AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE
10.1002/2014WR016124

Companion to *Hale et al.* [2016], doi:10.1002/2015WR017660.

Key Points:
- MTT scaling relationships controlled by bedrock permeability
- Similar catchment morphology and hydrologic regime can mask different MTTs
- Catchment intercomparison reveals difference in celerity-velocity relationships

Correspondence to:
V. C. Hale,
chale@nutterinc.com

Citation:
Hale, V. C., and J. J. McDonnell (2016), Effect of bedrock permeability on stream base flow mean transit time scaling relations: 1. A multiscale catchment intercomparison, *Water Resour. Res.*, *52*, 1358–1374, doi:10.1002/2014WR016124.

Received 13 JUL 2014
Accepted 17 MAR 2015
Accepted article online 12 FEB 2016
Published online 28 FEB 2016

Effect of bedrock permeability on stream base flow mean transit time scaling relations: 1. A multiscale catchment intercomparison

V. Cody Hale[1] and Jeffrey J. McDonnell[2]

[1]Nutter & Associates, Inc., Athens, Georgia, USA, [2]School of Geosciences, Global Institute for Water Security, National Hydrology Research Centre, University of Saskatchewan, Canada and Northern Rivers Institute, University of Aberdeen, Scotland, UK

Abstract The effect of bedrock permeability and underlying catchment boundaries on stream base flow mean transit time (MTT) and MTT scaling relationships in headwater catchments is poorly understood. Here we examine the effect of bedrock permeability on MTT and MTT scaling relations by comparing 15 nested research catchments in western Oregon; half within the HJ Andrews Experimental Forest and half at the site of the Alsea Watershed Study. The two sites share remarkably similar vegetation, topography, and climate and differ only in bedrock permeability (one poorly permeable volcanic rock and the other more permeable sandstone). We found longer MTTs in the catchments with more permeable fractured and weathered sandstone bedrock than in the catchments with tight, volcanic bedrock (on average, 6.2 versus 1.8 years, respectively). At the permeable bedrock site, 67% of the variance in MTT across catchments scales was explained by drainage area, with no significant correlation to topographic characteristics. The poorly permeable site had opposite scaling relations, where MTT showed no correlation to drainage area but the ratio of median flow path length to median flow path gradient explained 91% of the variance in MTT across seven catchment scales. Despite these differences, hydrometric analyses, including flow duration and recession analysis, and storm response analysis, show that the two sites share relatively indistinguishable hydrodynamic behavior. These results show that similar catchment forms and hydrologic regimes hide different subsurface routing, storage, and scaling behavior—a major issue if only hydrometric data are used to define hydrological similarity for assessing land use or climate change response.

1. Introduction

The effect of subsurface boundaries on flow and transport at the catchment scale is poorly understood. Improved understanding of these controls is critical for developing new constitutive relationships for catchments [e.g., *Beven*, 2006] and for better understanding the relative differences between velocities and celerities expressed at the catchment scale [*McDonnell and Beven*, 2014] as represented through water transit times and hydrograph response. Although much work has shown that bedrock geology is a dominant control on catchment flow dynamics in mountainous, headwater catchments [*Capell et al*., 2011; *Jefferson et al*., 2008; *Onda et al*., 2006; *Tague and Grant*, 2004], the effect of catchment bedrock lithology on stream water mean transit time (MTT) scaling relationships is relatively unknown. This knowledge gap exists despite growing bodies of ongoing work focused on two important research strands in catchment science: (1) the influence of catchment scale and landscape structure on MTT [e.g., *Broxton et al*., 2009; *Hrachowitz et al*., 2009; *McGlynn et al*., 2003; *McGuire et al*., 2005; *Rodgers et al*., 2005; *Tetzlaff et al*., 2009a; *Tetzlaff et al*., 2009b] and (2) the role of bedrock groundwater in runoff generation processes [e.g., *Anderson et al*., 1997; *Asano et al*., 2002; *Gabrielli et al*., 2012; *Haria and Shand*, 2004; *Kosugi et al*., 2006, 2011; *Millares et al*., 2009; *Soulsby et al*., 2007; *Wilson and Dietrich*, 1987]. While these efforts have progressed rather separately, few studies yet have isolated bedrock permeability, the geologic property affecting water movement through rock, to address how its control on the partitioning, storage, and release of water scales from small to large catchments (throughout this paper, unless otherwise specified, we use the term bedrock permeability to refer to the landscape-scale, bulk permeability of the bedrock, which is the combination of the primary permeability of the fresh rock matrix and secondary permeability created by fractures and weathering).

Although scaling is an "umbrella" problem common to nearly all aspects of hydrology and related disciplines [*Bloschl and Sivapalan*, 1995], one of the principal foci is developing relationships that connect catchment function across multiple scales [*Tetzlaff et al*., 2010]. Deriving scaling relationships that account for catchment function is a particularly important enterprise [*Sivapalan*, 2005] as it is a precursor for extending the process-based knowledge gained on experimental hillslopes and small catchments to larger, more management-relevant scales [*Tetzlaff et al*., 2008]. Thus, the ability to develop predictive models that work for the "right reasons" [*Kirchner*, 2006] (and are applicable outside of the comfort of data-dense research catchments) hinges on advancing these functional scaling relationships beyond specific sites to more broadly generalizable attributes [*McDonnell et al*., 2010; *Sivapalan*, 2003; *Soulsby et al*., 2010]. As a result of its inherent process-inference at the catchment scale, MTT has become a primary hydrologic research tool used in studies aiming to better understand the controls on catchment function and their scaling relationships [*McDonnell et al*., 2010; *Soulsby et al*., 2009].

Initial investigations of MTT scaling behavior set out to test the intuitive hypothesis that MTT increases with increasing catchment area [*McGlynn and McDonnell*, 2003; *McGuire et al*., 2005; *Rodgers et al*., 2005]. Although this hypothesis originated from preliminary findings by *DeWalle et al*. [1997] and *Soulsby et al*. [2000], to date, no studies have shown a strong correlation between catchment area and MTT [*Tetzlaff et al*., 2009b] (we do note that *Frisbee et al*. [2011] used geochemical tracers to infer greater contributions of longer residence time waters with increasing catchment scale). Instead, researchers have found that MTT is more closely linked to landscape organization [*McGlynn et al*., 2003], catchment topography [*McGuire et al*., 2005], soil type and drainage class [*Soulsby et al*., 2006], catchment aspect [*Broxton et al*., 2009], or some combination thereof [*Hrachowitz et al*., 2009; *Rodgers et al*., 2005]. *Tetzlaff et al*. [2009b] found no emergent relationship(s) between proxies of MTT and topographic indices when intercomparing the results of MTT studies performed across five geomorphic provinces. They suggested that the influence of subsurface permeability and connectivity may override any topographical controls on MTT.

Several recent studies have advanced our understanding of subsurface controls on the spatial variability of MTT at the hillslope and small headwater catchment scale ($<$5 km^2). *Asano et al*. [2002] and *Kabeya et al*. [2007] both showed that MTT was influenced by flow paths through bedrock while *Uchida* et *al*. [2006] and *Katsuyama et al*. [2010] implicated bedrock permeability as a dominant control on MTT. *Asano and Uchida* [2012] built on these findings and showed that the spatial variation of MTT for a group of nested catchments at the 4.27 km^2 Fudoji research site were linked to the depth of hydrologically active soil and bedrock, a metric that is fundamentally linked to bedrock permeability. These findings may provide a pathway to predicting MTT scaling behavior. However, it is unknown if the link between bedrock permeability and MTT holds over a large range of catchment scales or across contrasting geologies—a necessary next step research question.

Here we use a catchment intercomparison framework to investigate the role of bedrock permeability in setting MTT scaling relationships. We build on the work of *McGuire et al*. [2005], where they found strong relationships between flow path length and flow path gradient and MTT for seven variably sized (0.1–62 km^2) headwater catchments in the Western Cascades Range of Oregon, USA. We repeat the *McGuire et al*. [2005] analysis in a neighboring set of eight nested research catchments (0.12–86 km^2) in the central Coast Range of Oregon, less than 140 km to the west, having nearly identical climate, topography, and vegetation to the *McGuire et al*. [2005] catchments but contrasting lithology and structure which give rise to significantly different bedrock permeabilities. This unique experimental design, whereby a multiscale catchment hydrological study is replicated in another nearby mountain range sharing all of the same characteristics except bedrock, affords us the opportunity to isolate the permeability differences of the contrasting bedrocks to more fully explore the *Asano and Uchida* [2012] finding that the hydrologically active depth controls the spatial distribution of MTT. Further, we utilize streamflow measurements from a subset of the catchments to investigate how differences in the celerity and velocity of subsurface water movement might be controlled by bedrock permeability. Our specific questions are:

1. how does bedrock permeability influence MTT and MTT scaling relations across 15 subcatchments distributed equally across these two mesoscale catchments?; and
2. how do these similarities or differences relate to measureable rainfall-runoff characteristics?

2. Study Sites

2.1. Drift Creek Catchments-Central Oregon Coast Range

Our Coast Range research catchments lie within the upper Drift Creek subbasin (Figure 1) of the Alsea River in the central Oregon Coast Range. Drift Creek is a fourth-order stream draining a highly dissected mountainous

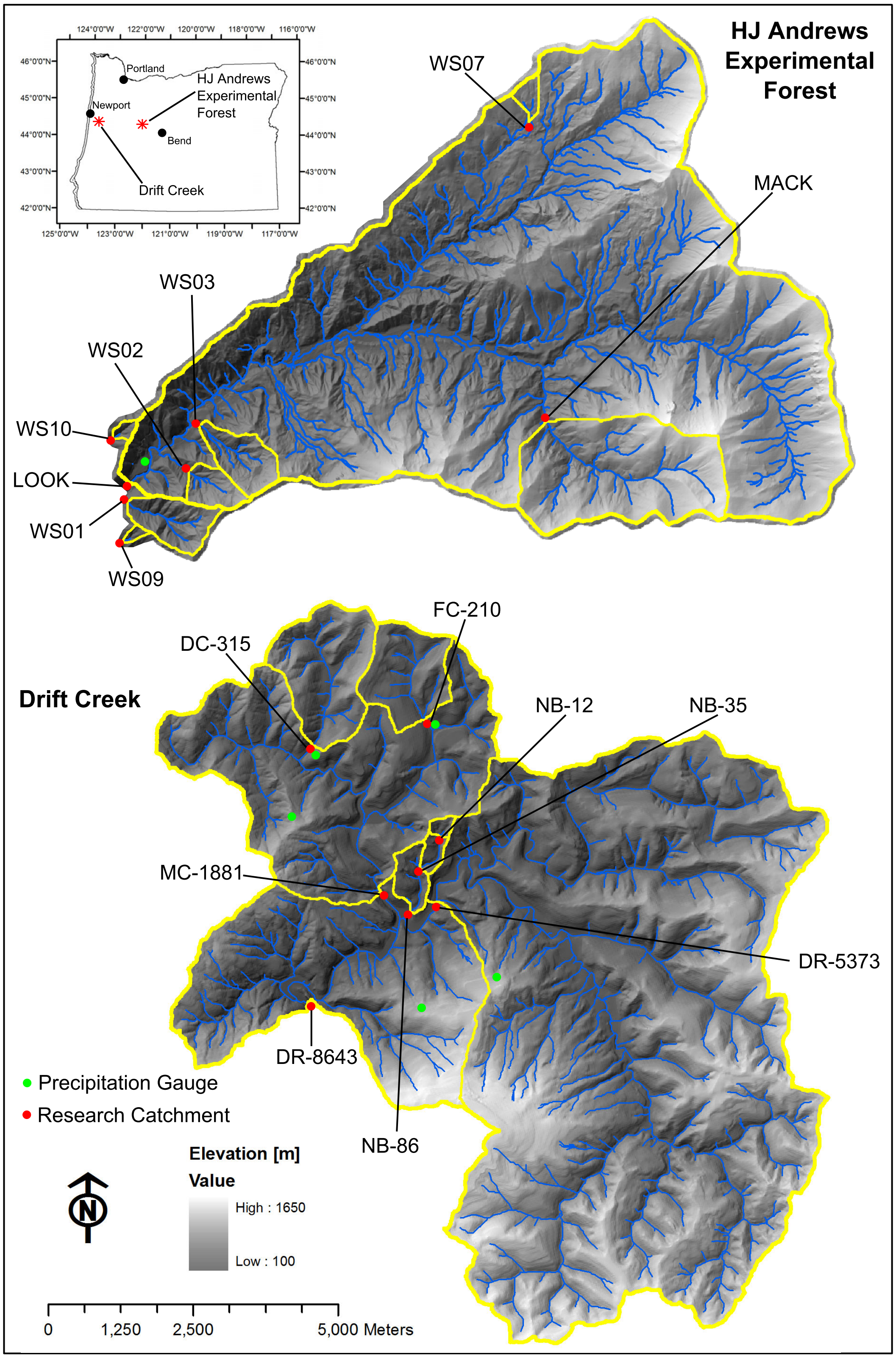

Figure 1. Map of the Drift Creek and HJ Andrews Experimental Forest with inlay showing their general locations within the state of Oregon. The research catchments and precipitation gauges used in this study are labeled.

Table 1. Summary of Drift Creek and the HJ Andrews Experimental Forest Characteristics

	Drift Creek	HJ Andrews
Geography		
Mountain range	Oregon coast range	Western cascades
Latitude/longitude	44.5°N 123.9°W	44.2°N 122.2°W
Elevation (m)	110–857	422–1628
Climate		
Mean annual precipitation (mm)	2500[a]	2800[a]
Precipitation seasonality	October–April[b]	October–April[b]
Snow accumulation	Occasional, but highly transient	Occasional but transient at lower elevation[c]; frequent with seasonal persistence at higher elevations[d]
Average maximum temperature (°C)	14.3[e]	16.5[f]
Average minimum temperature	5.4[e]	3.9[f]
Upland soils		
Texture	Loam to gravelly loam[g]	Loam to clay loam[h]
Hydraulic conductivity (mm h^{-1})	>1000[i]	>360[h]
Porosity (%)	70[i]	65[h]
Vegetation		
Dominant vegetation type	Evergreen conifer	Evergreen conifer
Primary canopy species	*Pseudotsuga menziesii, Tsuga heterophylla, Thuja plicata*, and *Alnus rubra*	*Pseudotsuga menziesii, Tsuga heterophylla, Thuja plicata, Abies procera, Abies amabilis*, and *Alnus rubra*

[a]PRISM 1971–2000 "normals" grid, PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 16 June 2006.
[b]On average, greater than 85% of the annual precipitation occurs from October–April in "long-duration, low-to-moderate intensity frontal storms" [*Harr*, 1976].
[c]*Bierlmaler and McKee* [1989].
[d]*Harr* [1981]; *Mazurkiewicz et al*. [2008].
[e]Normals published by Western Regional Climate Center for Alsea Fish Hatchery station (#350145) from 1954 to 2011.
[f]Derived from daily maximum and minimum temperatures measured at the PRIMET station from 1972 to 2011.
[g]*Corliss* [1973].
[h]*Ranken* [1974].
[i]Field measurements of saturated hydraulic conductivity at the Needle Branch experimental catchment were not possible in most hillslope locations using a constant-head permeameter [*Amoozegar*, 1989] due to extremely high conductivities (that exceed field permeametry limits of ~1000 mm h^{-1}). *Torres et al*. [1998] experienced the same problem using a Guelph Permeamter at Mettman Ridge. Hillslope soils at Mettman Ridge are the same mapped soil series as those in Drift Creek; therefore soil hydraulic properties measured at Mettman Ridge are assumed to be representative of those within Drift Creek.

area, characterized by short, steep slopes that give rise to medium to high-gradient stream channels [*Thorson et al*., 2003]. Needle Branch, a headwater tributary to Drift Creek has been gauged intermittently since 1959 as part of the Alsea Watershed Study (1959–1973) [*Harris*, 1977], and now part of the Alsea Watershed Study Revisited (2005–2019) [*Ice et al*., 2007; http://watershedsresearch.org/alsea/alsea-details.html]. The primary land cover in the catchment is coniferous forest, but several home sites exist. Residential wells for these homes represent the only water abstraction in the catchment and the abstraction rates are minimal with respect to the overall water balance. Small seeps occurring near the base of the hillslope are common along the stream corridors. The climate, soils, and vegetation of the area are summarized in Table 1.

The bedrock underlying the Drift Creek research area is the Eocene-aged Tyee Formation. The Tyee is composed of rhythmic-bedded layers of marine-derived greywacke sandstones and siltstones [*Snavely et al*., 1964]. The beds range from 0.6 to 3.0 m and average 0.9–1.5 m thickness. Boring logs from eleven wells installed in NB-12 and NB-86 show that the shallow bedrock is highly fractured with fracture density decreasing with depth (see Figure 2 for descriptions from two representative wells). Our onsite lithostratigraphic characterization is corroborated by boring logs from a series of shallow (to 5 m) wells and one 35 m geotechnical hole at the nearby (120 km south of our site) Mettman Ridge research site near Coos Bay, Oregon [*Montgomery et al*., 1997], which also overlies the Tyee Formation. *Snavely et al*. [1964] report that the primary porosity of the Tyee ranges from 5 to 21% (mean = 14%, n = 17) and the primary permeability 2.2E-16–4.4E-15 m^2 (mean = 2.7E-15 m^2; equivalent to 2.7 mD). These permeability values are within the range of expected values for local permeability of fresh sandstone [*Freeze and Cherry*, 1979] and match

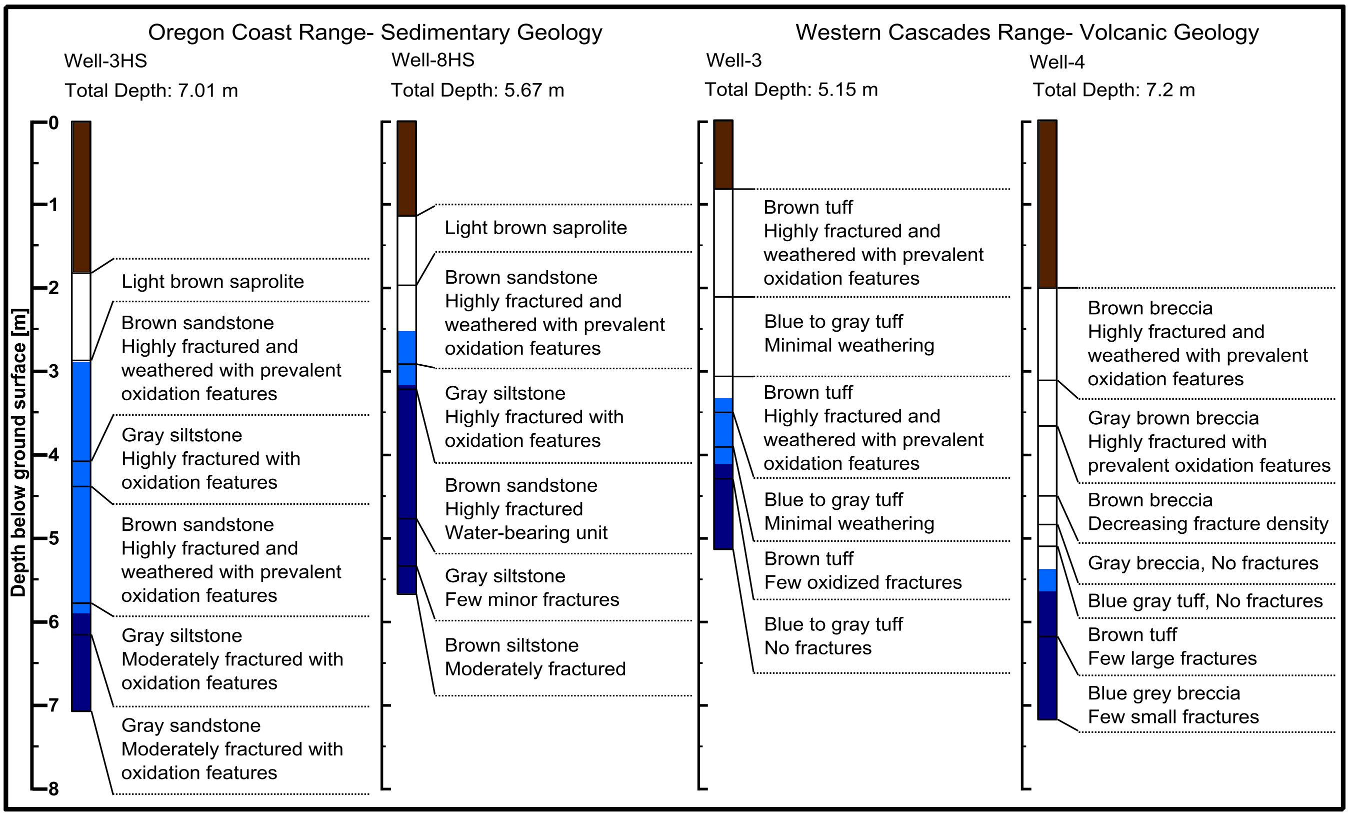

Figure 2. Boring logs from shallow bedrock wells installed within NB-12 in the Drift Creek basin of the Oregon Coast Range (Well-3HS and Well-8HS) and WS10 in the HJ Andrews Experimental Forest in the Western Cascades range (Well-3 and Well-4). Brown denotes soil, dark blue shows the minimum water level, and light blue shows the range of measured water level fluctuations.

recently reported landscape-scale estimates for this area [*Gleeson et al.*, 2011]. As a result of secondary permeability created by the extensive fracturing documented above, bulk permeability at our site is expected to be orders of magnitude higher than the primary permeability.

2.2. HJ Andrews Experimental Forest Catchments-Central Oregon Cascades

The HJ Andrews Experimental Forest (HJA; http://andrewsforest.oregonstate.edu/lter/) is located in the Western Cascades range near Blue River, Oregon, USA (Figure 1). The HJA is generally defined by the Lookout Creek drainage, which is a tributary to the Blue River and part of the larger McKenzie River basin of the central Cascades Range. Similar to the Coast Range catchments, the landscape of the HJA is steep, highly-dissected, and drained by medium to high-gradient streams [*Thorson et al.*, 2003]. Small seeps occurring near the base of the hillslope are common along the stream corridors. The climate, soils, and vegetation of the area are summarized in Table 1.

The bedrock geology consists of three mapped formations that occur as a function of elevation [*Swanson and James*, 1975]. At elevations less than 760 m, Oligocene to early-Miocene age hydrothermally-altered rock (massive breccias and tuffs) originating predominantly from mudflows and pyroclastic flows make up the Little Butte Formation. At elevations ranging from 760 to 1200 m, Miocene ash flows and basalt and andesite lava flows comprise the Sardine Formation. The Pliocascade Formation, consisting of Pliocene to early-Miocene andesite lava flows, underlies elevations greater than 1200 m. The permeability of these volcanically derived materials can be highly variable, but is generally a function of age [*Jefferson et al.*, 2010] and depth [*Saar and Manga*, 2004] as a result of hydrothermal alteration [*Ingebritsen et al.*, 1992]. Primary porosity ranges from 2 to 10% and primary permeability ranges from 5.0E-16 to 2.5E-14 m^2 (equivalent to 0.5–25 mD) for the rock types and ages underlying HJA [*Ingebritsen et al.*, 1992].

Fracturing associated with the cooling and shrinking of flow material is common near the top margin of individual flow units [*Peck et al.*, 1964], which can range from less than a meter to several tens of meters in thickness. Fractures connecting units vertically are associated with faulting [*Swanson and James*, 1975]. Boring logs from seven wells installed in a lower elevation catchment (Watershed 10 (WS10) [*Gabrielli et al.*, 2012], gauge elevation = 462 m) and six located in a higher elevation catchment (WS07, gauge elevation = 938 m) both indicate fracture densities grade from many to few within the top 3 m of the bedrock (see Figure 2 for representative borehole diagrams from WS10). Secondary permeability associated with these fractures therefore is only effective near the bedrock surface. Deep rock aquifers are present at the HJA as observed from a drinking water well installed to 88 m, but little is known about the water source, flow directions, or connectivity associated with these deeper units (the drinking water well supplies water for the HJA research facilities and is the only known abstraction well in the study catchment; water withdrawal from the well is believed to be minimal relative to the overall water balance and is therefore not considered in our analysis).

3. Methods

3.1. Terrain Analysis

Indices of catchment form and organization were derived from 10 m grid digital elevation models (DEM). Flow direction was defined by the D-infinity algorithm [*Tarboton*, 1997] and stream cells were identified using the area threshold method (2.5 ha threshold most closely matched field mapped channels). We then calculated slope (*S*), drainage density (D_d), area-to-perimeter ratio (*A-P*), subcatchment area (*SCA*) [*McGlynn and Seibert*, 2003], flow path length (*L*), flow path gradient (*G*), topographic wetness index (*TWI*) [*Beven and Kirkby*, 1979b], and downslope index (DSI_d) [*Hjerdt et al.*, 2004]. As the D-infinity algorithm splits flow between cells, *L* and *G* were determined using the weighted-average flow path length. For DSI_d, we set $d = 5$ m as that value was determined to be indicative for steep terrain [*Hjerdt et al.*, 2004] and to remain consistent with other intercomparison studies [*Tetzlaff et al.*, 2010].

3.2. Transit Time Estimation

Mean transit times of stream base flow were estimated by *McGuire et al.* [2005] for seven catchments within the HJA research area (WS02, WS03, WS08, WS09, WS10, MACK, and LOOK) using water isotopes in combination with lumped-parameter convolution models following the methodology of *Maloszewski and Zuber* [1982]. Water isotopes are ideal hydrological tracers as they are a part of the water molecule (rather than a separate molecule as typical of most artificial tracers) and, consequently, are fully conservative. Estimating MTT using the convolution approach assumes that the isotopic composition of the water coming out of the system, δ_{out} (stream water), will be equal to the composition of the water coming in, δ_{in} (precipitation), lagged by some time, τ, and weighted by the transit time distribution, $g(\tau)$, and recharge weighting function $w(t-\tau)$ (used to conserve tracer mass in the system by weighting δ_{in} according to the fraction of precipitation estimated to be contributing to recharge [*Stewart and McDonnell*, 1991]). This is expressed mathematically as,

$$\delta_{out}(t)=\frac{\int_0^\infty g(\tau)w(t-\tau)\delta_{in}(t-\tau)d\tau}{\int_0^\infty g(\tau)w(t-\tau)d\tau} \quad . \tag{1}$$

We used the same approach of *McGuire et al.* [2005] to estimate MTT for eight nested catchments in the Drift Creek basin (Figure 1; NB-12, NB-34, NB-86, FC-210, DC-315, MC-1881, DR-5373, and DR-8643). We used the deuterium (δ^2H) composition of precipitation and stream waters as δ_{in} and δ_{out}, respectively, in the lumped-parameter convolution models. We collected bulk precipitation samples at locations representing low, mid, and high-elevations within the Drift Creek basin on weekly to biweekly intervals from January 2006 through September 2010 (bulk collectors utilized a floating rubber disc to protect the accumulated precipitation from evaporation). Grab samples of stream water were collected by hand at the same frequency beginning in July 2007. All samples were protected from evaporation during storage through the use of glass vials with urea polyseal cone caps that eliminated head space and created an air-tight seal.

Water samples were analyzed for δ^2H composition using off-axis integrated cavity output laser spectroscopy on a Los Gatos Research Liquid Water Isotope Analyzer (LWIA-24d, Los Gatos Research, Inc.) at the Oregon State University Water Isotope Collaboratory. Laboratory standards were routinely verified using isotope ratio mass spectrometry (multiple laboratories). Analytical precision for δ^2H was 1.0‰ (using standard "delta" notation relative to Vienna Standard Mean Ocean Water).

Mean transit time estimation was accomplished using an inverse modeling procedure where the modeled δ^2H composition of streamflow was fitted to the measured δ^2H composition by iteratively adjusting the parameters of the transit time distribution, $g(\tau)$. We used the gamma model to approximate $g(\tau)$ as it has been shown to be more theoretically representative of real catchment systems than the more commonly used single-parameter exponential model [*Kirchner et al.*, 2000]. It is modeled as,

$$g(\tau)=\frac{\tau^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)}e^{\left(-\frac{\tau}{\beta}\right)} \tag{2}$$

where α is the shape parameter, β is the scale parameter, and the MTT is equal to $\alpha\beta$.

A model warm-up period of 15 years was used to "prime" the model before fitting the measured δ_{out} record [following *Hrachowitz et al.*, 2010a]. The warm-up data set was created by first extending the δ_{in} to the beginning of the 2006 water year using regression relationships ($r^2=0.63$) between δ_{in} and δ^2H values of precipitation collected at the US Environmental Protection Agency office in Corvallis, OR (Renee Brooks, unpublished data). The δ_{in} record was then looped three times to create the 15 year data set and appended to the beginning of the calibration data set.

Parameter and predictive uncertainty was estimated using a Bayesian approach [following *Hrachowitz et al.*, 2010a] where the posterior distribution, $p(\theta, \sigma|Y)$, of the parameters, θ, are related to the likelihood function, $p(Y|\theta,\sigma)$, and prior distribution of the parameters, $p(\theta,\sigma)$, as,

$$p(\theta,\sigma|Y)\propto p(Y|\theta,\sigma)p(\theta,\sigma) \tag{3}$$

and σ is the standard deviation. The prior distributions of the parameters were defined as $0<\alpha<3$ and $0<\beta<30{,}000$ and assumed to be distributed uniformly. The likelihood function is expressed as,

$$p(Y|\theta,\sigma)=\prod_{i=1}^{N_y}N\left(\xi_i(\theta,Y)|0,\sigma^2\right) \tag{4}$$

where $N(\xi_i(\theta,Y))$ is the distribution of the residual errors, ξ, assumed independent and following a normal distribution with mean, μ, and variance, σ^2.

We used a Markov Chain Monte Carlo (MCMC) search procedure implemented within the DREAM-ZS algorithm [*Schoups and Vrugt*, 2010] to sample the prior parameter distribution. We ran the search procedure for 15,000 iterations using three parallel chains to find the parameter set that maximized the log-likelihood function. Results from the first 5000 iterations were discarded as these were considered a warm-up period for the search algorithm. The remaining 10,000 iterations were used in the uncertainty estimation.

3.3. Hydrometric Analysis

We performed hydrometric analyses using hourly and daily streamflow and precipitation (Q_h, Q_d, P_h, and P_d, respectively) records from 1 October 2005 through 30 September 2009, with the exception of NB-12 where gauging did not begin until 1 October 2007. Precipitation inputs for NB-12 and NB-86 were taken as the areal average of a spatially distributed network of rain gauges present near the NB catchment (shown in Figure 1). The precipitation input for WS10 and WS01 was measured at the PRIMET meteorological station, which is the closest measurement point at the HJA (horizontally and in elevation; also shown in Figure 1).

For our intercomparison, we used basic hydrological statistics as well as several indices of hydrodynamic response [*Olden and Poff*, 2003; *Wagener et al.*, 2007] that were both relevant to our objectives and applicable based on the length of our data record. Basic statistics, such as mean annual flow (*MAF*), mean annual peak flow (*MAPF*), mean annual low flow (*MALF*), and coefficient of variation of stream discharge (CV_Q), were computed for each stream using the daily discharge record. We selected mean runoff ratio (R_{QP}), base flow index (*BFI*) [*Arnold et al.*, 1995], local slope of the flow duration curve between the 33rd and 66th flow percentiles ($FDC_{33\text{-}66}$) [*Sawicz et al.*, 2011], and the Richards-Baker flashiness index (FI_{RB}) [*Baker et al.*, 2004] as relevant hydrodynamic response indices. Runoff ratio and BFI were calculated using the constant-slope base flow separation method of *Hewlett and Hibbert* [1967] to be consistent with other forested headwater catchment research (slope = 0.55 L s^{-1} km^{-2} h^{-1}).

Table 2. Maximum Likelihood Estimates (mle) for the Alpha (α) and Beta (β) Parameters of the Gamma Transit Time Distribution Model, Mean Transit Times (MTT), Uncertainties, and Nash-Sutcliffe Efficiencies (NSE) for Catchments in the Drift Creek Basin in the Oregon Coast Range

Location	α_{mle}	$\alpha_{10/90\%}$	β_{mle} (y)	$\beta_{10/90\%}$ (y)	MTT_{mle} (y)	$MTT_{10/90\%}$ (y)	NSE_{mle}
NB-12	1.44	(1.01/1.46)	3.5	(2.9/8.2)	5.0	(4.0/8.7)	0.34
NB-35	1.48	(1.30/1.49)	2.5	(2.2/3.3)	3.7	(3.2/4.5)	0.38
NB-86	1.44	(1.28/1.49)	2.8	(2.4/3.7)	4.0	(3.5/4.9)	0.47
FC-210	1.33	(1.30/1.49)	4.7	(3.4/7.5)	6.3	(5.0/10.1)	0.30
DC-315	1.32	(0.98/1.46)	3.5	(2.6/12.5)	4.7	(3.7/11.6)	0.23
MC-1881	1.37	(1.04/1.47)	4.0	(3.0/13.7)	5.5	(4.3/14.0)	0.33
DR-5373	1.37	(1.22/1.50)	7.6	(5.6/10.8)	10.4	(8.3/15.7)	0.30
DR-8643	1.49	(1.42/1.51)	6.8	(5.3/12.8)	10.2	(7.8/18.3)	0.46

We compared event runoff (Q_{evt}) to total precipitation for a given event (P_{evt}) as a way to directly assess catchment response to precipitation inputs [*Graham and McDonnell*, 2010]. Our event rule specified that 5 mm or more of precipitation during a 12 h period was required to initiate the delineation of a precipitation event. Events were considered separate when a period of at least 10 h with mean precipitation intensity less than 0.1 mm h^{-1} occurred between them. Hydrograph separation was carried out using the previously described constant-slope method.

We used the recession coefficient as a metric for comparing how the catchments released stored water during base flow periods [*Brutsaert and Nieber*, 1977]. The base flow time series was developed using the constant-slope separation method described above. Additionally, recession periods with measured rainfall were removed from the analysis. Finally, time dependence was removed, such that,

$$-\frac{dQ}{dt}=f(Q) \tag{5}$$

where *f* can be described as a power law function [*Rupp and Woods*, 2008],

$$f(Q)=aQ^b \ . \tag{6}$$

The exponent, *b*, of the resulting fits was used to compare the behavior of the $-dQ/dt-Q$ relationships.

4. Results

4.1. Mean Transit Times and Scaling Relationships

Precipitation δ^2H values measured within the Drift Creek basin ranged from -120 to $-10‰$ and varied seasonally (lower values typically occurred during the colder winter months). No elevation effect was observed ($r^2 = 0.03$), so values from each bulk precipitation collector were used to create a spatially averaged precipitation δ^2H record as the model input, δ_{in}. Stream δ^2H values ranged from -55 to -45 ‰ and were highly damped compared to the precipitation record.

We compared our MTT estimates from the Drift Creek basin (Table 2) to values reported by *McGuire et al*. [2005] for seven catchments within the HJA (Table 3). Overall, MTTs were longer in the sedimentary Drift Creek catchments (3.7–10.4 years) than they were in the volcanic HJA catchments (0.8–3.3 years). Excluding WS08 (MTT = 3.3 years), which has deeper soils (>3 m) and is lower gradient (mean slope = 30%) than the other catchments *McGuire et al*. [2005] characterized, MTTs ranged from only 0.8 to 2.2 years at HJA. Mean transit times for NB-12 and NB-86 were 5.0 and 4.0 years; distinctly longer than for WS10 (1.2 years; Table 2) and WS01 (*McGuire et al*. [2005] did not estimate MTT for WS01. We therefore used the regression relationship between MTT and the ratio of median flow path length, L, and median flow path gradient, *G*, to estimate an MTT of 1.3 years for WS01 ($MTT=0.0021*(L/G)+0.71$; $r^2=0.91$).).

Unlike the *McGuire et al*. [2005] findings at the HJA, MTTs for the sedimentary Drift Creek catchments were not significantly correlated to median slope length *L*, median slope gradient *G*, or *L/G* at an alpha level of 0.05 (Figure 3). Instead, we found a significant positive relationship between MTT and basin area, $\log(A_c)$ ($r^2 = 0.67$, $p = 0.01$), at Drift Creek ($\log(A_c)$ was used in the analysis to better meet the normality assumption of the regression model, although A_c showed the same positive relationship). Correlation analysis showed, that in addition to A_c, MTT was positively correlated to *A-P* ($r = 0.91$, $p < 0.01$), a metric of catchment shape,

Table 3. Catchment Area (A_c), Mean Transit Times (MTT), Uncertainties, and Nash-Sutcliffe Efficiencies (NSE) Estimated Using the Exponential Transit Time Distribution for Catchments at the HJ Andrews Experimental Forest in the Western Cascades Range of Oregon (Data Sourced From *McGuire et al*. [2005])

Location	A_c (ha)	MTT (y)	MTT $\pm$ $2\sigma_p$ (y)	NSE
WS02	60.1	2.2	(1.6/2.8)	0.45
WS03	101.1	1.3	(1.0/1.6)	0.48
WS08	21.4	3.3	(2.0/4.6)	0.40
WS09	8.5	0.8	(0.6/1.0)	0.46
WS10	10.2	1.2	(0.9/1.5)	0.49
MACK	581	2.0	(1.5/2.5)	0.54
LOOK	6242	2.0	(1.0/3.0)	0.32

at Drift Creek (Table 4). At the HJA, median S was negatively correlated to MTT ($r = -0.86$, $p = 0.03$), which is not surprising given the topographic dependence already reported by *McGuire et al*. [2005].

The best-fit values of the gamma distribution's α parameter ranged from 1.3 to 1.5 for the Drift Creek catchments, resulting in the estimated transit time distributions (TTD) having a distinctly different shape than those of the HJA catchments (Figure 4). At Drift Creek, the probability density of transit times begins low for very short transit times, increases to a peak at transit times between 1 and 5 years, and then declines towards a long tail. Contrastingly, the probability density for the HJA catchments is greatest initially (i.e., at very short transit times) and decays with increasing transit time. Although *McGuire et al*. [2005] found the exponential distribution to be the best and most parsimonious approximation of the TTD for the HJA, the best-fit parameters for the gamma distribution (also reported by *McGuire et al*. [2005]) confirm the exponential shape (the exponential distribution is a special case of the gamma distribution where $\alpha = 1$). The reported best-fit α values for the HJA catchments ranged from 0.74 to 0.97, with the exception of WS08 where $\alpha = 1.23$ (see Table 3 in *McGuire et al*. [2005] for individual parameter values, uncertainty ranges, and fitting statistics). We note that the nontrivial uncertainty in parameter estimates for Drift Creek arise from use of the conservative tracer-convolution integral method at the upper extent of its applicable range (discussed further in section 5.3). However, the α parameter uncertainty ranges for Drift Creek being almost exclusively greater than 1 at Drift Creek and generally less than or equal to 1 at HJA indicate a clear difference in the general shape of the TTD between the two sites.

4.2. Hydrologic Response

In general, the annual hydrographs for the Drift Creek and HJA catchments selected for our analysis displayed the same seasonality, with distinct high flow and low flow periods (Figure 5). The high flow periods were marked by rapid rainfall-runoff response and the low flow periods were characterized by a gradual decline to annual minima. Precipitation totals were strikingly similar for the Drift Creek and HJA catchments in water years 2006 and 2007 (difference of 122 and -43 mm, respectively, Drift Creek minus HJA; water year spans from 1 October to 30 September), but Drift Creek was drier in water years 2008 and 2009 (by 569 and 542 mm, respectively).

Comparison of the hydrologic metrics for the four catchments generally supported the similarities observed in the stream hydrographs (Table 5; topographic indices are also presented in Table 5 for comparative purposes). Mean annual flow varied by only 0.75 mm d^{-1} and *MAPF* was within 5 mm d^{-1} across all of the catchments. The CV_Q, BFI, $FDC_{33\text{-}66}$, and FI_{RB} metrics were also in general agreement for all catchments. Differences in streamflow dynamics were indicated by a higher R_{QP} for the Drift Creek catchments, with NB-12 being significantly higher than the others (0.95). NB-12 was also different than the other catchments with respect to the recession coefficient, b; NB-12 had a b value of 1.64, while NB-86, WS10, and WS01 ranged from 1.10 to 1.23.

Flow duration analysis showed that the distributions of discharge magnitudes were comparable across catchments, particularly for the mid to upper flow ranges (Figure 6). Some separation amongst the duration curves is evident for exceedance probabilities of 0.70 and greater (relative to higher discharges), with NB-12 departing more significantly than the rest as a result of higher specific discharges in the low flow range. The rainfall-runoff dynamics, as represented by the relationship between Q_{evt} and P_{evt}, indicated that the catchments responded similarly to precipitation inputs (Figure 7).

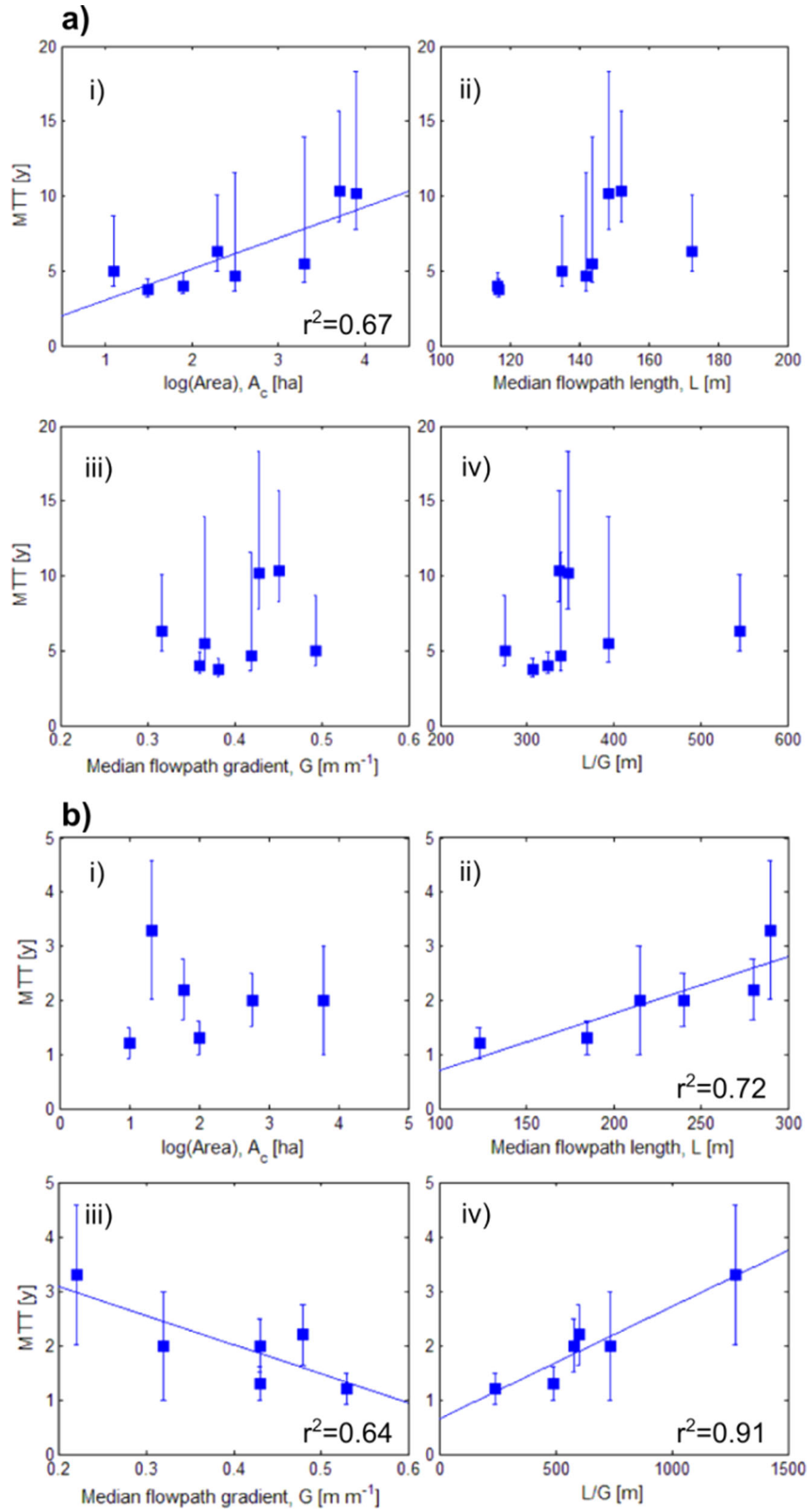

Figure 3. Mean transit time (MTT) as a function of the logarithm of (i) catchment area, (ii) median flow path length, (iii) median flow path gradient, and (iv) the ratio of median flow path length and flow path gradient for (a) the sedimentary Drift Creek catchments and (b) the volcanic HJ Andrews catchments.

Table 4. Pearson's Correlation Coefficients and Associated *p* Values Between Mean Transit Time (MTT) and Catchment Attributes for Catchments Within the Drift Creek Basin in the Oregon Coast Range and the HJ Andrews Experimental Forest (HJA) in the Western Cascades Range of Oregon

	Upper Drift Creek Basin		HJA Experimental Forest	
Catchment Attribute	Correlation Coefficient	*p* Value	Correlation Coefficient	*p* Value
A_c	0.91	<0.01	0.00	0.99
log(A_c)	0.82	0.01	−0.03	0.95
DD	0.17	0.70	0.69	0.13
A-P	0.91	<0.01	−0.01	0.99
S	−0.15	0.73	−0.86	0.03
L	0.58	0.13	0.87	0.03
G	0.31	0.45	−0.80	0.05
L/G	0.13	0.75	0.95	<0.01
SCA	−0.15	0.73	−0.54	0.27
TWI	−0.12	0.79	0.65	0.16
DSI_5	−0.12	0.79	0.65	0.16

5. Discussion

5.1. The Link Between Bedrock Permeability and MTT Scaling Relationships

Although bedrock permeability has been implicated as a control on MTT in previous studies [*Asano and Uchida*, 2012; *Katsuyama et al.*, 2010; *Uchida et al.*, 2006], no other MTT scaling study to date, that we are aware of, has been able to systematically compare such distinct differences in geology across multiscale catchments. Our calculated mean transit times are up to an order of magnitude longer in the sedimentary Drift Creek catchments than the volcanic HJA catchments and increase with increasing basin area. This scaling behavior is effectively opposite to the HJA where MTT showed no relation to catchment area and was controlled by topographic-based attributes (flow path length and gradient). Drift Creek, along with *Frisbee et al.*'s [2011] Saguache Creek, are the first catchments (with multiple nested subcatchments) that we are aware of to exhibit the area-dependence for MTT that motivated the first MTT scaling studies [*Hracowitz et al.*, 2010b; *McGlynn and McDonnell*, 2003; *McGuire et al.*, 2005; *Rodgers et al.*, 2005].

Since the Drift Creek and HJA catchments are so similar in all characteristics but their bedrock permeability, we were able to explicitly "control" for the effect of this characteristic. Interestingly, the primary permeability of the Tyee sandstone at Drift Creek is similar to that of the various volcanic rock types at HJA. However, coring at the two catchments confirms extensive weathering and fracturing near the surface of the Drift Creek bedrock that slowly grades to a lower density of fractures to depths of at least 30 m [*Hale et al.*, 2016] while the majority of the fracture distribution at HJA is limited to the upper 3 m of bedrock [*Gabrielli et al.*, 2012]. We therefore infer that the disparities in MTTs and their scaling relationships between Drift Creek and HJA are a result of the differences in how bedrock permeability varies with depth, confirming the *Asano and Uchida* [2012] hypothesis that spatial variability in MTT is controlled by the hydrologically active depth.

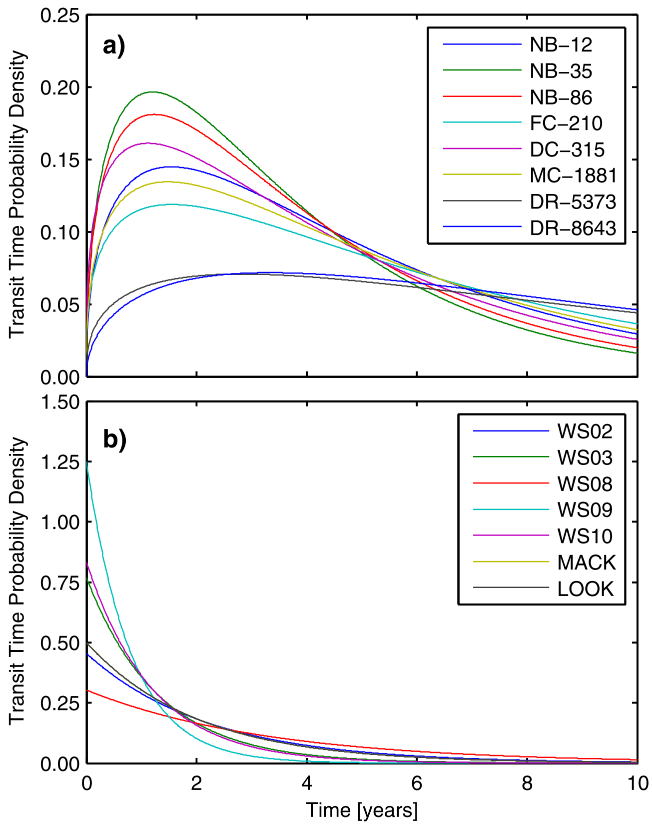

Figure 4. Transit time probability density for (a) Drift Creek and (b) HJ Andrews catchments.

The longer MTTs of the sedimentary Drift Creek catchments indicate that slow, and presumably deep, flow paths play an important role in supplying water for streamflow, as evidenced by the delayed peak and long tail of the TTD (Figure 4a). Further, the positive relationship between MTT and

Table 5. Terrain and Hydrologic Metrics Calculated for the Sedimentary (NB-12 and NB-86) and Volcanic Research Catchments (WS10 and WS01)

	NB-12	NB-86	WS10	WS01
Terrain metrics				
A_c (ha)	11.9	85.7	10.2	95.9
E_{min} (m)	207	132	462	440
E_{rng} (m)	162	237	226	570
DD (km km^{-2})	2.53	3.70	3.01	3.72
A-P (km^2 km^{-1})	0.07	0.15	0.06	0.175
Median *S* (%)	51	34	66	68
Median *L* (m)	134	98	137	139
Median *G* (m m^{-1})	0.47	0.34	0.63	0.61
Median *SCA* (ha)	4.1	12.3	7.2	10.3
Median *TWI*	6.30	6.58	4.27	4.41
Median DSI_5	0.45	0.32	0.52	0.57
Hydrologic metrics				
MAF (mm d^{-1})	4.46	4.24	4.04	3.71
MAPF (mm d^{-1})	65.38	62.79	62.39	60.52
MALF (mm d^{-1})	0.32	0.04	0.02	0.03
CV_Q	1.85	1.76	1.99	1.91
R_{QP}	0.95	0.78	0.65	0.59
BFI	0.64	0.72	0.62	0.68
$FDC_{33\text{-}66}$	3.54	3.41	4.21	3.61
FI_{RB}	0.42	0.33	0.45	0.40
b	1.64	1.10	1.23	1.20
Mean transit time (y)	5.0	4.0	1.2	1.3[a]

[a]*McGuire et al.* [2005] did not estimate MTT for WS01. We therefore used the regression relationship between MTT and the ratio of median flow path length, L, and median flow path gradient, G, to estimate an MTT of 1.3 years for WS01 (MTT = 0.0021*(L/G) + 0.71; r^2 = 0.91).

catchment area (Table 4) suggests the presence of flow paths that not only age in a down-valley direction, but also contribute proportionately more water to the stream in a down-valley direction. These findings are similar to recent results from the San Juan Mountains of southern Colorado, where geochemical analysis in a nested catchment with permeable bedrock (i.e., highly fractured) revealed Tothian flow characteristics with long residence time, regional groundwater sources increasing with larger catchment scales [*Frisbee et al.*, 2011]. This contrasts with the effect of the tighter volcanic bedrock of the HJA which induces shallow lateral subsurface flow at the soil-bedrock interface [*Harr*, 1977; *McGuire and McDonnell*, 2010]. This runoff generation mechanism has been linked to exponential or gamma (with $\alpha > 1$) TTDs in other studies [e.g., *Hrachowitz et al.*, 2010b; *Godsey et al.*, 2010] and matches well with the strong correlation found between MTT and *L/G* at HJA, as transport via lateral subsurface flow is dependent on both *L* and *G* [*McGuire et al.*, 2005].

Notwithstanding the distinct differences in bedrock permeability, as well as landscape age and formation processes, the topographic form of the Drift Creek catchment is remarkably similar to that of HJA. In both research areas, the steep, highly dissected landscape is a result of fluvial incision and colluvial processes—

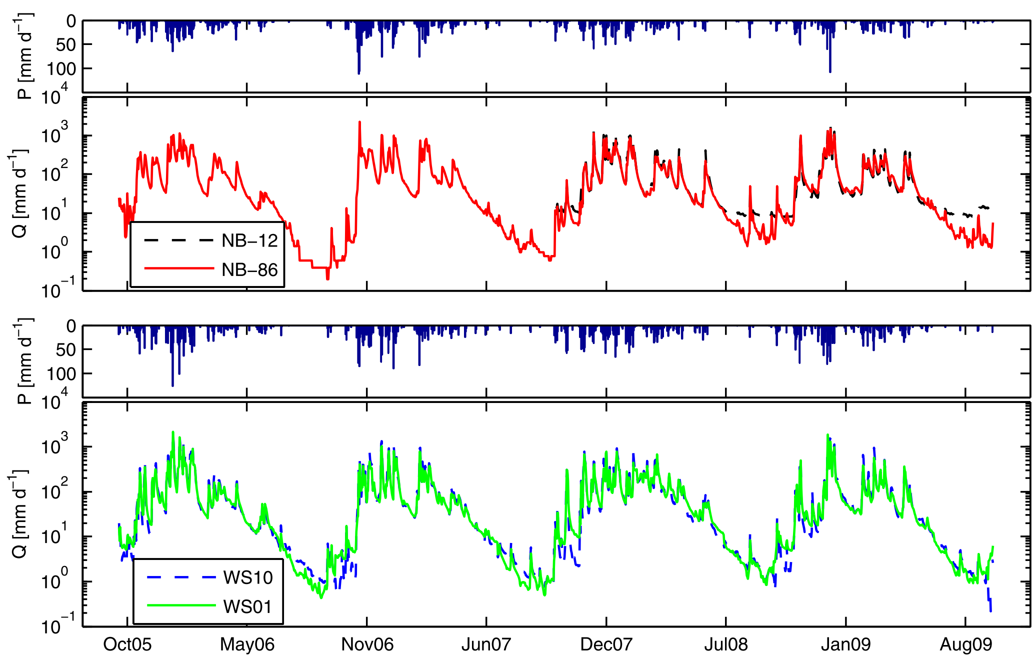

Figure 5. Plot of mean daily discharge (Q) and daily precipitation (P) measured at NB-12 (black), NB-86 (red), WS10 (blue), and WS01 (green) during the intercomparison period.

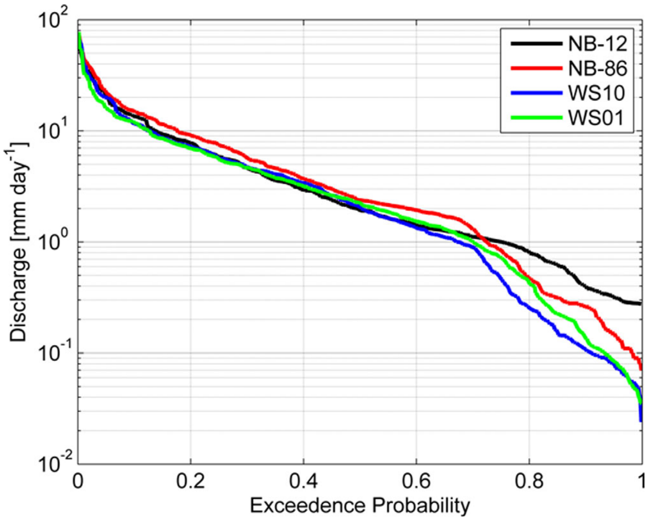

Figure 6. Flow duration curves for NB-12, NB-86, WS10, and WS01.

namely shallow landsliding [*Dietrich and Dunne*, 1978; *Jefferson et al*., 2010]. In landscapes with steep terrain, catchment flow path distributions have traditionally been expected to be a function of topography [*Beven and Kirkby*, 1979a; *McGuire et al*., 2005]. While the scaling relations at HJA followed this expected trend, the sedimentary Drift Creek catchments did not. This discrepancy arises from the assumption that a restrictive layer (i.e., low permeability bedrock or, in some cases, clay or glacial till) mimics the surface topography in mountainous catchments; however, this assumption is true for only a subset of headwater catchments. Our findings show that bedrock permeability is a higher-order control on flow path distribution across catchment scales, and hence on MTT scaling relationships. This is particularly significant as more and more researchers are finding that bedrock groundwater makes significant contributions to streamflow in catchments where the bedrock was previously thought to be impermeable [*Gabrielli et al*., 2012].

5.2. Significantly Different MTTs Masked by Similar Hydrologic Response and Topographic Form

Recent papers have helped clarify the general understanding that catchments transmit hydraulic potentials (the rate at which potentials are transmitted is referred to as "celerity") differently than they transmit water itself ("velocity") [*McDonnell et al*., 2010; *McDonnell and Beven*, 2014]. However, to date, such examples have been limited to single catchments. Our catchment scaling work across the two contrasting bedrock geologies clearly shows such differences in velocity and celerity. More importantly, our work suggests that similar celerity responses across different bedrock types can hide significantly different velocities and velocity scaling behavior. Our hydrometric analysis showed that the Drift Creek and HJA catchments were both highly responsive to precipitation events despite their dissimilar MTTs. Considering only the similar climate, vegetation, and topography of the Drift Creek and HJA catchments, it is not surprising that our catchments exhibited such similar hydrological regimes. However, it is quite surprising that the differences in MTTs and their scaling relationships could be hidden by such strong similarities in hydrologic response. This finding clearly shows that hydrologic response typology and topographic form alone cannot consistently be relied upon to predict the transport rate of water or water-transported chemicals across geographically distinct catchments.

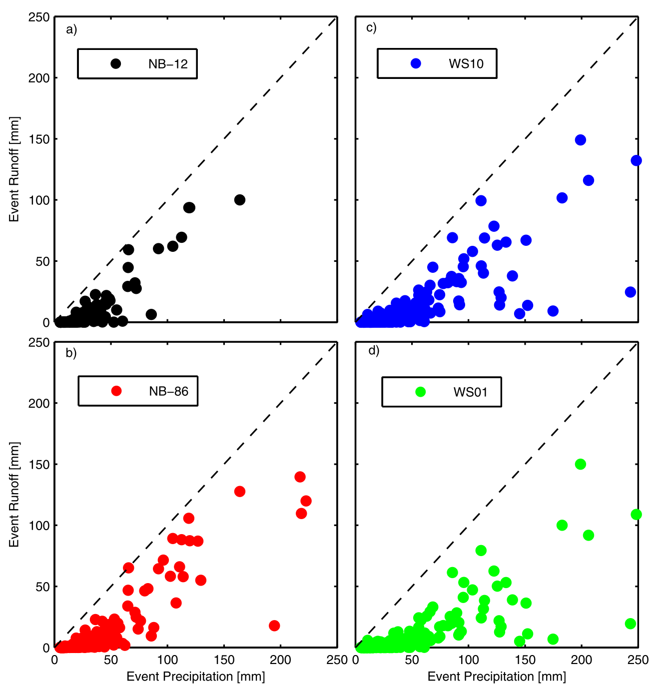

Figure 7. Event runoff (Q_{evt}) versus event precipitation (P_{evt}) for (a) NB-12, (b) NB-86, (c) WS10, and (d) WS01.

Although the discharge traces among the four streams are generally similar, two distinctions can be made that may help explain the differences in MTT. The most obvious difference is that summer base flow in NB-12 remains elevated relative to its downstream counterpart (NB-86), WS10, and WS01 (Figure 5). This is reflected in the higher, *MALF*, R_{QP}, and *b* at NB-12. Elevated summer base flow paired with a high R_{QP} value may signify interbasin groundwater contributions. This scenario is plausible based on the tilted, layered bedrock of Drift Creek's Tyee Formation, with fracturing known to occur along the bedding planes [*Snavely et al*., 1964]. Interbasin groundwater flow paths likely contribute to the tail or late time behavior of a catchment's flow path distribution, thus acting to increase MTT. The second difference is that the troughs of the NB-12 and NB-86 hydrographs seem to be shallower during interstorm periods of the wet season, suggesting potentially continued contributions via slower flow paths after the initial runoff response in the sedimentary Drift Creek catchments. While this behavior is consistent with the longer MTTs estimated at these sites and the shapes of their corresponding TTDs (Figure 4), a more thorough hydrometric investigation—including monitoring of the various groundwater stores contributing to runoff—is needed to fully characterize how the contrasting geologies (and MTTs) can lead to such similar hydrological flow regimes. *Hale et al.* [2016] investigate these detailed processes for the Drift Creek catchment.

5.3. On the Assumptions and Limitations of Our Approach

The application of conservative tracers, in this case stable isotopes, in lumped-parameter convolution models has theoretical limitations based on the transit time distributions selected [*Frisbee et al*., 2013; *Stewart et al*., 2010]. While the gamma model allows characterization of slower flow paths via its long-tail (relative to other distributions), our data set pushes the limit of its application and may result in underestimation of the true MTT value if the actual TTD has a long tail with significant mass. In addition, the simplification of the catchment system as assumed in the lumped-parameter convolution models inherently introduces additional uncertainty into the MTT estimations (*McGuire and McDonnell* [2006] provide a detailed assessment of the assumptions). It is therefore appropriate to consider our MTT estimations indicative rather than absolute, as advocated generally by *Soulsby et al*. [2010]. Such caution notwithstanding, there is a significantly large degree of separation between the Drift Creek and HJA MTTs so that we stand confidently by our finding of longer MTTs in the sedimentary catchments relative to that of the volcanic catchments. We confirm this using a two-sample, single-tailed *t* test to show that, indeed, the mean of the lower MTT uncertainty bounds at Drift Creek, 5.0 years, is significantly larger than the mean of the upper MTT uncertainty bounds at HJA, 2.4 years (p value = 0.005, t stat = −2.95, 13 degrees of freedom). The robustness of the positive MTT-catchment area relationship, given the MTT uncertainty at the Drift Creek catchments, was checked by conducting 1000 regressions where, in each case, the MTT values were randomly sampled from their uncertainty range. Of all MTT combinations, 78% resulted in positive MTT-catchment area relationships significant at the 0.05 alpha level. Significant ($p < 0.05$) regression coefficients ranged from 1.3 to 5.0 and nonsignificant ($p > 0.05$) regression coefficients ranged from 0.5 to 3.4, both providing additional confidence in our finding of the positive MTT-catchment area relationship in the sedimentary Drift Creek basin.

Despite the strong inference of bedrock permeability as the primary control on MTT and MTT scaling relationships for these two research catchments, our top-down approach does not allow for a process-based explanation of (1) how bedrock permeability influences MTT or (2) how catchments with such starkly different MTTs could have such similar hydrologic flow regimes. Therefore, it is still unclear, mechanistically, how the sedimentary catchments of the Drift Creek have longer MTTs and why they scale differently than the volcanic HJA catchments. *Hale et al.* [2016] address these questions using a detailed field-based study to better understand the role of subsurface catchment storage on setting stream water MTTs in Drift Creek.

6. Conclusions

Our findings show that MTTs were longer in the catchments with more permeable fractured and weathered sandstone bedrock than in the catchments with tight, volcanic bedrock. In the permeable bedrock catchments, MTT was positively correlated to basin area, whereas MTT was most strongly linked to the ratio of median flow path length to median flow path gradient in the volcanic catchments. Despite the differences in MTT magnitude and scaling relationships, the catchments displayed remarkable similarities in landscape morphometry and hydrological flow regimes. Thus, we show that similar catchment forms and hydrologic response characteristics can hide different MTTs and MTT scaling relationships. This finding is a clear example of how the celerity-velocity relationship can vary in catchments that are indistinguishable at the surface.

Beyond adding yet another unique scaling relationship from yet another research catchment to the MTT scaling literature, our intercomparison framework confirmed the *Asano and Uchida* [2012] hypothesis that the hydrologically active depth of a catchment controls the spatial variability in MTT across a broader range of catchment scales than their study allowed (0.085–86 km^2 versus 0.001–4 km^2). The fact that their hypothesis was confirmed at larger scales and in different bedrock lithologies (i.e., sandstone and basalt/breccia) provides further evidence that bedrock permeability is the overarching control on base flow MTT in mountainous catchments.

These findings are particularly relevant to the commonly applied regionalization approaches for parameterizing hydrologic models when calibration data is not available [*Yadav et al*., 2007]. Topographic metrics and hydrodynamic response indices are the primary variables used in building the regression models that predict parameter sets across a region. Although many indices currently used in regionalization studies are considered to capture catchment function [*Oudin et al*., 2010; *Sawicz et al*., 2011; *Yadav et al*., 2007], our results show that MTT, an established proxy for catchment function, can be poorly represented by topography and hydrologic response alone. This could result in misleading results when model outcomes are dependent on proper process representation (i.e., in predicting water quality or contaminant transport). Our results suggest that the inclusion of more fundamental characteristics, in our case bedrock permeability, may represent a useful path forward to capture catchment function—i.e., measures of water storage and release—in the regionalization process.

Acknowledgments
The authors thank George Ice and National Council for Air and Stream Improvement and the AGU Horton Research grant for support of this work. The CUASHI Pathfinder grant program provided opportunity for Cody Hale to receive valuable feedback from the University of Aberdeen's Northern Rivers Institute team, led by Doerthe Tetzlaff and Chris Soulsby. Christian Birkel and Rene Capell are also thanked for their feedback on this research. Tina Garland is thanked for field assistance and isotope analysis assistance. Jakob Garvelmann from the Univeristy of Freiburg is thanked for his field efforts. Agustín Millares, Markus Hrachowitz, and one anonymous reviewer are thanked for their suggestions for improving this manuscript (as well as Doerthe Tetzlaff and two anonymous reviewers for their comments on an earlier draft). Data used for the analyses presented here will be made available upon request from the corresponding author.

References

Amoozegar, A. (1989), A compact constant-head permeameter for measuring hydraulic conductivity of the vadose zone, *Soil Sci. Soc. Am. J.*, *53*, 1356–1361.

Anderson, S. P., W. E. Dietrich, D. R. Montgomery, R. Torres, M. E. Conrad, and K. Loague (1997), Subsurface flow paths in a steep, unchanneled catchment., *Water Resour. Res.*, *33*(12), 2637–2653, doi:10.1029/97WR02595.

Arnold, J. G., P. M. Allen, R. Muttiah, and G. Bernhardt (1995), Automated base flow separation and recession analysis techniques, *Ground Water*, *33*(6), 1010–1018.

Asano, Y., and T. Uchida (2012), Flow path depth is the main controller of mean base flow transit times in a mountainous catchment, *Water Resour. Res.*, *48*, W03512, doi:10.1029/2011WR010906.

Asano, Y., T. Uchida, and N. Ohte (2002), Residence times and flow paths of water in steep unchannelled catchments, Tanakami, Japan, *J. Hydrol.*, *261*(1–4), 173–192.

Baker, D. B., R. P. Richards, T. T. Loftus, and J. W. Kramer (2004), A new flashiness index: Characteristics and applications to midwestern rivers and streams, *J. Am. Water Resour. Assoc.*, *40*(2), 503–522.

Beven, K. J. (2006), Searching for the Holy Grail of scientific hydrology: Qt=(S, R, Δt)A as closure, *Hydrol. Earth Syst. Sci.*, *10*(5), 609–618.

Beven, K. J., and M. J. Kirkby (1979a), A physically-based variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*, 43–69.

Beven, K. J., and M. J. Kirkby (1979b), A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*(1), 43–69.

Bierlmaler, F. A., and A. McKee (1989), Climatic summaries and documentation for the primary meteorological station, H.J. Andrews Experimental Forest, 1972 to 1984, *Gen. Tech. Rep. PNW-GTR-242*, 61 p., U.S. Dep. of Agric., For. Serv., Pac. Northwest Res. Stn., Portland, Oreg.

Bloschl, G. and Sivapalan, M. (1995), Scale issues in hydrological modelling: A review, in *Scale Issues in Hydrological Modelling*, edited by J. D. Kalma, and M. Sivapalan, pp. 9–48, John Wiley, Chichester.

Broxton, P. D., P. A. Troch, and S. W. Lyon (2009), On the role of aspect to quantify water transit times in small mountainous catchments, *Water Resour. Res.*, *45*, W08427, doi:10.1029/2008WR007438.

Brutsaert, W., and J. L. Nieber (1977), Regionalized drought flow hydrographs from a mature glaciated plateau, *Water Resour. Res.*, *13*(3), 637–644, doi:10.1029/WR013i003p00637.

Capell, R., D. Tetzlaff, I. A. Malcolm, A. J. Hartley, and C. Soulsby (2011), Using hydrochemical tracers to conceptualise hydrological function in a larger scale catchment draining contrasting geologic provinces, *J. Hydrol.*, *408*(1–2), 164–177.

Corliss, J. F. (1973), *Soil Survey, Alsea Area, Oregon*, 82 pp., U.S. Dep. of Agric., Soil Conserv. Serv., Washington, D. C.

DeWalle, D. R., P. J. Edwards, B. R. Swistock, R. Aravena, and R. J. Drimmie (1997), Seasonal isotope hydrology of three Appalachian forest catchments, *Hydrol. Processes*, *11*(15), 1895–1906.

Dietrich, W. E., and T. Dunne (1978), Sediment budget for a small catchment in mountainous terrain, *Z. Geomorph. Suppl.*, *29*, 191–206.

Freeze, R. A., and J. A. Cherry (1979), *Groundwater*, 1st ed., 604 pp., Prentice Hall, Englewood Cliffs, N. J.

Frisbee, M. D., F. M. Phillips, A. R. Campbell, F. Liu, and S. A. Sanchez (2011), Streamflow generation in a large, alpine watershed in the southern Rocky Mountains of Colorado, USA: Is streamflow generation simply the aggregation of hillslope runoff responses, *Water Resour. Res.*, *47*, W06512, doi:10.1029/2010WR009391.

Frisbee, M. D., J. L. Wilson, J. D. Gomez-Velez, F. M. Phillips, and A. R. Campbell (2013), Are we missing the tail (and the tale) of residence time distributions in watersheds?, *Geophys. Res. Lett.*, *40*, 4633–4637, doi:10.1002/grl.50895.

Gabrielli, C. P., J. J. McDonnell, and W. T. Jarvis (2012), The role of bedrock groundwater in rainfall-runoff response at hillslope and catchment scales, *J. Hydrol.*, *450–451*, 117–133, doi:10.1016/j.jhydrol.2012.05.023.

Gleeson, T., L. Smith, N. Moosdorf, J. Hartmann, H. H. Dürr, A. H. Manning, L. P. H. van Beek, and A. M. Jellinek (2011), Mapping permeability over the surface of the Earth, *Geophys. Res. Lett.*, *38*, L02401, doi:10.1029/2010GL045565.

Godsey, S. E., et al. (2010), Generality of fractal 1/f scaling in catchment tracer time series, and its implications for catchment travel time distributions, *Hydrol. Processes*, *24*, 1660–1671, doi:10.1002/hyp.7677.

Graham, C. B., and J. J. McDonnell (2010), Hillslope threshold response to rainfall: (2) Development and use of a macroscale model, *J. Hydrol.*, *393*(1-2), 77–93.

Hale, V. C., J. J. McDonnell, M. K. Stewart, D. K. Solomon, J. Doolitte, G. G. Ice, and R. T. Pack (2016), Effect of bedrock permeability on stream base flow mean transit time scaling relationships: 2. Process study of storage and release, *Water Resour. Res.*, *52*, doi:10.1002/2015WR017660.

Haria, A. H., and P. Shand (2004), Evidence for deep subsurface flow routing in a forested upland Wales: Implications for contaminant transport and stream flow generation, *Hydrol. Earth Syst. Sci.*, *8*(2), 334–344.

Harr, R. D. (1976), Hydrology of small forest stream in western Oregon, *Gen.Tech. Rep. PNW-55*, 15 pp., Pac. Northwest For. and Range Exp. Stn., U.S. Dep. of Agric., For. Serv., Portland, Oreg.

Harr, R. D. (1977), Water flux in soil and subsoil on a steep forested slope, *J. Hydrol.*, *33*, 37–58.

Harr, R. D. (1981), Some characteristics and consequences of snowmelt during rainfall in western, Oregon, *J. Hydrol.*, *53*, 277–304.

Harris, D. D. (1977), Hydrologic changes after logging in two small Oregon coastal watersheds, *U.S. Geol. Surv. Water Supply Pap., 2037*, 31 pp.

Hewlett, J. D., and A. R. Hibbert (1967), Factors affecting the response of small watersheds to precipitation in humid areas, in *Forest Hydrology*., edited by W. E. Sopper and H. W. Lull, pp. 275–291, Pergamon, N. Y.

Hjerdt, K. N., J. J. McDonnell, J. Seibert, and A. Rodhe (2004), A new topographic index to quantify downslope controls on local drainage, *Water Resour. Res.*, *40*, W05602, doi:10.01029/02004WR003130.

Hrachowitz, M., C. Soulsby, D. Tetzlaff, J. J. C. Dawson, and I. A. Malcolm (2009), Regionalization of transit time estimates in montane catchments by integrating landscape controls, *Water Resour. Res.*, *45*, W05421, doi:10.1029/2008WR007496.

Hrachowitz, M., C. Soulsby, D. Tetzlaff, I. A. Malcolm, and G. Schoups (2010a), Gamma distribution models for transit time estimation in catchments: Physical interpretation of parameters and implications for time-variant transit time assessment, *Water Resour. Res.*, *46*, W10536, doi:10.1029/2010WR009148.

Hrachowitz, M., C. Soulsby, D. Tetzlaff, and M. Speed (2010b). Catchment transit times and landscape controls – does scale matter? *Hydrol. Processes*, *24*, 117–125.

Ice, G. G., V. C. Hale, J. Light, J. J. McDonnell, S. H. Schoenholtz, and J. D. Stednick (2007), Testing contemporary forest practices: The Alsea watershed study revisited, in *Sustaining America's Forests: Proceedings of the 2007 Society of American Foresters National Convention*, pp. 923–930, Soc. of Am. For., Portland, Oreg.

Ingebritsen, S. E., D. R. Sherrod, and R. H. Mariner (1992), Rates and patterns of groundwater flow in the Cascade Range volcanic arc, and the effect on subsurface temperatures, *J. Geophys. Res.*, *97*(B4), 4599–4627, doi:10.1029/91JB03064.

Jefferson, A., A. Nolin, S. Lewis, and C. Tague (2008), Hydrogeologic controls on streamflow sensitivity to climate variation, *Hydrol. Processes*, *22*(22), 4371–4385.

Jefferson, A., G. E. Grant, S. L. Lewis, and S. T. Lancaster (2010), Coevolution of hydrology and topography on a basalt landscape in the Oregon Cascade Range, USA, *Earth Surf. Processes Landforms*, *35*(7), 803–816, doi:10.1002/esp.1976.

Kabeya, N., M. Katsuyama, M. Kawasaki, N. Ohte, and A. Sugimoto (2007), Estimation of mean residence times of subsurface waters using seasonal variation in deuterium excess in a small headwater catchment in Japan, *Hydrol. Processes*, *21*, 308–322.

Katsuyama, M., M. Tani, and S. Nishimoto (2010), Connection between streamwater mean residence time and bedrock groundwater recharge/discharge dynamics in weathered granite catchments, *Hydrol. Processes*, *24*(16), 2287–2299.

Kirchner, J. W. (2006), Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology, *Water Resour. Res.*, *42*, W03S04, doi:10.1029/2005WR004362.

Kirchner, J. W., X. Feng, and C. Neal (2000), Fractal stream chemistry and its implications for contaminant transport in catchments, *Nature*, *403*(6769), 524–527.

Kosugi, K. i., S. y. Katsura, M. Katsuyama, and M. Takahisa (2006), Water flow processes in weathered granitic bedrock and their effects on runoff generation in a small headwater catchment, *Water Resour. Res.*, *42*, W02414, doi:10.1029/2005WR004275.

Kosugi, K. i., M. Fujimoto, S. y. Katsura, H. Kato, Y. Sando, and T. Mizuyama (2011), Localized bedrock aquifer distribution explains discharge from a headwater catchment, *Water Resour. Res.*, *47*, W07530, doi:10.1029/2010WR009884.

Maloszewski, P., and A. Zuber (1982), Determining the turnover time of groundwater systems with the aid of environmental tracers. 1. models and their applicability, *J. Hydrol.*, *57*, 207–231.

Mazurkiewicz, A. B., D. G. Callery, and J. J. McDonnell (2008), Assessing the controls of the snow energy balance and water available for runoff in a rain-on-snow environment, *J. Hydrol.*, *354*(1–4), 1–14.

McDonnell, J. J., and K. Beven (2014), Debates: The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities, and residence time distributions of the headwater hydrograph, *Water Resour. Res.*, *50*, 5342–5350, doi:10.1002/2013WR015141.

McDonnell, J. J., et al. (2010), How old is streamwater? Open questions in catchment transit time conceptualization, modelling and analysis, *Hydrol. Processes*, *24*(12), 1745–1754.

McGlynn, B., J. McDonnell, M. Stewart, and J. Seibert (2003), On the relationships between catchment scale and streamwater mean residence time, *Hydrol. Processes*, *17*(1), 175–181.

McGlynn, B. L., and J. J. McDonnell (2003), Quantifying the relative contributions of riparian and hillslope zones to catchment runoff, *Water Resour. Res.*, *39*(11), 1310, doi:10.1029/2003WR002091.

McGlynn, B. L., and J. Seibert (2003), Distributed assessment of contributing area and riparian buffering along stream networks, *Water Resour. Res.*, *39*(4), 1082, doi:10.1029/2002WR001521.

McGuire, K. J., and J. J. McDonnell (2006), A review and evaluation of catchment transit time modeling, *J. Hydrol.*, *330*(3–4), 543–563.

McGuire, K. J., and J. J. McDonnell (2010), Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities, *Water Resour. Res.*, *46*, W10543, doi:10.1029/2010WR009341.

McGuire, K. J., J. J. McDonnell, M. Weiler, C. Kendall, B. L. McGlynn, J. M. Welker, and J. Seibert (2005), The role of topography on catchment-scale water residence time, *Water Resour. Res.*, *41*, W05002, doi:10.1029/2004WR003657.

Millares, A., M. J. Polo, and M. A. Losada (2009), The hydrological response of baseflow in fractured mountain areas, *Hydrol. Earth Syst. Sci.*, *13*(7), 1261–1271.

Montgomery, D. R., W. E. Dietrich, R. Torres, S. P. Anderson, J. T. Heffner, and K. Loague (1997), Hydrologic response of a steep, unchanneled valley to natural and applied rainfall, *Water Resour. Res.*, *33*(1), 91–109, doi:10.1029/96WR02985.

Olden, J. D., and N. L. Poff (2003), Redundancy and the choice of hydrologic indices for characterizing streamflow regimes, *River Res. Appl.*, *19*(2), 101–121.

Onda, Y., M. Tsujimura, J.-i. Fujihara, and J. Ito (2006), Runoff generation mechanisms in high-relief mountainous watersheds with different underlying geology, *J. Hydrol.*, *331*(3–4), 659–673.

Oudin, L., A. Kay, V. Andréassian, and C. Perrin (2010), Are seemingly physically similar catchments truly hydrologically similar?, *Water Resour. Res.*, *46*, W11558, doi:10.1029/2009WR008887.

Peck, D. V., A. B. Griggs, H. G. Schlicker, F. G. Wells, and H. M. Dole (1964), Geology of the central and nothern parts of the western Cascade Range in Oregon, *U.S. Geol. Surv. Prof. Pap., 449*, 56 pp.

Ranken, D. W. (1974), Hydrologic properties of soil and subsoil on a steep, forested slope, MS thesis, 114 pp., Oreg. State Univ., Corvallis.

Rodgers, P., C. Soulsby, and D. Tetzlaff (2005), Using stable isotope tracers to assess hydrological flow paths, residence times and landscape influences in a nested mesoscale catchment, *Hydrol. Earth Syst. Sci.*, *9*, 139–155.

Rupp, D. E., and R. A. Woods (2008), Increased flexibility in base flow modelling using a power law transmissivity profile, *Hydrol. Processes*, *22*(14), 2667–2671.

Saar, M. O., and M. Manga (2004), Depth dependence of permeability in the Oregon Cascades inferred from hydrogeologic, thermal, seismic, and magmatic modeling constraints, *J. Geophys. Res.*, *109*, B04204, doi:10.1029/2003JB002855.

Sawicz, K., T. Wagener, M. Sivapalan, P. A. Troch, and G. Carrillo (2011), Catchment classification: Empirical analysis of hydrologic similarity based on catchment function in the eastern USA, *Hydrol. Earth Syst. Sci.*, *15*(9), 2895–2911.

Schoups, G., and J. A. Vrugt (2010), A formal likelihood function for parameter and predictive inference of hydrologic models with correlated, heteroscedastic, and non-Gaussian errors, *Water Resour. Res.*, *46*, W10531, doi:10.1029/2009WR008933.

Sivapalan, M. (2003), Process complexity at hillslope scale, process simplicity at the watershed scale: Is there a connection?, *Hydrol. Processes*, *17*(5), 1037–1041.

Sivapalan, M. (2005), Pattern, process, and function: Elements of a unified theory of hydrology at the catchment scale, in *Encyclopedia of Hydrological Sciences*, edited by M. G. Anderson, pp. 193–219, John Wiley, Hoboken, N. J.

Snavely, P. D., H. C. Wagner, and N. S. MacLeod (1964), Rythmic-bedded eugeosynclinal deposits of the Tyee Formation, Oregon Coast Range, in *Symposium on Cyclic Sedimentation: Kansas Geological Survey, Bulletin*, vol. 169, pp. 461–480, edited by D. F. Merriam, University of Kansas, Lawrence, Kansas.

Soulsby, C., R. Malcolm, R. C. Ferrier, R. C. Helliwell, and A. Jenkins (2000), Isotope hydrology of the Allt a'Mharcaidh catchment, Cairngorms, Scotland: Implications for hydrological pathways and residence times, *Hydrol. Processes*, *14*, 747–762.

Soulsby, C., D. Tetzlaff, P. Rodgers, S. Dunn, and S. Waldron (2006), Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation, *J. Hydrol.*, *325*(1–4), 197–221.

Soulsby, C., D. Tetzlaff, N. van den Bedem, I. A. Malcolm, P. J. Bacon, and A. F. Youngson (2007), Inferring groundwater influences on surface water in montane catchments from hydrochemical surveys of springs and streamwaters, *J. Hydrol.*, *333*(2–4), 199–213.

Soulsby, C., D. Tetzlaff, and M. Hrachowitz (2009), Tracers and transit times: Windows for viewing catchment scale storage?, *Hydrol. Processes*, *23*(24), 3503–3507.

Soulsby, C., D. Tetzlaff, and M. Hrachowitz (2010), Are transit times useful process-based tools for flow prediction and classification in ungauged basins in montane regions?, *Hydrol. Processes*, *24*(12), 1685–1696.

Stewart, M. K., and J. J. McDonnell (1991), Modeling base flow soil water residence times from deuterium concentrations, *Water Resour. Res.*, *27*(10), 2681–2693, doi:10.1029/91WR01569.

Stewart, M. K., U. Morgenstern, and J. J. McDonnell (2010), Truncation of stream residence time: How the use of stable isotopes has skewed our concept of streamwater age and origin, *Hydrol. Processes*, *24*(12), 1646–1659.

Swanson, F. J., and M. E. James (1975), Geology and geomorphology of the H.J. Andrews Experimental Forest, western Cascades, Oregon, *Rep. Res. Pap. PNW-188*, 14 pp, U.S. Dep. of Agric., For. Serv., Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Tague, C., and G. E. Grant (2004), A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon, *Water Resour. Res.*, *40*, W04303, doi:10.1029/2003WR002629.

Tarboton, D. G. (1997), A new method for the determination of flow directions and upslope areas in grid digital elevation models, *Water Resour. Res.*, *33*(2), 309–319, doi:10.1029/96WR03137.

Tetzlaff, D., J. J. McDonnell, S. Uhlenbrook, K. J. McGuire, P. W. Bogaart, F. Naef, A. J. Baird, S. M. Dunn, and C. Soulsby (2008), Conceptualizing catchment processes: Simply too complex?, *Hydrol. Processes*, *22*(11), 1727–1730.

Tetzlaff, D., J. Seibert, and C. Soulsby (2009a), Inter-catchment comparison to assess the influence of topography and soils on catchment transit times in a geomorphic province; the Cairngorm mountains, Scotland, *Hydrol. Processes*, *23*(13), 1874–1886.

Tetzlaff, D., J. Seibert, K. J. McGuire, H. Laudon, D. A. Burns, S. M. Dunn, and C. Soulsby (2009b), How does landscape structure influence catchment transit time across different geomorphic provinces?, *Hydrol. Processes*, *23*(6), 945–953.

Tetzlaff, D., S. K. Carey, H. Laudon, and K. McGuire (2010), Catchment processes and heterogeneity at multiple scales—benchmarking observations, conceptualization and prediction, *Hydrol. Processes*, *24*(16), 2203–2208.

Thorson, T. D., S. A. Bryce, D. A. Lammers, A. J. Woods, J. M. Omernik, J. Kagan, D. E. Pater, and J. A. Comstock (2003), Ecoregions of Oregon, scale 1:1,500,000, U.S. Geol. Surv., Reston, Va.

Torres, R., W. E. Dietrich, D. R. Montgomery, S. P. Anderson, and K. Loague (1998), Unsaturated zone processes and the hydrologic response of a steep, unchanneled catchment, *Water Resour. Res.*, *34*(8), 1865–1879, doi:10.1029/98WR01140.

Uchida, T., J. J. McDonnell, and Y. Asano (2006), Functional intercomparison of hillslopes and small catchments by examining water source, flowpath and mean residence time, *J. Hydrol.*, *327*, 627–642.

Wagener, T., M. Sivapalan, P. Troch, and R. Woods (2007), Catchment classification and hydrologic similarity, *Geogr. Compass*, *1*, 901–931.

Wilson, C. J., and W. E. Dietrich (1987), The contribution of bedrock groundwater flow to storm runoff and high pore pressure development in hollows, in *Erosion and Sedimentation in the Pacific Rim*, IAHS Publ., *165*, 49–59.

Yadav, M., T. Wagener, and H. Gupta (2007), Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins, *Adv. Water Resour.*, *30*(8), 1756–1774.