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Key Points:

- A distributed hydrochemical model reproduces transport without a priori transit time functions at the catchment scale
- Water parcels rained over 2 years on a catchment are tracked to compute forward and backward transit time distributions
- Hydrometeorological conditions and spatial heterogeneity controls on transit time distributions are quantified

Supporting Information:

- Figure S1–S7

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Water Flux Tracking With a Distributed Hydrological Model to Quantify Controls on the Spatio-temporal Variability of Transit Time Distributions

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Abstract Water transit times and flow pathways are crucial elements in characterizing catchment hydrologic response. Understanding their variability in space and time sheds light on the link between discharge formation and water quality at the catchment scale. Here, we introduce a novel modeling framework to explore water transport mechanisms using the Hafren catchment in Wales (UK) as a case study. We show that a fully distributed hydrological model coupled with a transport component for conservative tracers is useful in analyzing how hydrometeorological conditions and spatial heterogeneity may affect water transit times and age distributions in a real catchment. We use the model to track the paths of water parcels that entered the catchment as rainfall over 2 years, labeling each day of rain individually. There is a reasonable agreement between tracer simulations and observations, suggesting that dynamic transit time distributions (TTDs) both forward and backward in time can be approximated using a high spatial and temporal resolution hydrochemical model, without assuming a priori any transit and storage selection functions at the catchment scale. TTDs are quantified for the modeled internal dynamics of the study catchment. TTDs conditional on a given rainfall time are mostly correlated to the season in which the rain event occurs, whereas TTDs conditional on a given exit time are mostly affected by catchment wetness. When TTDs for individual rainfall events are re-scaled as functions of cumulative discharge, they collapse around a single common distribution, suggesting a potential characteristic catchment function.

1. Introduction

Understanding transport processes through catchment systems is crucial for addressing water quality issues and for protecting and managing water resources (Hrachowitz et al., 2016; Turner et al., 2006). Over the past decade, the study of hydrological processes in catchments has evolved toward describing not only flow amounts, but also ages, origins and pathways of water (Birkel & Soulsby, 2015; Botter et al., 2011; McDonnell et al., 2010; Rinaldo et al., 2011). These advances in catchment hydrology have relied heavily on conservative tracers (such as water isotopes and chloride) to identify dominant sources and temporal dynamics of runoff (e.g., Jasechko et al., 2016; Kendall & McDonnell, 2012; Kirchner & Neal, 2013; Rodgers et al., 2005; Tetzlaff et al., 2015). Conservative tracer data can also provide an important check on the internal consistency of hydrological models, i.e., testing if they give the right answers for the right reasons (Kirchner, 2006).

Two fundamental quantities in this regard are the transit time (or equivalently the travel time), which indicates the time that it takes for rainfall parcels to travel through a catchment and reach the outlet as discharge, and the residence time, which indicates how long water parcels have been stored in the catchment (i.e., their age). Their probability density functions, referred to as the transit time distribution (TTD) and residence time distribution (RTD), reflect the integrated storage and mixing processes that water parcels and conservative solutes in them undergo as they travel through catchments (e.g., Rinaldo et al., 2011).

TTDs and RTDs will typically differ from one another (Berghuijs & Kirchner, 2017), and both will be variable in time and space. In addition, the TTD conditional on the rainfall time, or forward TTD (i.e., the distribution of transit times for a given rainfall parcel) will usually be different from the TTD conditional on the exit time, or backward TTD (i.e., the distribution of ages of a given water parcel leaving the outlet at a given time)

(e.g., Rinaldo et al., 2011). These different time perspectives need to be accounted for in a comprehensive analysis of integrated catchment behavior.

Many studies have sought to estimate mean transit times and TTD shapes using conservative tracers, but TTD variability in time and space due to catchment non-stationarity and spatial heterogeneity has only recently been explored (Benettin et al., 2013; Birkel et al., 2015; Botter et al., 2010; Engdahl et al., 2016; Gomez & Wilson, 2013; Harman & Kim, 2014; Heidbüchel et al., 2013; Kirchner, 2016a; Klaus et al., 2015; Rinaldo et al., 2011; van der Velde et al., 2012). Most of these efforts are based on tracer-aided conceptual hydrological models where the storage components respond to different mixing and/or sampling processes (Benettin et al., 2015a; Birkel & Soulsby, 2015; Hrachowitz et al., 2013; Hrachowitz et al., 2016; McMillan et al., 2012). Many studies have simulated transit time by means of lumped parameter models based on convolution, fitting of seasonal sine wave functions, or a-priori definition of the TTDs shape (e.g., Birkel et al., 2012; Seeger & Weiler, 2014; Timbe et al., 2014; van der Velde et al., 2010). Conceptual models have been developed assuming additional tracer storage elements that are hydrologically passive (e.g., Benettin et al., 2015b; Birkel et al., 2011; Fenicia et al., 2010; Hrachowitz et al., 2015; van Huijgevoort et al., 2016). A recent framework combining catchment scale flow and transport processes is based on StorAge Selection (SAS) functions, which define the relationship between the distribution of ages available in the hydrologic storage and the ages removed as outflows (Harman, 2015; Rinaldo et al., 2015). These approaches have contributed to the understanding of catchment transport processes and have explored the dynamics of TTDs, but require a priori assumptions concerning the transport behavior. Other studies aim to provide more complex and physically based descriptions of hydrological processes, but they are often limited to small spatial scales or short temporal scales due to their high computational demand, or they lack validation against tracer observations. Examples include approaches using individual water particles tracked in the flow (Bearup et al., 2016; Davies & Beven, 2015; Davies et al., 2013; Engdahl et al., 2016; Niu & Phanikumar, 2015; Weill et al., 2011) and 3-D numerical simulations of advective-diffusive transport on single hillslopes (Fiori & Russo, 2008; Fiori et al., 2009; Jones et al., 2006; Rinaldo et al., 2011; Russo, 2015).

Here we present an intermediate-complexity approach to explore the effects of spatial heterogeneity and hydrologic non-stationarity on catchment TTDs. We introduce a spatially distributed hydrological model coupled with a solute transport component that can efficiently reproduce water and tracer flows for a small experimental catchment (Hafren, Plynlimon, UK). Iterative runs of the model allowed us to track the flow-paths of long series of precipitation inputs to the catchment. The aims of this study are: (1) to test the ability of a fully distributed model to reproduce tracer flows without defining a priori mixing or sampling laws at the catchment scale and without including passive storages, (2) to obtain TTDs, young water fractions, and water age compositions directly from model results without making prior assumptions about their distributions, (3) to assess the effects of hydrometeorological variability on modeled TTDs, and (4) to examine the influence of topographic and land-use properties on streamflow formation as reflected in TTDs.

2. Methods

In this section, we first present a new fully distributed hydro-chemical model for simulating water and tracer movement (section 2.1). The model was calibrated for the Hafren subcatchment within the Plynlimon river basin (UK), where its ability to replicate water and tracer fluxes was tested (section 2.2, 2.3 and 2.4). We then describe how we used the model to track water from various precipitation events and subcatchments, and explicitly obtain forward and backward TTDs (section 2.5).

2.1. Model Formulation

In order to characterize water transit and residence time distributions, we developed a fully distributed hydrochemical model that tracks water and solutes from individual precipitation events, and solutes falling on different parts of the catchment. The WATET (Water Age and Tracer Efficient Tracking) model couples a spatially fully-distributed hydrological model with a module that simulates solute transport and water aging. A distributed physically explicit model has been chosen as it allows computing flow paths and distributed state variables while applying realistic physical constraints (Fatichi et al., 2016). Specifically, WATET has been developed to include only the essential components of a process-based hydrological model, while remaining relatively efficient in terms of computational time for catchment-scale, long-term, and high-resolution distributed simulations. The hydrologic components of the model were conceived as a simpler version of

Figure 1. Illustration of how WATET models water and tracer flows in one grid cell.

the fully distributed rainfall-runoff model TOPKAPI-ETH (e.g., Fatichi et al., 2015; Ragetti & Pellicciotti, 2012). TOPKAPI-ETH has been successful in a broad range of applications where efficient simulations of catchment hydrological dynamics were required together with parsimonious parameterization and high-resolution representation of catchment processes (e.g., Fatichi et al., 2014a, 2015; Ragetti et al., 2016; Remondi et al., 2016). As in TOPKAPI-ETH, WATET provides spatially explicit simulations of all major hydrological processes at the catchment scale, resolving the mass and momentum conservation equations at each time step. It is based on a mosaic of cells on a regular grid, each one characterized by elevation, land use and soil properties.

The hydrological component of WATET simulates water flow between and within cells on the surface, in the channel, and in the soil and aquifer layers, which mimic shallow and deep water storage (Figure 1). Each cell is connected to the surrounding ones in the surface and subsurface along topographic gradients. After accounting for precipitation, actual evapotranspiration (limited by available soil moisture)

and infiltration, WATET simulates overland and channel flow using a kinematic wave approximation that accounts for surface roughness and follows the local topographic slope (Ciarapica & Todini, 2002). Overland flow can be generated by saturation excess and infiltration excess runoff. In the model, the soil water storage in each cell is recharged by infiltration, the rate of which is assumed to be the minimum between the precipitation rate and the soil saturated hydraulic conductivity. Soil water flow in the horizontal and vertical directions is controlled by hydraulic conductivity, whose dependence on saturation state is parameterized with van Genuchten conductivity functions (Van Genuchten, 1980). Saturated cells can feed the surface flow. Subsurface lateral flow is modeled by the kinematic wave equation, after vertical deep leakage toward the aquifer is computed. Groundwater storage is schematized as a non-linear reservoir equivalently to Benettin et al. (2015b) for the same catchment: each cell drains to its adjacent downslope groundwater storage or streamflow cells at a rate that is a power function of its local groundwater storage. The non-linear groundwater drainage function is assumed to be the same at every grid cell. If maximum groundwater storage is exceeded, water is transferred to the soil and potentially becomes saturation excess runoff. In order to improve the computational performance, water dynamics are solved with a 5 min simulation time step, and internal time steps for surface overland and channel flow routing are set to 20 and 6 seconds, respectively. With these time steps, the adopted cell size (24.4 m) preserves the Courant criterion for almost all flow conditions (up to 1.2 m/s for overland flow and 4 m/s for channel flow).

The transport component of WATET explicitly calculates the spatially distributed water age and conservative tracer concentrations in the soil, aquifer and channels. The passive tracer can be introduced to the system with precipitation input and it can assume different concentrations in each cell and storage compartment (channel, soil, aquifer) at each time step. Moreover, dry deposition and evapoconcentration can be explicitly simulated in WATET. We assumed that the conservative tracer follows the water (i.e., a purely advective behavior) and that each storage compartment in each cell is well-mixed, without the presence of a residual or passive storage (e.g., Hrachowitz et al., 2013; Kirchner et al., 2010). Flow is non-age-selective, so the discharge from each storage compartment has the same mean age and tracer concentration as the water in that compartment during that time step. Tracer concentrations and mean ages differ among layers and cells, thus allowing catchment structure and geomorphology to play a major role in the tracer dynamics of the entire catchment, and to act as a distributed selection function. Note that while passive storage is not explicitly assumed, it can occur in practice because certain parts of the catchment or the groundwater exhibit slow hydrological response but contribute to the mixing, thus behaving similarly to a lumped passive storage at the catchment scale. The model is based on the hypothesis that macroscale heterogeneity can explain a large part of the conservative tracer response, acting as a distributed selection function.

The required input variables for the model are the distributed fields of precipitation rates and tracer concentrations, and potential evapotranspiration (PET) at each time step. PET depends on land cover, wind speed, air temperature, solar radiation, and humidity. It is calculated externally and it is used as input to WATET. In

this study, we used the ecohydrological model T&C to compute PET, as it has been shown to provide satisfactory results in simulating evapotranspiration dynamics in a number of sites worldwide (e.g., Fatichi et al., 2014b; Fatichi & Ivanov, 2014; Pappas et al., 2016; Paschalis et al., 2016, 2017). T&C is a mechanistic model intended to simulate various components of the hydrological and carbon cycles, resolving exchanges of energy, water, and CO₂ at the land surface and at the hourly time scale. Actual evapotranspiration is subsequently calculated in WATET from PET by applying a reduction coefficient that takes into account the available soil moisture content (Fatichi et al., 2015).

2.2. Case Study

The model framework described above has been applied to the Hafren catchment in Mid Wales (UK), to test the model performance against observed discharge and tracer data. The Hafren watershed is part of the Plynlimon experimental catchments run by the Centre for Ecology and Hydrology (CEH). Intensive measurement campaigns have been conducted at Plynlimon, providing both high-frequency (Neal et al., 2012, 2013) and long-term passive tracer (chloride) data (Neal et al., 2010, 2011), in addition to hydrological and meteorological data sets. A remarkable number of studies over the last 40 years have documented the climatic, geomorphic, and hydrological characteristics of the catchment (see Bell, 2005; Brandt et al., 2004; Kirby et al., 1997; Kirchner, 2009; Marc & Robinson, 2007; Robinson et al., 2013; Shand et al., 2005, and references therein). Particular attention has been devoted to the dynamics of chloride, as it can be considered a conservative tracer that sheds light on transport processes (Benettin et al., 2015b; Chen et al., 2002; Harman, 2015; Kirchner & Neal, 2013; Kirchner et al., 2000; Neal, 2004; Neal & Kirchner, 2000; Neal et al., 1988; Neal et al., 2001; Page et al., 2007).

The Hafren catchment covers 3.6 km² of the headwaters of the Severn River, with elevations ranging from 352 m to 738 m above sea level. The basin can be divided in two parts with different vegetation and soil characteristics, as shown in supporting information Figure S1. The Upper Hafren (UHF) drains 1.2 km² of moorland, mostly overlying peat and gley soils. The Lower Hafren (LHF), by contrast, is a conifer plantation forest underlain by peaty podzol soils. The geology is Palaeozoic shales, grits and mudstones. The region has a humid maritime climate with moderate seasonality and frequent rainfall, amounting to more than 200 rain days per year and resulting in a mean annual precipitation of 2,673 mm over the period 1984–2010. The catchment has a fast hydrologic response, with peak flows typically occurring within 1 hour of precipitation and with a non-linear relationship between storage and discharge (Benettin et al., 2015b; Kirchner, 2009).

Chloride is the water tracer used in the study, because it is predominantly nonreactive under typical catchment conditions, particularly at the high atmospheric loading rates that characterize maritime catchments such as Plynlimon. In the Hafren catchment, chloride is derived mostly from Atlantic Ocean sea salt aerosols, which reach the catchment in the form of rainfall, mist droplets, and dry deposition, with concentrations varying greatly among storms (Benettin et al., 2015b; Neal & Kirchner, 2000). The chloride fluctuations in discharge and groundwater are strongly damped compared to those in the rain, reflecting storage and mixing in the catchment (Neal & Kirchner, 2000). As shown by Kirchner et al. (2000) and Kirchner and Neal (2013), the system acts as a fractal filter, transforming the concentration fluctuations from white noise in the rainfall to 1/*f* noise in streamflow. Reflecting seasonal input variations, streamflow chloride concentrations vary seasonally, with higher means in the winter months (Neal & Kirchner, 2000; Page et al., 2007). Moreover, the stream chloride time series exhibits a time-varying correlation with discharge, with high-flow concentrations deviating upward or downward from relatively stable base flow values, following seasonal patterns in rainfall chloride (e.g., Figure 4 of Neal et al. (2012)).

2.3. Model Setup, Calibration, and Confirmation

The WATET parameter set used in this study was obtained by calibration. To set up the model for the Hafren catchment we used spatially distributed data provided by CEH, including elevation, stream network position, vegetation and soil type. A DEM retrieved from the METI and NASA's product ASTER GDEM Version 2 (NASA JPL, 2009) was used to represent the catchment topography with a spatial resolution of 24.4 m (supporting information Figure S1a). Consistent with the DEM, the model regular cell size was set to 24.4 m. Hourly meteorological data were available from two automatic weather stations close to the top and bottom of the Hafren catchment (Carreg Wen and Tanllwyth, respectively) and 15 min hydrological measurements were available from the Upper Hafren (UHF) and the Lower Hafren (LHF) gauging stations (see

Table 1
Model Constant Parameters

Parameter	Value	Unit	Reference
Saturated water content – woodland	0.61		Jackson et al. (2008)
Saturated water content – moorland	0.59		Jackson et al. (2008)
Residual water content – woodland	0.18		Jackson et al. (2008)
Residual water content – moorland	0.20		Jackson et al. (2008)
Manning roughness – river	0.04	$s\ m^{-1/3}$	McCuen (2005)
Manning roughness – woodland	0.36	$s\ m^{-1/3}$	McCuen (2005)
Manning roughness – moorland	0.20	$s\ m^{-1/3}$	McCuen (2005)
Groundwater lateral flow and seepage – exponent	28		Benettin et al. (2015b)

supporting information Figure S1a). In addition, our analysis uses 7-hourly and longer-term weekly measurements of chloride concentrations, in precipitation deposition at the Carreg Wen station, and in the catchment outlet at the UHF and LHF gauging stations.

In order to calibrate the model parameters, we ran the model with a 5 min time step for the entire year of 2008, for which high-frequency discharge measurements are available at the UHF and LHF stations and 7-hourly chloride measurements are available at the UHF station. High-frequency chloride measurements are available also for the LHF station, but only until mid-March 2008. In the 1 year of calibration, the soil component could reach a dynamic equilibrium after a couple of months of spin-up given the high precipitation rates in the Hafren basin. The groundwater component would have benefited from a longer

initial “training,” but chloride data allowed setting a reasonable initial concentration amount in the groundwater cells. However, because this ultimately affects the reference value for the entire series, we emphasized the temporal dynamics rather than the actual values of simulated chloride. Input time series comprise rainfall rates (linearly downscaled from the sampled hourly resolution and spatially distributed with the Thiessen polygon method (Thiessen, 1911)), PET, and chloride concentration in the rainfall. The 7-hour chloride observations were firstly corrected following Benettin et al. (2015b) and then assigned to precipitation on all the 5 min time steps within each sampling interval (Harman, 2015). When possible, model parameters were set a priori on the basis of field observations and previous studies as summarized in Table 1. This was the case for parameters such as the saturated and residual water content and the Manning roughness parameters. Chloride mist and dry deposition was set as a fraction of the precipitation chloride, equal to 12% over moorlands and 35.5% over forests (Harman, 2015; Neal & Kirchner, 2000; Wilkinson et al., 1997). Given limited evidence of evapoconcentration influencing the chloride concentrations in the simulation period (Benettin et al., 2015b), chloride evapoconcentration was not accounted for in the model and the transpired water kept the same chloride concentration as that of the soil storage for the corresponding cell. The remaining 14 parameters were identified through manual trial-and-error calibration (Table 2). Despite being more time-consuming and characterized by some degree of subjectivity, manual calibration helps reduce the risk of considering parameter sets that fit the calibration data but lead to poor internal consistency in model response (Boyle et al., 2000; Fatichi et al., 2015; Moradkhani & Sorooshian, 2008). The model was run more than 200 times with different sets of parameters, which were varied over ranges suggested by literature (Table 2) (e.g., Bell, 2005; Benettin et al., 2015b; Brandt et al., 2004; Halliday et al., 2013; Kirby et al., 1997; Shand et al., 2005). The different parameter combinations were tested in each model run and the parameter sets which resulted in higher performance measures and physically plausible simulations of the simulated variables (e.g., amount of groundwater seepage or mean basin saturation) were then

Table 2
Model Calibration Parameters

Parameter	Lower bound	Upper bound	Calibrated value	Unit
Active soil depth – hilltop	150	400	350	mm
Active soil depth – colluvium	300	600	400	mm
Active soil depth – soliflucted head	300	600	500	mm
Active soil depth – boulder clay	600	1,000	700	mm
Curvature parameter Van Genuchten – woodland	1.5	3	1.8	–
Curvature parameter Van Genuchten – moorland	1.5	3	2.5	–
Saturated hydraulic conductivity – hilltop	30	150	45	$mm\ h^{-1}$
Saturated hydraulic conductivity – colluvium	20	100	30	$mm\ h^{-1}$
Saturated hydraulic conductivity – soliflucted head	20	100	30	$mm\ h^{-1}$
Saturated hydraulic conductivity – boulder clay	2	30	20	$mm\ h^{-1}$
Anisotropy ratio	10	100	50	–
Bedrock-soil interface hydraulic conductivity	0.001	0.1	0.01	$mm\ h^{-1}$
Maximum groundwater storage	2,000	5,000	2,500	mm
Groundwater lateral flow and seepage – coefficient	10^1	10^6	$10^{5.8}$	$mm\ h^{-1}$

Table 3

WATET Performance Measures for Simulated Discharge and Chloride Concentration in the Discharge in Model Calibration

	Upper Hafren station (UHF)	Lower Hafren station (LHF)
<i>Discharge</i>		
NSE	0.84	0.90
logNSE	0.72	0.86
VE	0.71	0.76
<i>Cl concentration</i>		
NSE	0.03	0.33 ^a
R ²	0.79	0.82 ^a
VE	0.88	0.91 ^a

^aComparison with Cl concentration observations limited to the period from 2008-01-01 to 2008-03-11.

selected for finer manual tuning. The performance measures selected for comparing model results and observations at the two gauging stations were the Nash-Sutcliffe efficiency (NSE), together with the NSE of the logarithm of the flows (NSE-log), and the volumetric efficiency (VE) (Criss & Winston, 2008) for discharge. The performance for chloride concentration was assessed using NSE, VE, and the coefficient of determination R^2 . The coefficient of determination was selected in order to emphasize the simulated temporal dynamics and ignore the effects of systematic concentration biases, which may originate from uncertain initial conditions and input concentrations. The calibration aimed to finally achieve the highest R^2 value for fitting the chloride concentration time series, while simultaneously scoring over 0.7 on all the performance measures used to evaluate the discharge time series (i.e., NSE, NSE-log, VE) and achieving qualitatively satisfactory internal consistency in the model response (Table 3).

In order to consolidate the set of parameters chosen by manual calibration and to estimate the effect of parametric uncertainty on model outputs (i.e., TTDs), we ran the model over the calibration period with 1,000 different parameter sets, sampled using Sobol's quasi-random number generator. In this way, a better coverage of the multi-dimensional parameter space is achieved with a smaller sample size (e.g., Pappas et al., 2013). The five best simulations in terms of NSE for discharge and R^2 for chloride concentrations were used to re-compute the transit time distributions as explained in section 2.5. The variability between the resulting TTDs and the ones from the calibrated model was assessed by looking at the mean difference between the 25th and 50th percentile of the TTDs. These results are reported in section 3.5.

2.4. Evaluation of Model Behavior on Long-Term Simulation

An additional evaluation of the model performance was sought by running the model for the 1984–2010 period at hourly time steps. Chloride precipitation concentration data are available over this period at 7 day resolution, with 26% of weeks having no reported data (usually due to precipitation volumes that were too small for chemical analysis). The 7 day chloride measurement gaps were filled as in Harman (2015) and then assigned to the previous hours since the last measure. Moreover, we rescaled the hourly precipitation data set in order to agree with the total precipitation amounts measured every 7 days with the chloride samples because of non-negligible differences between the precipitation weekly totals. To assess the model performance, in addition to NSE and R^2 , we analyzed the output in the frequency domain using spectral analysis. The power spectral density is an important indicator of the way catchments transform tracer inputs to outputs (Kirchner et al., 2000, 2001), reflecting the storage, transport, and mixing of waters over different space and time scales (Kirchner & Neal, 2013; Kollet & Maxwell, 2008). Therefore, we compared the observations and simulations for both water flow and chloride concentrations in the frequency domain, to assess how well the model captures the observed persistence and damping of the time series.

2.5. Tracking of Water Dynamics

After calibration, WATET was run multiple times in parallel, tracking the fate of each rainfall event separately. We labeled each rainy day or rain in specific areas of the basin with a different tracer. To do so, the water amounts to track are added with a known concentration of artificial tracer, which is assumed to not otherwise exist anywhere in catchment storage. Consequently, we can track the tracer concentration variability throughout space and time, reflecting solely the quantity we introduced and for which we know the origin. We ran the model with a 5 min resolution over the years 2004–2010. In the first experiment, we separately tracked several precipitation days over the entire catchment, whereas in the second experiment we tracked precipitation onto different catchment regions.

In the first experiment, all 546 days with precipitation during the years 2005 and 2006 were individually labeled and tracked over the simulation period from 2004 to 2010 with the calibrated WATET model. These simulations allowed us to derive transit time distributions given rainfall time (forward TTD) and given exit time (backward TTD), as discussed e.g., by Rinaldo et al. (2011). In the forward approach, we focused on when precipitation reaches the outlet as discharge. In the backward approach, we analyzed how the discharge in each day is composed of water of different ages, i.e., water that entered the system at different

times. To do so, we also made use of the young water fraction F_{yw} defined by Kirchner (2016a, 2016b). For the Plynlimon catchment, this metric is determined as the fraction of runoff with transit times up to (and including) 69 days (Kirchner, 2016b). Moreover, we extended the use of the young water fraction, calculating multiple water fractions corresponding to a series of young water thresholds, which directly express the catchment cumulative distribution of transit times as suggested by Kirchner (2016a).

In the second experiment, we divided the catchment into different regions according to three main catchment characteristics (land cover, soil type and topography) that are expected to drive the hydrologic response. These included two vegetation cover units (moorland and forest), four soil types (hilltop, colluvium, soliflucted head, and boulder clay) and five classes of topographic wetness index (<4.8 , $4.8-8.8$, $8.8-12.8$, $12.8-16.8$, >16.8). The topographic wetness index was computed as $\ln(\alpha/\tan\beta)$, where α is the upslope cumulated area per unit contour width and β is the cell slope angle (Beven & Kirkby, 1979). The model was run over the years 2004–2010 multiple times, separately tracking the precipitation that fell on a different region of the catchment. We could therefore analyze the influence of topography, soil and vegetation characteristics on discharge formation.

3. Results

3.1. Model Performance

In the calibration year, we tracked water and chloride fluxes in every layer and grid cell. The model is able to reproduce the discharge data at the Upper and Lower Hafren stations with NSE's of 0.84 and 0.90, respectively (Table 3). The temporal dynamics of chloride concentrations in the discharge are satisfactorily captured by the model (R^2 of 0.79 and 0.82), although there is a systematic bias and the variance is bigger in the simulations than the data, resulting in low NSE scores. Possible reasons for the chloride bias could be the initial conditions assigned to the chloride in the catchment, the disaggregation of the chloride data, or the limited complexity of process representations in the model. Simulated discharge rates and chloride concentrations are shown in Figure 2 along with the observed values for the Upper and Lower Hafren stations.

Figure 2. Time series of simulations for the 2008 calibration year compared with observed values in the Hafren catchment, Plynlimon, Wales. The left plots compare the observed (blue) and simulated (red) discharge at the (a) Upper Hafren (UHF) and (b) Lower Hafren (LHF) stations. The right plots compare the observed (blue) and simulated (red) chloride concentrations at the (c) UHF and (d) LHF stations. The simulated groundwater chloride concentration averaged over the catchment is also shown (green).

Figure 3. Power spectra of observed (blue) and simulated (red) time series of water fluxes (left column) and chloride concentrations (right column). The dashed lines show the power spectra from observed precipitation rates (left) and observed chloride concentration (right) at the precipitation sampling point (Carreg Wen station). The top plots compare the power spectra at the Upper Hafren station (UHF) for discharge and chloride concentrations in the discharge, whereas the bottom plots compare the power spectra for the Lower Hafren station (LHF). Observations and simulations display similar slopes. In particular, the slopes of simulated chloride concentrations exhibit fractal $1/f$ scaling (gray lines).

At both locations, flow peaks as well as recessions are successfully captured by the model. During base flow periods, the discharge is substantially fed by groundwater seepage (as seen in Benettin et al., 2015b; Neal et al., 2012). This is also reflected in the chloride concentration values, which rapidly shift toward the concentration of the groundwater storage after the rainfall events (Figures 2c and 2d).

The mean soil saturated area in the model that can potentially lead to localized overland flow is 13%, of which 9% is accounted for by cells that overlap with the stream network. This behavior is in line with Bell (2005) and Knapp (1979) who reported that at Plynlimon overland flow is mainly confined to areas near the streams, although the spatial resolution (24.4 m) of our model is likely to exaggerate the saturated area relative to Plynlimon's much narrower channels.

In order to evaluate the longer term performance of the model, we ran WATET on an hourly time step from 1984 to 2010 (supporting information Figure S2). The simulation results capture the observed hourly discharge rates well, with NSE values of 0.80 for UHF and 0.86 for LHF. The comparison with the weekly time series of chloride concentrations yields R^2 values of 0.53 and 0.55 for the two stations and a significant bias in the chloride concentration (negative NSE). These results may be partially explained by model deficiencies in representing long-term storage and mixing processes and by the calibration being limited to just one year (2008). They may also arise from uncertainties in the rainfall inputs and in downscaling the chloride input data (measured in this case every 7 days instead of every 7 hours). Results from this long simulation are presented in the form of power spectra for both observed and simulated water fluxes and chloride concentration (Figure 3). Power spectral density, here computed following the methods described in Kirchner and Neal (2013), allowed us to evaluate persistence in the simulated time series compared to the observed ones. The model acts as a filter of the input signal. The power spectra slopes of both water fluxes and chloride concentrations are satisfactorily reproduced. The simulated chloride fluctuations at the two discharge stations are strongly damped relative to chloride fluctuations in the precipitation (Kirchner & Neal,

2013), following $1/f^\alpha$ spectral scaling with $\alpha=0.96$ in the observations at UHF and LHF and $\alpha=1.01$ in the simulation. For frequencies higher than about 1/month, the model shows a slope of about -2 , which indicates that simulations over-damp the signal in the short-term. This can be due to the intrinsic model structure but also to the fact that the downscaling of the 7 day chloride data to the hourly scale, assuming constant concentration, erases input fluctuations on shorter time scales and thus affects the short-term correlation in the input. Another difference is represented by the offset of the chloride power spectra. This is not due to different sampling frequencies (hourly scale in simulations and every 7 days in the collected measurements) because the spectra have been properly normalized. Despite this, the spectral power of simulations is higher than observations across the frequency range, indicating a larger variability in the chloride simulations than observations, possibly due to a lack of damping by passive storage. We emphasize that the model has not been re-calibrated for this long-term simulation, and the parameters values derived from the 2008 calibration are probably not optimal for the 1984–2010 long-term simulation. Nonetheless, the spectral slopes of the simulation and observations agree for frequencies below $\sim 20 \text{ yr}^{-1}$, suggesting that some key features of the underlying process dynamics are still captured in the model.

3.2. Forward Transit Time Distributions

We ran the calibrated model from 2004 to 2010, tracking each day's precipitation for the years 2005 and 2006. As explained in section 2.5, the model permits tracking the amount of water arriving each day and its flowpath through the basin as shown in Figure 4. The partitioning of water entering the model on two example days is shown in the supporting information Figure S3. For each day, the proportion of event water stored in the

Figure 4. Fate of the water parcels rained in the catchment in the years 2005 and 2006. The top plot shows the daily precipitation amounts colored according to the date. The three lower plots represent the fractions of the discharge, soil storage, and groundwater storage that are made up of the colored inputs. The black lines indicate the total amounts, whereas the white areas indicate water that was already in the catchment before 2005.

Figure 5. Forward cumulative transit time distributions for the 2005–2006 precipitation events, plotted as a function of (a) exit time and (b) cumulated discharge. When the distributions are rescaled as a function of cumulative discharge, they tend to collapse around a single distribution representing all of the precipitation events.

groundwater, soil, surface or channel compartment is tracked together with the proportion recovered as outflow or lost as evapotranspiration.

Individual transit time distributions for each precipitation event were obtained from the model results. The collection of cumulative transit time distributions for the 2005 and 2006 precipitation events is presented in Figure 5a. These quantities are normalized by the total rainfall amount of each day once the part lost through ET is subtracted. The figure allows one to extract some basic information on the average behavior of the model. For instance, 50% of the precipitation that becomes discharge takes on average 59 days to reach the outlet. Linearly extrapolating the cumulative distributions for exit times larger than 1,200 days, we can estimate that 99% of the discharge water would reach the outlet on average in 7.5 ± 0.9 years and 99.9% in 8.9 ± 0.9 years. TTDs at the Upper Hafren and Lower Hafren gauging stations are broadly similar, with the lower half of the Upper Hafren curves slightly shifted to the left, i.e., having faster transit times (supporting information Figure S4). For the Upper Hafren, 50% of the

Figure 6. Variations in transit time of 25 and 50% of water (the lower quartile and median of the forward transit time distribution) from the 2005 and 2006 precipitation events, for different modeled basin conditions at the time that rain fell. Transit time varies systematically with (a) season, (b) precipitation amount, (c) evapotranspiration, (d) basin effective saturation, and (e) groundwater storage.

precipitation that becomes discharge takes on average 67 days to reach the outlet and a median of 53 days, compared to an average of 59 and a median of 47 days for the LHF.

Figure 6 explores how catchment hydrological conditions affected the modeled transit time distributions for the entire Hafren. Specifically, we analyzed the variation of transit time for the first 25% and 50% of the water to exit from individual precipitation events (that is, the lower quartile and the median of the forward transit time distribution) in relation to the month, precipitation amount, ET amount, basin effective soil saturation, and groundwater storage at the time of rainfall. The median transit time varied between 6 and 177 days among the individual rainfall events. The time to reach the exit was generally much longer during the drier months, e.g., the forward transit time distribution exhibited strong seasonality (Figure 6). On average, rainfall events between September and April discharged 25% of their water in less than 17 days, whereas events between May and August needed 23 days on average. The median transit time for events between September and April was 47 days, versus 60 days for events between May and August. Precipitation amount, basin effective saturation and groundwater storage at the time of the event were negatively correlated with the transit time, whereas ET was positively correlated. The boxplots for these properties are large, showing a less clear dependence of transit time on process controls than on seasonality. When precipitation was under 5 mm/d, half of the precipitated water became discharge after an average of 70 days, whereas after heavy precipitation events (over 30 mm/d), half of the water exited the system after an average of 27 days. The dependence on ET shows an opposite trend: half of the precipitated water took 43 days to exit the catchment when ET at the day of rainfall was under 0.25 mm/d, but more than 114 days when ET was over 3 mm/d. Basin effective saturation and groundwater storage conditions also affect exit times. Half of the precipitated water was discharged in 81 and 76 days during periods with relatively dry soil and low groundwater, respectively, versus only in 29 and 26 days when soil was particularly wet and groundwater storage was high.

As one would expect, the various controls are correlated one with each other. Including all process controls as factors in a multiple quadratic regression model explained 50% of variability in the median exit time with the month of the year and ET as the best predictors (R^2 of 0.37 and 0.19 respectively and R^2 of 0.40 when combined). Precipitation alone explained 9% of the variability and it contributed only marginally when combined with ET and the month ($R^2=0.43$). Soil saturation was correlated with groundwater storage, and combining them together explained a relatively small fraction of exit time variability ($R^2=0.22$). When both were combined with the month, R^2 increased to 0.45.

When the cumulative transit distributions are plotted as a function of the cumulative discharge following each rain event, rather than as a function of the exit time, the curves are much more tightly clustered (Figure 5b). The coefficients of variation of the 25th and 50th percentiles are reduced by more than a factor of two, from 0.73 to 0.24 and from 0.68 to 0.27, respectively.

3.3. Backward Transit Time Distributions

Keeping records of the modeled fluxes from 2 years of precipitation events allowed us not only to study their transit time through the catchment, but also to analyze the proportion of discharge with different ages and coming from different storages. Figure 7 shows the dynamics of water storage in the model, including the young water fractions F_{yw} (<69 days) in the soil, groundwater and discharge. The F_{yw} in the discharge is strongly negatively correlated to the fraction of groundwater in the discharge, because the soil storage always consists of more than 65% of young water (91% on average), whereas the groundwater storage holds mostly old water (its F_{yw} is always less than 16%). The storage volume and young water fraction in the soil vary faster than those in groundwater (Figure 7d).

F_{yw} values vary with shifts in flow regime. With increasing discharge, the F_{yw} modestly increases in the soil and groundwater storage, whereas it increases logarithmically in the discharge itself (Figure 8), reflecting a decrease in the proportion of groundwater and an increase in the proportion of soil water. The F_{yw} in the entire storage, considering both soil and groundwater, is always lower than 0.24 and the discharge always has a higher proportion of young water than the storage does (Figure 8b).

Figure 7. Time series from the WATET simulation for the years 2005 and 2006. (a) Precipitation events result in rapid discharge increases at the outlet. (b) Groundwater contributes a larger proportion to the streamflow during drier periods, but rapid shifts to dominance of soil and surface contributions are seen after larger precipitation events. (c) Young water fractions for discharge, soil layer, and groundwater storage vary widely, with soil water largely composed of young water, in contrast to groundwater which has always less than 20% of young water. (d) Soil and groundwater storages are also shown.

Figure 8. Relation between young water fractions F_{yw} simulated in the various model compartments and discharge. (a) Daily values of young water fractions in streamflow exhibit a roughly logarithmic increase with discharge (blue), whereas young water fractions in the soil (red) and groundwater (green) compartments change more gradually with discharge. (b) The young water fraction in discharge is always higher than in the entire storage.

So far, we have presented the fraction of young water computed for a fixed threshold age. Varying the threshold ages and computing the associated younger water fraction yields the cumulative distribution of travel time conditioned on sampling time (Kirchner, 2016a). Figure 9a shows the cumulative distributions of travel time for each discharge event. The colors indicate the mean basin effective saturation at the exit day, which is correlated to the wetness of the previous days. A strong effect of wetness is visually evident, but we refer to supporting information Figure S5 of the SI for a better representation of how water ages in discharge vary with catchment conditions. Figure 9b shows the average behavior of the backward TTDs under four catchment wetness regimes: wet, dry, wetting-up and drying-up (Heidbüchel et al., 2012; Hrachowitz et al., 2013). The four wetness regimes exemplify the “end-members” of possible wetness conditions and are defined by the combinations of high or low soil and groundwater storages, as these have the major influence on the daily discharge age composition. Wet regimes were defined as those days with water volumes in the soil and groundwater exceeding their 65th percentiles, that is, mean saturation over 0.72 and storage higher than 1,440 mm. Although the Hafren catchment never reaches properly dry conditions, we defined dry regimes by mean soil saturation lower than 0.62 and groundwater storage lower than 1,420 mm, that is, each not exceeding their respective 35th percentiles. We defined the wetting-up regime by mean soil saturation over 0.72 (that is, above the wet threshold) and groundwater storage of less than 1,420 mm (that is, below the dry threshold), whereas the drying-up regime was defined by mean soil saturation lower than 0.62 (i.e., below the dry threshold) but groundwater storage above 1,440 mm (that is, above the wet threshold). The four categories exclude the transitional regimes with soil and groundwater storage values in between the ones mentioned above. Consistently, the main contribution to the shape of the transit time distribution is given by the soil saturation, whereas the groundwater level is less able to shift the curve. The medians of the transit time distributions average 15, 19, 125, and 205 days in wetting-up, wet, drying-up, and dry conditions, respectively.

Finally, the WATET simulations also allow us to calculate the residence time distributions for the soil and aquifer storage (see supporting information Figure S6). The distributions of ages in the discharge and in the storage allow a direct evaluation of the StorAge Selection functions (Rinaldo et al., 2015). For clarity, Figure 9c shows the SAS results averaged among the set of events for the four catchment conditions described above. The results agree with previous studies in the Hafren catchment by Benettin et al. (2015b) and Harman (2015). During wet conditions there is a strong preference for younger water in the discharge, whereas in drier conditions, the storage is sampled more uniformly. The lines for dry conditions go below the $SAS = 1$ line only at older ages, reflecting the high proportion of old water in the groundwater storage.

3.4. Effect of Spatial Heterogeneity on TTDs

The capability of the WATET model to track water origin was additionally used to explore the influence of different catchment regions on discharge formation. We focused on spatial variations in three controls: vegetation cover, soil type, and topographic index. Figure 10 reveals how the various discharge amounts are composed by

Figure 9. Age composition of daily discharge. (a) The cumulative age distribution of each daily discharge is colored according to the mean effective saturation of the basin on that day. (b) The mean age distributions of discharge events during different wetness regimes following the combination of high and low storage in the groundwater and soil. (c) Averaged StorAge Selection (SAS) functions for various combinations of groundwater and soil conditions.

flows from various catchment regions, after normalizing for the effect of the area size. The biggest difference is seen among parts of the catchment with different topographic wetness index values. As expected, precipitation that arrives in regions with lower topographic wetness index values is more likely to recharge the groundwater or be evapotranspired, rather than being discharged at the outlet. On the other hand, precipitation on areas with high topographic index values contributes more directly to discharge. The different soil and vegetation types have an influence on the TTDs, but their time-aggregated control on simulated discharge formation appears to be not particularly relevant for the Hafren catchment (Figure 10a, b).

3.5. Sensitivity of TTDs to Model Parameters

Given the practical infeasibility of exploring the entire space of model parameters, we evaluated a subset (described below) of 1,000 parameter sets sampled using Sobol's quasi-random number generator and tested over the calibration period. No simulation yielded higher values for all the performance indexes than those of the calibrated model as in Table 3. Simulations with higher NSE for the chloride concentration (up to 0.61) were achieved, but were disregarded in favor of parametrizations that achieved a high R^2 . Simulations with high R^2 are representative of a good reproduction of the chloride temporal variability, while simulations with higher NSE for the chloride concentration were mostly minimizing the bias with respect to the mean chloride concentration but were less satisfactorily in representing the correct temporal dynamics (supporting information Figure S7). Among the tested parameters, we retained only five sets capable of best reproducing discharge (as measured by NSE), and chloride concentrations as measured by R^2) at the two gauge stations.

Running the WATET model with the five selected parameter sets allowed us to evaluate the role of parameter uncertainty in the forward TTDs of the 2005 precipitation events. In particular, we looked at the modeled distribution of exit times (with a focus on the 25th and 50th percentiles) of the amount of water precipitated in the catchment on days with more than 10 mm/day precipitation. The difference between the 25th percentile TTD's from the five parameter sets and the calibrated simulation averaged 7 days (as a reference, the 25th percentile TTDs from the calibrated simulation averaged 17 days) and 50th percentile TTD's differed by an average of 15 days (compared to a mean of 54 days for the 50th percentile TTD's in the calibrated simulation). This suggests that model parameter uncertainty is relatively large (on the order of 30–40%) for the TTD values and distributions presented in this study.

4. Discussion

4.1. The WATET Model

The WATET model was designed to track water and conservative tracers in a distributed manner. It was calibrated to reproduce discharges and chloride concentrations for the year 2008 at two stream locations in the Hafren catchment where high-temporal resolution (7-hourly) chloride data were available. A longer-term confirmation test yielded good discharge estimates (NSE = 0.84 and 0.90), but showed less satisfactory simulations of the stream chloride time series, which yielded values of R^2 equal to 0.53 and 0.55 but negative NSE due to a persistent bias. This result was affected by uncertainty induced by the coarse temporal resolution, by a significant fraction (26%) of

Figure 10. Topographic controls on discharge composition. After having normalized for catchment areas in each category, discharge is decomposed into the contributions from water precipitating on different (a) vegetation covers, (b) soil types, and (c) topographic wetness index areas.

missing values in the long-term chloride inputs and by precipitation measurement uncertainties. However, the analysis in the spectral domain showed that the model is able to reproduce the catchment damping of the chloride input signal and to correctly reproduce the power-spectrum slope for frequencies lower than roughly 1 month^{-1} (i.e., time intervals longer than roughly 1 month). Water and conservative solute fluxes were tracked through the system for time scales between 1 hour and 1 year. WATET explicitly describes the dynamics of watershed storage, concurrently solving for the celerity and velocity (McDonnell & Beven, 2014) of catchment transport. The perfect mixing hypothesis, which was used here for the various storages of each cell, yields plausible solute dynamics at the catchment scale when applied to relatively small volumes within the catchment, i.e., 24.4 m cell size and up to four storages (channel, surface, soil, and groundwater). However, this hypothesis is well known to fail if the entire catchment is treated as a single well-mixed storage (e.g., Kirchner et al., 2000).

While being complex enough to represent water and tracer transport processes, WATET is also fast enough to allow the parallel tracking of multiple rainfall events in a reasonable amount of time (tracking one precipitation event for 7 years of simulation takes around 20 hours laptop runtime). Many studies have estimated transit time by means of lumped models with a-priori definition of the TTD shape or conceptualized models with slowly responsive passive storages and/or pre-defined sampling age selection functions. In this study, instead, the forward and backward TTDs, residence time distributions, and SAS functions are time- and space-variant and are derived from the model results; thus they are free from various a priori assumptions, such as the shape of the distribution. The results are, however, still influenced by the model assumptions (e.g., complete mixing for each cell layer), cell size and the chosen model parameters as explored in section 3.5. While uncertainty in model parameters can affect the reported values for TTD up to 30–40%, the simulated patterns and environmental dependencies are more robust and consistent with expectations of catchment behavior (Figure 6).

4.2. Influence of Nonstationarity and Heterogeneity on TTDs

The results highlight the influence of catchment nonstationarity and heterogeneity on modeled TTDs. Both forward and backward TTDs are seen to vary greatly throughout the year and with catchment hydrologic conditions. Forward TTDs vary strongly with the season in which the rain event occurs, as well as with variables such as precipitation volumes, ET rates, soil saturation and groundwater storage at the time of the event. In other words, the conditions when water enters the system are a major indicator of how long it will take to exit. Seasonality appears to be a strong predictor of the forward TTD because it is correlated not only with the current catchment status, but also with the future wetness evolution and, thus, catchment response. Similar findings are seen in Danesh-Yazdi et al. (2016) and Heße et al. (2017) for watersheds with different physical structures and climatic conditions. On the other hand, backward TTDs are strongly dependent on the soil saturation and, to a lesser degree, on groundwater storage.

To highlight the different age compositions in the discharge, we computed the wetness-dependent temporal dynamics of the distributions. Although absolute storage differences are small in the wet Welsh climate

with its moderate seasonality, we could clearly see differences in the exit TTDs from one wetness regime to another. For example, very wet conditions in the soil compartment generate discharge that is ten times younger than discharge during drier conditions. This is consistent with recent findings by Soulsby et al. (2015) that illustrate how, in wet conditions, hillslopes and riparian zones have strong connectivity, allowing high proportions of relatively young water to reach the channel. Other studies have found similar differences between wet and dry antecedent conditions, (e.g., Benettin et al., 2015b; Heidbüchel et al., 2012; Hrachowitz et al., 2013).

Further, we have explored how discharge in the Hafren catchment is related to catchment heterogeneity in vegetation types, soil properties, slope and drainage area (the last two being reflected in the topographic wetness index). Not surprisingly, the topographic wetness index, which predicts the most likely saturated areas (Beven, 2011; Quinn et al., 1991; Tetzlaff et al., 2007), is highly correlated with specific discharge. The wetter the location where rain falls, the greater the local contribution to discharge formation. This result agrees with our conceptual understanding and with studies in other catchments (e.g., McGlynn et al., 2004; McGuire et al., 2005). Our modeling approach complements these observational studies by separating and directly quantifying the effects of nonlinear interactions between different landscape controls in a spatially explicit way.

4.3. TTDs and Cumulative Discharge

Transit time distributions (TTDs) were obtained from the simulation results for each precipitation event over 2 years. As seen in section 3.2, the curves display a large spread. Fiori and Russo (2008) and more recently Ali et al. (2014) have used numerical simulations to show that modeled TTDs for the transport of pulses of passive solutes exhibit a limited spread when one rescales time by the cumulative outflow, as previously proposed by Niemi (1977) and Rodhe et al. (1996). Consistent with this previous work, TTDs from our catchment-scale simulations also converged to a much narrower range after rescaling (Figure 5b). Even though we looked at more than 500 rainfall events spanning wide ranges of catchment conditions, all the non-exceedance probability curves converged within a narrow band when plotted as a function of the cumulative discharge. This finding, obtained from simulations with a physically explicit model reproducing a broad spectrum of hydrologic conditions, suggests that the representation of TTDs using the cumulative outflow may be an effective way to filter the temporal variability of meteorological controls. The resulting rescaled transport function encapsulates catchment characteristic behavior with respect to complex transport processes, and could potentially be used to rapidly calculate catchment-scale transport if discharge data are available.

5. Conclusion

In this study, we introduced a new model-based framework to explore water age and transport mechanisms in a real catchment. We presented a simple yet fully distributed hydrological model coupled with a transport component for conservative tracers. The WATET model was applied to a well-instrumented catchment in Wales (UK) and, once calibrated, it successfully reproduced water and conservative tracer fluxes. However, a longer-term validation test, based on more uncertain and potentially biased forcings, challenged the model ability to reproduce transport processes at high frequency in a multiyear time series.

We used the model as a tracking tool to follow the fate of water from 2 years of daily rainfall events in their individual paths toward the catchment outlet. This approach allowed us to derive, directly from the model results and with limited a priori assumptions, the dynamic TTDs both forward and backward in time and the young water fraction F_{yw} in the various storage compartments.

The analysis illustrates how the coupled processes of water flow and tracer transport can be inferred from plausible model simulations without assuming any particular form of the general TTD or StorAge Selection function at catchment scale, but instead by representing the catchment response with a physically explicit distributed model at high spatial and temporal resolution. Results suggest that in this catchment the forward TTDs are mostly dependent to the season in which the rain event occurs, whereas the backward TTDs vary primarily according to the catchment wetness. The spread of the forward TTDs decreases considerably when they are expressed as functions of cumulative discharge, extending the results seen in Fiori and Russo

(2008) for a hillslope model, and thus revealing a potentially simple way of summarizing catchment transport characteristics, which may also hold for larger catchments.

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Erratum

The title of the originally-published version of this article omitted the hyphen in the word “spatio-temporal.” This correction has been made to the online version, which may be considered the authoritative version of record.