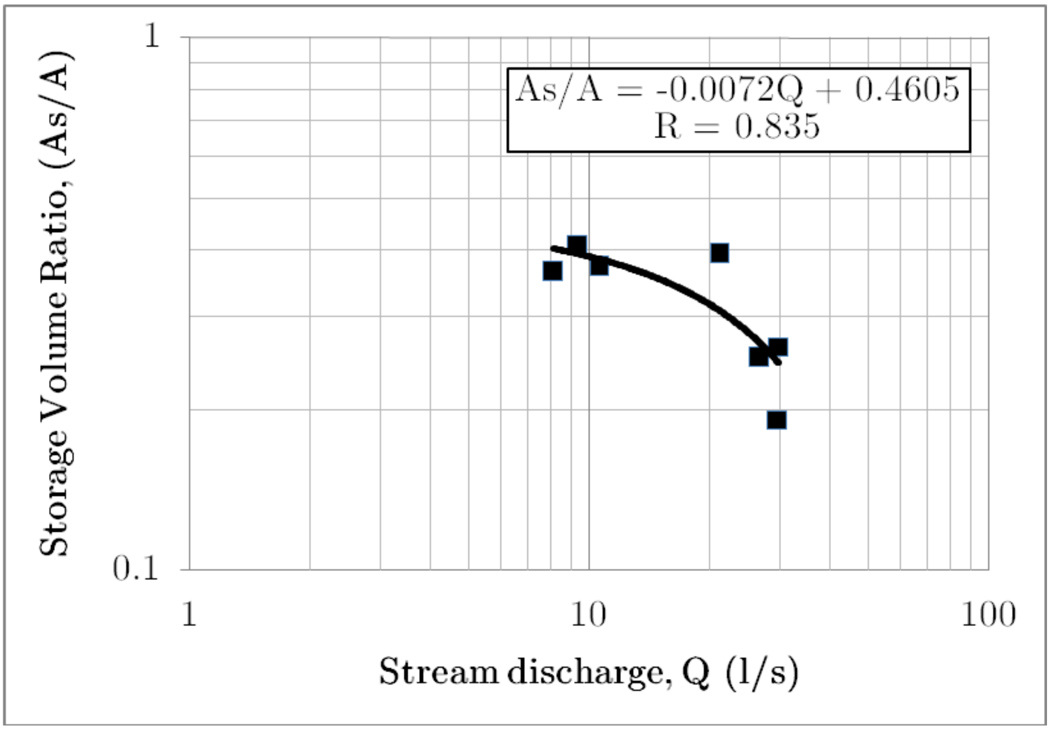


**Figure 4:** Values of the storage volume parameter plotted against stream discharge for the two experimental streams.

## CONCLUSIONS

We described a combined computational and experimental approach for characterising and quantifying the "transient storage zone" in upland Scottish streams. The zone is characterised by the stream bed interstices and other stagnant water regions that occur in natural channels in terms of their total volume and the rate at which material is transferred in and out of these regions. These regions represent a multitude of micro-environments for biota to survive in and hence the volume of these regions should correlate with habitat complexity. We found that for these streams the storage zone volume was about 20% to 40% of the main channel area and varies inversely with flow. An exchange parameter describing how fast mass moves in and out of the storage zone ($\alpha$) was found to correlate (albeit weakly) with flow. Further work is required to better understand how combined field experiments and computational analyses may be refined to better understand such systems.

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