Executive Summary

The complexity of water flow paths and storages in a catchment has been a central focus in catchment hydrology since the early work of Horton. Recent reviews have indicated that basic questions such as “Where does water go when it rains?”; “What pathway does water take to the stream?”; and “How long does water reside in the catchment?” are still not well understood. Advances in our understanding of catchment hydrology will require both upward (field-based) and downward (modeling) approaches to answer these very basic questions.

The water residence time distribution is a fundamental description of flow path diversity and transport time (and storage), and thus, is critical in answering the questions above. Residence time is closely related to the quality of water draining catchments and is therefore tied to land management activities. Recently, residence time distributions have been determined for whole catchments, hillslopes, and stream/hyporheic zones. However, there has been very limited work done to integrate these landscape units in order to develop a better understanding of the effect of landscape organization on residence time. Scaling research in general has been lacking empirical data and process-level information to adequately develop relationships between scale and hydrological processes. Residence time also offers an ability to extend that information across scale.

The inspection of rainfall-runoff relationships shows that streams react quickly to rainfall events, but recede slowly between events. This simple phenomenon presents a challenge in runoff generation theory because during an event, pre-event water with a certain age distribution and a particular fraction of new rainwater are transferred to the stream with potentially different transfer functions and respective ages. Yet, most event-based studies do not consider the distribution of residence time and only separate the storm runoff into two time components (i.e. pre-event and event). The residence time distribution of event water (i.e. new rainfall), which is often mistakenly assumed to be instantaneous, is necessary for the elucidation of runoff processes, and is a potentially useful comparison tool between catchments or events. Alternatively, residence time studies have focused on baseflow conditions and have not considered event periods in estimating the residence time distribution. The integration of event and inter-event timescales would provide more accurate distributions of residence time and allow researchers to ask questions about dynamic and non-dynamic hydrological processes to develop better runoff generation conceptual models.

Historically, residence time has been estimated using “black-box” models where theoretical distributions were parameterized by an inverse procedure comparing simulated tracer output with conservative tracer observations during baseflow. Oxygen-18 of water ($\delta^{18}O$) is an ideal tracer for this purpose because it is part of the water molecule, applied naturally during precipitation events, and only changes composition by mixing with other water. Information about hydrological processes and uncertainty due to input (tracer and rainfall) variability has not been incorporated into the determination of the residence time distribution. Coupling hydrometric measurements, such as spatial rainfall, soil matric potentials, and groundwater levels, with tracer experiments will provide the necessary information for the selection of appropriate theoretical residence time distributions to include in black-box models. However, the plausibility of the residence time distribution to explain hydrological processes decreases with added catchment complexity and increased basin scale. Thus, the examination of individual landscape units is important to reconcile the integrated transport behavior of a catchment.

This study, as defined by the objectives below, presents a new approach to examining hydrological processes in a landscape context. First, by breaking up the landscape into runoff production units and targeting key field experiments within each unit, I hope to learn about how catchment components influence the distribution of residence times in space. Landscape discretization is extremely valuable because it provides a framework upon which to integrate the observed processes and conceptual models at the larger landscape level. Second, I hope to improve residence time estimation techniques through the development of a new model that links explicitly to hydrological processes in a catchment and incorporates both event and between-event periods. Lastly, my goal is to provide an empirically based hydrological underpinning to the development and use of residence time in a catchment and larger landscape context.
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| **Objective 1:** To characterize transport and hydrological processes in basic landscape units (i.e. hillslope, riparian zone, stream channel) to identify first-order controls on residence time distributions (RTDs) | H1: Solute and hydrological response from each landscape unit are related to the relative volumes of stored mobile water. 
H2: Water residence time is controlled by upslope flow path lengths, degree of dispersion along those flow paths, and relative mixing volumes between landscape units. 
H3: Stream channel RTD is negatively flow dependent, and thus only affects catchment RTD during baseflow conditions. |

**Approach:** Sites for experiments and instrumentation were selected to isolate landscape units deemed important in runoff generation – hillslopes, riparian zones, and stream channels. Two catchments at the H.J. Andrews [HJA] Experimental Forest (NSF-LTER) (8.5 and 10.2 ha)\(^8,19\) were selected to examine the influences of the riparian zone volume on the RTD: one catchment in which a debris flow removed the riparian storage volume, the other catchment with an intact riparian zone. The riparian zone was monitored with several wells at the hillslope/riparian zone interface. A separate hillslope was intensively monitored for continuous seepage and internally for soil matric potential, soil moisture, and groundwater levels to examine the effects of hillslope flow processes on residence time. This hillslope also has a very detailed dataset of soil hydrologic properties (i.e. K\(_{sat}\), soil water retention curves, bulk density) developed from 450 soil core samples\(^18\). Stream channel residence times and groundwater inflows were determined using steady-state solute tracer injections (rhodamine WT) under high and low baseflow conditions. At the hillslope scale, tracers (Amino G acid & Br\(^-\)) were applied to determine channel residence times and groundwater inflows were determined using steady-state solute tracer injections (rhodamine WT) under high and low baseflow conditions. 

**Objective 2:** To develop a new residence time modeling technique that incorporates uncertainty and the knowledge of hydrological processes | H1: The continuum of residence times in a catchment is determined by both event and inter-event hydrologic periods. 
H2: Lumped-parameter residence time models are strongly influenced by seasonal recharge variability. 
H3: Spatial input variability (i.e. isotopic composition and rainfall amount) can be used to constrain model uncertainty. |

**Approach:** A new model will be developed based on the tracer (i.e. \(\delta^{18}O\)) transfer function approach\(^17\) by combining a non-linear loss input function to represent seasonally variable recharge (i.e. effective precipitation), and an instantaneous unit hydrograph module to determine the overall runoff response. The model combines two well-known techniques to provide both the transfer of solutes (i.e. transport) and water-flux (i.e. hydraulic potentials) using the convolution of tracer flux and a RTD, and the convolution of effective precipitation and an instantaneous unit hydrograph, respectively. I will develop new theoretical transfer functions (e.g. power-law) to address the tailing behavior of the RTD at the HJA. A Monte Carlo procedure will be used with the knowledge of spatio-temporal input variability to estimate uncertainty (i.e. parameter identifiability) in the model. Input variability of \(\delta^{18}O\) and rainfall will be determined using a spatial array of 40 bulk collectors (elevations: 480 to 1460 m), spaced approximately 1.5 km apart, together with several throughfall collectors for estimating the spatial effects on the model outcome. The Mediterranean climate of my sites is ideal for residence time analyses because the hydrologic regime is extremely seasonal with 80% of the precipitation falling during winter periods. This climate effect should produce strong isotopic patterns seasonally and allow for the examination of RTD tailing (due to better resolution during dry periods) and recharge variability. |

**Objective 3:** To estimate RTDs for multiple catchments (0.2 ha to 6200 ha) and to provide a framework to scale up residence time to the large-scale (6200 ha) | H1: A catchment RTD is equal to the linear superposition of hillslope RTDs. This, combined with catchment geometry and riparian volume, can explain the RTD. 
H2: Geomorphic structure (e.g. degree of convergence, soil depth, geomorphic reservoirs – e.g. deep-seated earthflows\(^20\)) can explain the differences between residence time distributions from various catchments. 
H3: RTD does not scale with basin area, but with landscape organization measures (e.g. median sub-catchment area\(^24\)) |

**Approach:** Ten catchment scales at the HJA, from a 0.2 ha hillslope to small (10 ha) and large (100 to 580 to 6200 ha) catchments, were sampled weekly for \(\delta^{18}O\) over 28 months. These data will be calibrated to simulated output derived from the residence time model developed in objective 2 to determine the RTD for each site. Parameters from the RTDs will be compared with topographic variables (e.g. slope, convergence, accumulation of sub-catchments) and land-type maps developed to delineate different hydrogeomorphic units\(^25\). This landscape analysis will provide a framework to scale up the results to the larger scale and explore the possible relationships between RTDs and mappable landscape attributes.

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Kevin McGuire – PhD Proposal Summary
References

4. Sivapalan, M. Process complexity at the hillslope scale, process simplicity at the watershed scale: is there a connection?, *Hydrological Processes*, in press.