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Hydroclimatic influences on non-stationary transit time distributions in a boreal headwater catchment

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SUMMARY

Understanding how water moves through catchments – from the time it enters as precipitation to when it exits via streamflow – is of fundamental importance to understanding hydrological and biogeochemical processes. A basic descriptor of this routing is the Transit Time Distribution (TTD) which is derived from the input–output behavior of conservative tracers, the mean of which represents the average time elapsed between water molecules entering and exiting a flow system. In recent decades, many transit time studies have been conducted, but few of these have focused on snow-dominated catchments. We assembled a 10-year time series of isotopic data (δ^{18}O and δ^{2}H) for precipitation and stream water to estimate the characteristics of the transit time distribution in a boreal catchment in northern Sweden. We applied lumped parameter models using a gamma distribution to calculate the Mean Transit Time (MTT) of water over the entire period of record and to evaluate how inter-annual differences in transit times relate to hydroclimatic variability. The best fit MTT for the complete 10-year period was 650 days (Nash–Sutcliff Efficiency = 0.65), while the best fit inter-annual MTT ranged from 300 days up to 1200 days. Whilst there was a weak negative correlation between mean annual total precipitation and the annual MTT, this relationship was stronger ($r^2 = 0.53$, $p = 0.02$) for the annual rain water input. This strong connection between the MTT and annual rainfall, rather than snowmelt, has strong implications for understanding future hydrological and biogeochemical processes in boreal regions, given that predicted warmer winters would translate into a greater proportion of precipitation falling as rain and thus shorter MTT in catchments. Such a change could have direct implications for the export of solutes and pollutants.

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1. Introduction

In recent decades, using tracers to understand how water moves through catchments from precipitation through soil profiles and aquifers, across land–water boundaries, and into stream flow has been a major research focus in hydrology (McGuire and McDonnell, 2006). The transit time of the specific pathways water takes, as well as the time spent residing in different soil and groundwater subsystems, has important implications for watershed management as it is fundamental to the supply of water, cycling of nutrients, and export of contaminants to surface waters (van der Velde et al., 2010). While important advances have been made in recent years, increased understanding of the mechanisms that control how water makes the journey from precipitation to the stream remains an important research challenge.

Natural tracers have commonly been used for identifying and quantifying the linkages between precipitation inputs, soil/groundwater routing, and surface flow (Goller et al., 2005; Maulé and Stein, 1990; Soulsby et al., 2000). Compared to most other tracers, isotopes of water δ^{18}O and δ^{2}H (or D as in Deuterium), behave relatively conservatively once water has entered the soil/groundwater system and therefore represent a useful tool for resolving water sources and pathways. Recently, improved analytical techniques make it more economically and logistically feasible to analyze large numbers of isotope samples, leading to the generation of increasingly long time series of precipitation inputs and stream outputs (Birkel et al., 2012; Capell et al., 2012; van der Velde et al., 2015), which allow for better and more well-constrained estimates of water transit time in catchments.

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Transit time is commonly defined as the time elapsed between when water molecules from a particular input event enter and exit a flow system (Bolin and Rodhe, 1973; McGuire and McDonnell, 2006). The average and distribution of transit times can hence be used for disentangling and quantifying information about hydrological flow paths and catchment water storage. These descriptors of water flow also facilitate better understanding of biogeochemical processes in catchments (Burns et al., 2003). Despite the importance of transit time to catchment function, it can rarely be measured experimentally with the exception of manipulated catchments where all inputs can be controlled (Rodhe et al., 1996). Therefore, transit time distributions are most commonly inferred using lumped models with time-series of input and output of natural tracers.

Many studies have attempted to estimate the transit time of water using a variety of approaches and model functions. Among these, the lumped parameter inverse modeling method has been the most extensively used (Amin and Campana, 1996; Dinçer et al., 1970; Soulsby et al., 2010; Stewart and McDonnell, 1991). Within this modeling framework, different functions have been applied, including exponential (Rodhe et al., 1996), advection-dispersion (McGlynn et al., 2003; Stewart and McDonnell, 1991), and gamma distributions (Capell et al., 2012; Hrachowitz et al., 2010; Kirchner et al., 2001). The latter has come to be most widely used as it best captures the short- and long-tails of catchment transit times, which reflect rapid and longer flow paths respectively (Godsey et al., 2010). Moreover, the gamma distribution can be considered to have physical meaning in that it captures the advection-dispersion characteristics of hillslope solute transport (Kirchner et al., 2001) in a way that relates to catchment properties and hydroclimate (Hrachowitz et al., 2010). Uncertainty in quantifying the long-tail of the gamma distribution can be reduced with long time series (Kirchner et al., 2000; Tetzlaff et al., 2015); however, using conservative tracers such as stable water isotopes limit the estimations to 4–5 years maximum due to the loss of input signals through catchment mixing processes (Stewart et al., 2010).

Nevertheless, the appropriateness of different models for calculating water transit time remains a matter for discussion (Hrachowitz et al., 2009; van der Velde et al., 2015). In addition, there is an ongoing debate in the literature over time-variant and time-invariant models as well as their applicability for predicting catchment transit times (McDonnell et al., 2010; van der Velde et al., 2015). Where some authors report no significant difference between variant and invariant models in characterizing the transit time distributions of catchment flow systems provided that long-term data sets are used (Hrachowitz et al., 2010), others have emphasized that transit time distributions vary between storms which is important when examining short-term dynamics or using short-term data sets (Birkel et al., 2012; Lyon et al., 2008; Weiler et al., 2003). Recognition of the importance of time variance has inspired new modeling approaches for non-stationary systems (Heidbüchel et al., 2012; Hrachowitz et al., 2013; Rinaldo et al., 2011).

Snow-dominated catchments have been the focus of research for decades not only because of their large geographic extent (Koeniger et al., 2008; Lyon et al., 2010; Maloszewski et al., 1983), but also because of their significance for water resources in large areas of the world (Barnett et al., 2005) and their vulnerability to climate change (Laudon et al., 2013; Tetzlaff et al., 2013). A particular challenge related to the isotope hydrology of snowmelt is that the phase transition from snow to liquid water is associated with large isotopic fractionation (Rodhe, 1998). The build-up of seasonal soil frost during winter can also play an important role for partitioning water into different hydrological pathways during snowmelt (Shanley et al., 2002), although a set of investigations from boreal Sweden have reported a range of possible behaviors in this regard (Laudon et al., 2007; Nyberg et al., 2001; Peralta-Tapia et al., 2014). Crucially, rainfall in the summer and autumn can also be the dominant proportion of annual precipitation and may have a key role in generating larger flow events (Tetzlaff et al., 2015). Thus, in northern ecosystems, multi-year studies are essential for an improved mechanistic understanding of how watershed processes are influenced by variability in intensive rain storms versus prolonged snow melt episodes, as well as of the significance of evapotranspiration intensity and seasonal soil frost (Carey et al., 2013). Besides the scientific interest in snow-dominated catchments, transit time studies based on long time series of isotopic tracers extending greater than 5 months in completely snow covered catchments are scarce (Tetzlaff et al., 2015).

To characterize the transit time distributions in boreal landscapes, and avoid the uncertainty inherent in short data series, we evaluated 10 years of isotopic tracer data (δ^{18}O and δ^{2}H) and hydrometric information from an integrated field research infrastructure in northern Sweden. The primary objectives of this work were to (1) apply a simple gamma distribution model to preliminary estimates of the long-term mean transit time of water in a snow-dominated, boreal catchment, and (2) evaluate how inter-annual variability in the mean transit time varies as a function of hydroclimatic conditions. The wider implications for water and solute transport in boreal environments are discussed.

2. Study area

The study was carried out in the Svartberget catchment within the Krycklan Experimental Catchment (64°14′N, 10°46′E; www.slu.se/Krycklan) located in northern Sweden (Fig. 1; Laudon et al., 2013). This catchment is known as 'Site 7' and the associated stream has the longest monitoring time-series among the 15 regularly sampled stations described in previous studies of the Krycklan Catchment (e.g., Laudon et al., 2007). The catchment has a long history of hydrological research, beginning in the early 1980s with pioneering work by Rodhe (1987), who used isotopic approaches, as well as subsequent hydrometric, isotopic, and geochemical tracer studies to characterize hydrologic and solute transport along hillslopes (e.g. Laudon et al., 2004).

The 30-year mean annual air temperature, precipitation, and runoff in Krycklan (1981–2010) are 1.8 °C, 614 mm and 311 mm, respectively (Laudon et al., 2013). About 35–50% of total annual precipitation falls as snow and the average period of snow cover is 168 days per year (1980–2007; Haei et al., 2010).

The study catchment has structural characteristics that are typical of boreal landscapes, being dominated by coniferous forest with a mosaic of wetlands (mires) in the headwaters. The study stream drains a 47 ha catchment covered with 52% Scots pine (*Pinus sylvestris*), 29% spruce forest (*Picea abies*), and less than 1% birch (*Betula* spp.). The other 18% of the catchment is covered by peatland, which contributes a large portion of water to the stream through a minerogenic mire (Lidman et al., 2014). Catchment elevations range from 234 m AMSL at the outlet to 306 m at the highest point. The catchment is underlain by Svecofennian gneissic bedrock with metasediments and metagraywacke (Ågren et al., 2007) covered by a layer of quaternary deposits of glacial till that varies in thickness up to tens of meters (Ivarsson and Johnsson, 1988). The mineral soils in the forested areas are relatively homogeneous, dominated by quartz, plagioclase, and K-feldspar (Ledesma et al., 2013). During winter periods, frozen soils are fully covered by snow, favoring lateral, surface overland flow especially at the mire portion of the catchment during snow melt (Laudon et al., 2007; Peralta-Tapia et al., 2014).

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