We appreciate the comments by the reviewer and the generally positive assessment of the manuscript. Below we respond (in blue text) to the individual comments (in black text). The comments have helped us to clarify the manuscript.

**Response to reviewer 1 comments**

General comments

This article presents an interesting thought experiment about how riverine network length can influence the mean travel time distribution in catchments. The authors present a set of feasible river network extents across a range of wetness conditions, assume surface and subsurface flow velocities, and then estimate plausible distributions of travel times to the catchment outlet within these wetness scenarios. As this study is an initial exploration of how network extent can influence travel time distributions and modeling solute transport, I believe this study would be more powerful if the authors emphasized how future studies can build off of this initial exploration. For instance, emphasizing what the limitations of this study design are, and how others can use these concepts and apply real datasets and hydrologic measurements to confirm the results and interpretations of this study, would be greatly beneficial.

> We describe the limitations of the study (particularly the uniform and constant velocities and the 'steady state assumption' for each stream network) on P4L19-24 (last part of the methods) and P5L29-P6L5 (first part of the discussion). Our main goal was to show that the geometry of the flowing stream network affects the distribution of the hillslope travel distances to the flowing streams (and to a much smaller extent the travel distances in the stream) and thus the travel time distribution. We describe in the discussion what these results mean for interpreting travel time distributions obtained from tracer data and highlight that these results should be considered in solute transport models that - so far - tend to use a fixed (rather than dynamic) stream network.

Since this study estimates subsurface and surface velocities, it seems appropriate to provide results from a sensitivity analysis or provide ranges in the mean travel times. While the authors state they tested surface to subsurface velocity ratios (from 10 to 10000; P 4 L 14), they do not appear to present the results of that analysis. A powerful addition to this paper would be to show possible ranges in mean transit time distributions, given minimum and maximum velocities.

> We provide the results for different velocities in Figure 6 and describe them in the last paragraph of section 3. In short, the chosen velocities greatly affect the mean travel times and the range of travel times but have a minor effect on the shape of the travel time distribution or the differences in the travel time distributions for the different stream networks. Thus the main result of this study (namely, that the geometry of the flowing stream network affects the shape of the travel time distributions) does not depend on our chosen velocities. See also the response to specific comment 6 below.

Specific comments

1. P 3 L 26: How substantial of a rainfall event? Is the rainfall occurring in “wet” conditions? I suspect not as it occurs right before the “dry” conditions survey.

> There were 27 mm of precipitation on October 25th and another 31 mm fell on October 26th. There was no other rain after this event until November 2nd (total rainfall between October 15th and November 2nd was 83 mm). Streamflow in the catchment responds quickly to precipitation (within minutes to hours) and baseflow is generally reached within one to two days after an event. Thus, by November 2nd, streamflow had returned to baseflow conditions, although the lowest flows during this fall period were increasing slightly (see Figure R1 below).

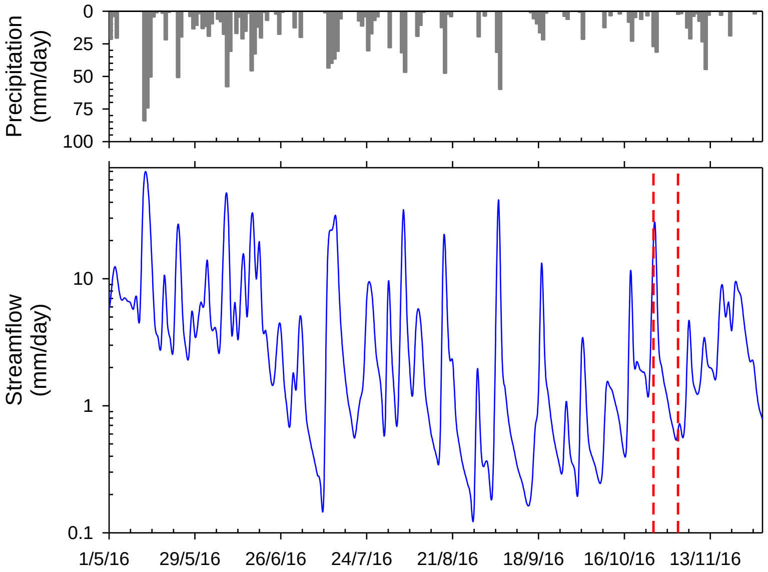


**Figure R1. Daily precipitation and streamflow at the Erlenbach gauging station during spring to-fall 2016. The red lines indicate the times of the two stream surveys in fall 2016. Note the log-scale for streamflow. The flow during the extremely dry conditions in summer 2018 was 0.18 mm/d. The data were obtained from Stähli (2018), Long-term hydrological observatory Alptal (central Switzerland); https://www.envidat.ch/dataset/longterm-hydrological-observatory-alptal-central-switzerland.**

2. P 3 L 20: The authors say that the field mapping is too slow during rainfall events to capture the entire extent of the stream work during rainfall events due to how dynamic it is. However, it appears the authors use a survey taken during a rainfall event in this analysis. Thus, it would be helpful to the reader if more information was provided on these surveys, e.g. how long did the surveys take, did the researchers start at the channel heads and walk down (to ensure they capture the most dynamic extents), was the network actively expanding during the survey, etc?

We didn't survey the stream starting at the channel heads but rather walked along the contours and then up the different streams (thus the surveys were done in more of a zigzag pattern across the catchment). Each survey took at least half a day to complete. Since the peak of the event is very short, we cannot survey the entire stream network at the peak of the event. We made it clearer in the text of the manuscript that the mapping is too slow to capture the peak flow conditions during an event (P3L20-21).

The October 2016 stream network was mapped in the afternoon of October 25th during an event with low intensity rainfall (see Figure R2 below). Total rainfall was 10 mm by noon (when the mapping started), 16 mm by 3 pm, and 20 mm at 5 pm when the mapping was completed.

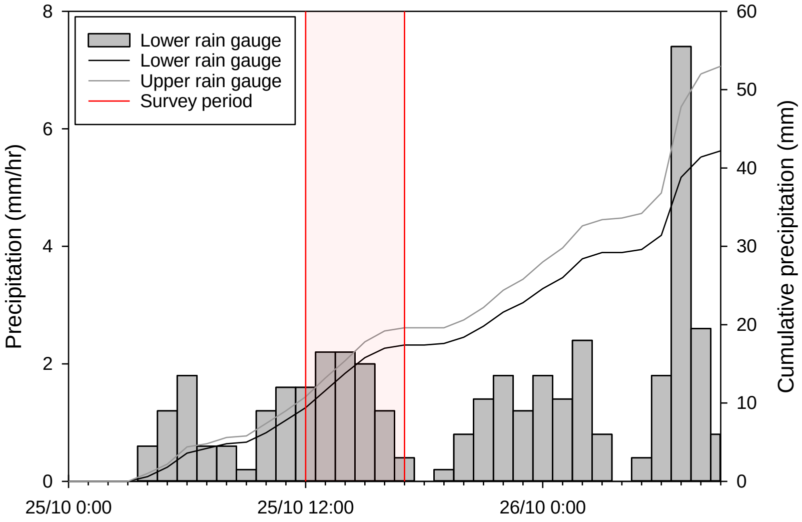


**Figure R2. Hourly and cumulative precipitation recorded at the lower and upper rain gauge in the Studibach before and during the stream survey on October 25, 2016.**

3. P 3 L 27: It may be more clear to the reader how survey #4 was accomplished (every other survey is described in parentheses, but this one).

> The stream network was surveyed on multiple occasions to ensure that we had mapped all streams. The complete network is assumed to represent the fully extended network during extremely wet or peak flow conditions. We did not observe flow in all streams at the same time; instead, #4 represents a hypothetical scenario in which all channels are flowing during extremely wet conditions. We explain this in the text on P3 and added a clarifying sentence to the caption of Table 1 that the complete network is assumed to represent the flowing stream network during extremely wet conditions.

4. There have been several recent studies that sought to predict river network extent, which can be used to model transit time distributions as suggested by the authors on P33. Some suggestions below for two recent studies that can be used:
P 7 L 1: Add another example of predictive modelling: Ward, A. S., Schmadel, N. M., & Wondzell, S. M. (2018). Simulation of dynamic expansion, contraction, and connectivity in a mountain stream network. Advances in Water Resources, 114, 64-82.
P 6 L 33- P 7 L 1: Add example of empirical generalization from field studies, such as: Zimmer, M. A., & McGlynn, B. L. (2018). Lateral, vertical, and longitudinal source area connectivity drive runoff and carbon export across watershed scales. Water Resources Research, 54(3), 1576-1598.
This study also relates network expansion and retraction to solute transport dynamics as well, which is suggested in this study, but few if any citations are provided.

> Thank you for these suggestions. We have added references to these papers and other stream network model studies to the manuscript (P6L29 and P7L8).

5. TABLE 1: While it is clear why the topographic map does not have an associated streamflow, please add brief explanation in caption as to why streamflow magnitude is not provided for complete network.

> We added the clarification to the table caption and now clearly state that we never observed flow in the entire stream network but that we assume that this is the case for peak flow conditions during very large events.

6. TABLE 2: This is an incredibly interesting results table and definitely made me think about possible travel times in other catchments and across wetness conditions. While I think the authors main

points from this paper were to show that travel times decrease substantially as the system wets up, the absolute values for the reported median travel times are very small. The median surface travel times are on the order of minutes – how did the authors determine this? Based on the catchment and previous field observations, does it seem reasonable that 71% of the water travel time are less than 2 days?

> The main point of the study was indeed to show that the changes in the flowing stream network geometry can significantly affect the travel time distribution. We did not intend to derive actual travel time distributions for this catchment but rather focus on how the distributions differ between the different stream networks.
>
> We don't know the average surface and subsurface velocities in the catchment and therefore state clearly that these are assumed values. We test the effect of using different velocities and show that the effect of the chosen velocities on the shape of the travel time distribution is minimal (see Figure 6 in the manuscript). Furthermore, we discuss on P5L29-P6L5 the implications of using uniform and constant velocities.
>
> The average surface velocity of 0.5 m/s is typical for mountain streams. The average subsurface velocity of 5 $10^{-4}$ m/s is high compared to the hydraulic conductivity of the soil near the surface in the grassland areas of the Studibach (5 $10^{-7}$ to 1 $10^{-5}$ m/s) but is not unrealistic for the forest sites (>1 $10^{-4}$ m/s; van Meerveld et al. (2017)). For comparison, Anderson et al. (2009) determined subsurface velocities of $10^{-4}$ m/s (and up to $10^{-1}$ m/s) for preferential flow pathways in forest soils, whereas Uchida et al. (2001) mention velocities of 5 $10^{-3}$ m/s (and up to 2 $10^{-1}$m/s) for pipeflow in forest soils. Most of the flow in the clay soils of the Studibach occurs through preferential flow pathways in the topsoil layers. However, as discussed on P4L19-27 and P6L1-5, the flowing stream network wouldn't be fully extended for many consecutive days and the velocities will decrease as the catchment dries out. Therefore, in reality the travel times will be much longer than shown in Figure 4 (see Figure 6b).
>
> We do not know the travel time distribution for the catchment but the streamflow response in the catchment is very flashy. Previous studies have shown that the event water contributions to streamflow in the Alptal catchments can be very large (Fischer et al., 2017; von Freyberg et al., 2018b) and that the young water fraction can be very high (von Freyberg et al., 2018a).

7. It is also interesting that the median travel time for the topographic map survey is 4.5days and the subsurface travel time is 4.5 days, which are both longer than the “dry” conditions survey, and yet the fraction of the catchment with travel time less than 1 day is greater for the topographic map. Perhaps this is driven by the hydrologic connectivity of the river network in the topographic map survey. This is an interesting dynamic that could be expanded on in this paper and could be related to recent papers on the topic of discontinuous network extents, such as:

Godsey, S. E., & Kirchner, J. W. (2014). Dynamic, discontinuous stream networks:hydrologically driven variations in active drainage density, flowing channels and stream order. Hydrological Processes, 28(23), 5791-5803.

Whiting, J. A., & Godsey, S. E. (2016). Discontinuous headwater stream networks with stable flowheads, Salmon River basin, Idaho. Hydrological Processes, 30(13), 2305-2316.

> It is indeed fascinating that the stream length and median travel time for the flowing stream network during dry conditions and the network from the topographic map are somewhat similar but the connected stream length (Table 1) and the area that likely contributes to the stream are very different (Figure 4). We highlight this on P5L10-13. We also highlight the effect of the dry section in the flowing stream network on the travel time distribution and the area with travel times shorter than two days on P5L14-18.
>
> We referenced the mentioned publications but now added references where we describe the discontinuity in the flowing streamwork as well (P4L1-2).

8. FIGURE 2: What is the role of disconnected stream channels in the model results? Do water parcels flow through these disconnected sections at the same rate as those coming from the terrestrial landscape outside the channel extent? Do the authors think that subsurface flow map be faster within the subsurface channel network than in the hillslopes adjacent to the network?

> The disconnected section causes the second peak in the travel time distribution (see P5L14-18).
>
> We only used one subsurface flow velocity in our calculations. We agree that the flow may be faster through the channel bed than on the hillslopes but adding a different velocity for the area around the channel will make the results less clear. As mentioned throughout the text, the velocities were kept constant in order to avoid blurring the effect of the change in the stream network geometry on travel times by having different velocities. Of course in reality there will be a distribution of velocities, rather than one velocity for the entire catchment, and this velocity distribution will change as the catchment wets up or dries out. We describe this limitation and the effects that this has on the travel times on P5L31-P6L2.

Technical corrections and editorial suggestions

P 5 L 11: missing “x” between “5” and “10”.

> We added a · between the 5 and the 10 (here and elsewhere in the text).

P 6 L 13: Delete “did” at end of sentence.

> We removed the "did" and rewrote the sentence based on the comments from reviewer 2.

TABLE 2: Change “travel times smaller than one and two days” to “travel times shorter than one and two days”

> We changed the text of the caption accordingly.

**References:**

Anderson, A. E., Weiler, M., Alila, Y., and Hudson, R. O.: Subsurface flow velocities in a hillslope with lateral preferential flow, Water Resour. Res., 45, W11407, doi:11410.11029/12008WR007121, 2009.

Fischer, B. M. C., Stähli, M., and Seibert, J.: Pre-event water contributions to runoff events of different magnitude in pre-alpine headwaters, Hydrol. Res., 48, 28-47, 10.2166/nh.2016.176, 2017.

Uchida, T., Kosugi, K., and Mizuyama, T.: Effects of pipeflow on hydrological process and its relation to landslide: a review of pipeflow studies in forested headwater catchments, Hydrological Processes, 15, 2151-2174, 2001.

van Meerveld, H. J. I., Fischer, B. M. C., Rinderer, M., Stähli, M., and Seibert, J.: Runoff generation in a pre-alpine catchment: A discussion between a tracer and a shallow groundwater hydrologist, https://publicaciones.unirioja.es/ojs/index.php/cig/article/view/3349, 10.18172/cig.3349, 2017.

von Freyberg, J., Allen, S. T., Seeger, S., Weiler, M., and Kirchner, J. W.: Sensitivity of young water fractions to hydro-climatic forcing and landscape properties across 22 Swiss catchments, Hydrol. Earth Syst. Sci., 22, 3841-3861, 10.5194/hess-22-3841-2018, 2018a.

von Freyberg, J., Studer, B., Rinderer, M., and Kirchner, J. W.: Studying catchment storm response using event- and pre-event-water volumes as fractions of precipitation rather than discharge, Hydrol. Earth Syst. Sci., 22, 5847-5865, 10.5194/hess-22-5847-2018, 2018b.

**Response to review comments from Anonymous Referee #2**

General Comments: This manuscript uses field-mapped stream extent and flow-routing from a digital elevation model to derive travel time distributions considering varying extents of the flowing stream network. The dynamic expansion and contraction of the stream network is not typically considered in this type of work. The manuscript makes a strong case for the acknowledgement of these processes in future travel time distribution work. I think the analysis is elegant and compelling and the manuscript is very well written. I have just a few questions and potential wording issues, which are noted below.

Thank you for these positive comments.

Specific Comments:

Page 6, Line 13: "in our study did ." I can't quite figure out what this means, it may need to be reworded.

We agree that this sentence was awkward. We meant to say that the travel times in the referenced studies were much longer than our calculated travel times (shown in Figures 4-6). We have rewritten this sentence.

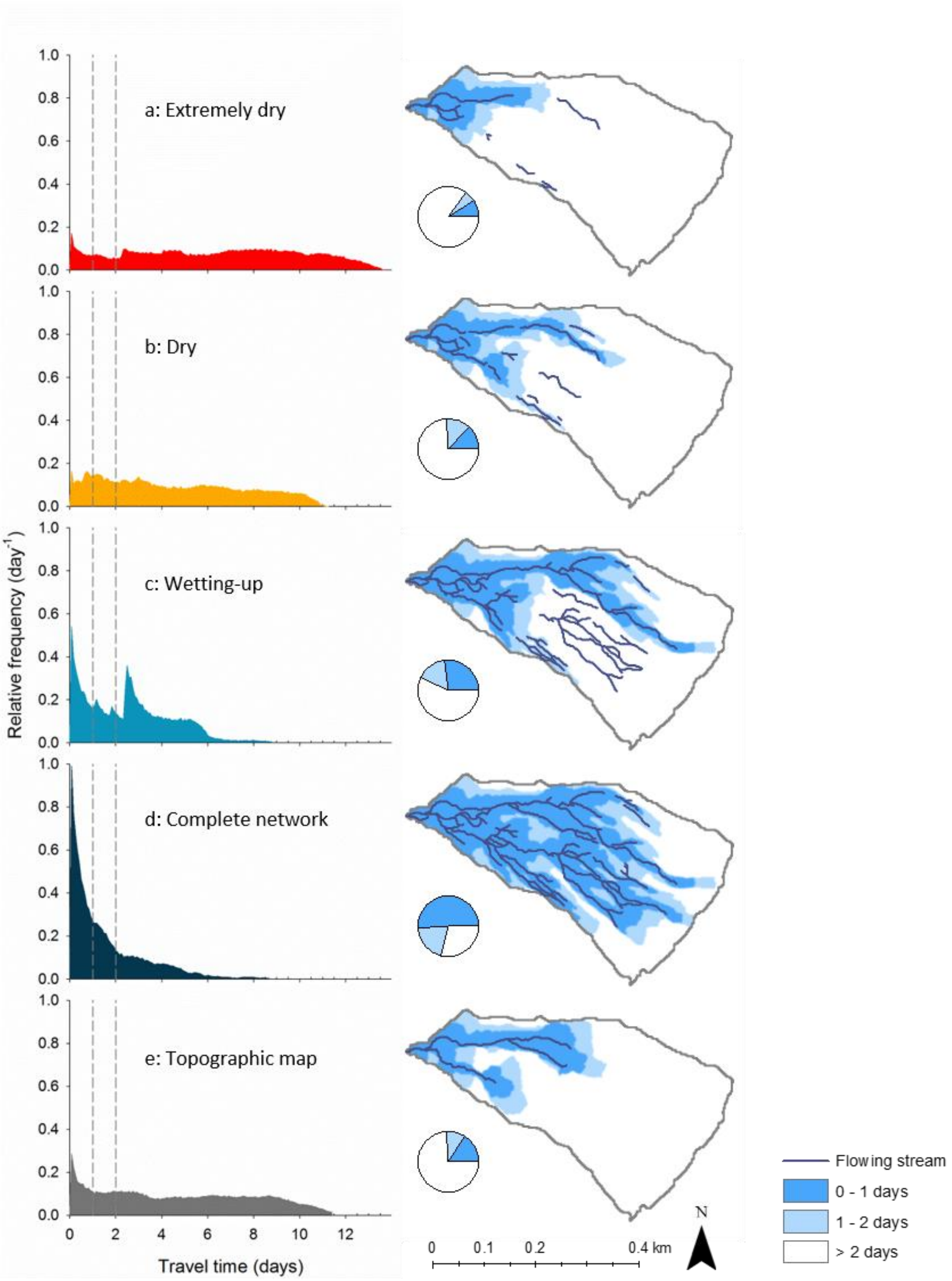
Figure 2: Definitely not critical, but it could offer helpful context to note the elevations of the lowest and highest contours in one of the maps.

We highlighted the 50 m contours as well and added the elevations to these contours in Fig 2e. Note that we give the elevation range on P3L6.

Figure 4: I had a hard time interpreting the pie charts. From reading the caption, it seems like the blue in the pie chart represents the portion of the catchment sourcing water to the stream in 0-2 days (I think?). But then it doesn't seem like the pie charts match up with the corresponding maps. Are they somehow mismatched? If not, I'd suggest being more explicit what the pie charts represent. Another suggestion: I think they would be clearer just from a visualization perspective if instead of pies, they were rectangles...kind of like a progress bar on a computer. I think these would be easier to read and compare than the pie.

Thank you for pointing us to this issue. Unfortunately, the colors in the pie charts changed when the document was converted to a pdf(the white part of the pie chart became blue, the darkest blue part of the pie chart disappeared, and the blue parts became white). This of course made it difficult to interpret the pie charts and caused the mismatch of the pie charts and the maps. We agree that a bar chart could also be nice but the space in the figure is limited and better suited to a pie chart.

We exported the figure differently and double checked that the pdf displays the figure correctly (see the figure below for the correct pie charts).


a: Extremely dry
b: Dry
c: Wetting-up
d: Complete network
e: Topographic map
Relative frequency ($day^{-1}$)
0.0
0.2
0.4
0.6
0.8
1.0
Travel time (days)
0
2
4
6
8
10
12
0
0.1
0.2
0.4 km
N
Flowing stream
0 - 1 days
1 - 2 days
> 2 days

**Response to comment by Kang Yang**

A very interesting study! It has been long known that hillslope and open-channel partition impacts catchment hydrographs but few studies have estimate this point using high-quality dataset. The main contribution of this study is to map multi-temporal, accurate flowing stream networks and investigate their impacts on catchment hydrographs. Some important implications have been reported as well. This reminds me of the work I've done for routing surface meltwater on the Greenland ice sheet. I've found hillslope and open-channel partition impacts surface meltwater discharge at the catchment outlet. However, I used a series of cumulative area thresholds to create dynamic supraglacial stream networks from DEMs (see Figure 7). This study has done a better work: instead of using DEM simulations, real field-measured stream networks are used. If the authors are interested, see my paper published in The Cryosphere:

Yang, K., Smith, L.C., Karlstrom, L., Cooper, M.G., Tedesco, M., As, D.v., Cheng, X., Chen, Z., Li, M., 2018. A new surface meltwater routing model for use on the Greenland Ice Sheet surface. Cryosph. 12, 3791-3811. https://www.the-cryosphere.net/12/3791/2018/

> Thank you very much for pointing us to this interesting paper. We were not aware of it and agree that it is relevant. We find it indeed very interesting that, although this is a very different system, the results are similar (and even the optimized velocities match the ones used in our study). Figure 7 in your manuscript clearly shows the importance of using a dynamic network for simulating the hydrograph. The difference in the optimized interfluve velocities for the conservative and non-conservative networks is precisely what we alluded to in the discussion of our manuscript (P6L30), where we describe the importance of using dynamic stream networks for solute transport modeling because the use of a static network (as shown on maps) would lead to "slower modeled transport of pollutants, unless compensated otherwise (e.g. via velocities that are unrealistically high or large areas with surface runoff)".
> Thank you for pointing us to this interesting paper. We now reference it in our revised manuscript (P6L31).

# Expansion and contraction of the flowing stream network ~~change~~ alter hillslope flowpath lengths and the shape of the travel time distribution

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**Abstract.** Flowing stream networks dynamically extend and retract, both seasonally and in response to precipitation events. These network dynamics can dramatically alter the drainage density, and thus the length of subsurface flow pathways to flowing streams. We mapped flowing stream networks in a small Swiss headwater catchment during different wetness conditions and estimated their effects on the distribution of travel times to the catchment outlet. For each point in the catchment, we determined the subsurface transport distance to the flowing stream based on the surface topography, and determined the surface transport distance along the flowing stream to the outlet. We combined the distributions of these travel distances with assumed surface and subsurface flow velocities to estimate the distribution of travel times to the outlet. These calculations show that the extension and retraction of the stream network can substantially change the mean travel time and the shape of the travel time distribution. During wet conditions with a fully extended flowing stream network, the travel time distribution was strongly skewed to short travel times, but as the network retracted during dry conditions, the distribution of the travel times became more uniform. Stream network dynamics are widely ignored in catchment models, but our results show that they need to be taken into account when modeling solute transport and interpreting travel time distributions.

## 1. Introduction

Flowing stream networks extend and retract seasonally and during rainfall events (Ågren et al., 2015; Day, 1978; Gregory and Walling, 1968; Jensen et al., 2017; Peirce and Lindsay, 2015; Shaw, 2016). Some networks are less dynamic than others, depending on their geological and topographic settings (e.g., Whiting and Godsey, 2016), but many stream networks that are not strongly controlled by persistent springs expand dramatically with increasing wetness conditions and streamflow. For example, the length of the flowing stream network in Sagehen Creek in California was 35 km during wet conditions in April

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2008 but only 15 km during dry conditions in September 2006 (Godsey and Kirchner, 2014). The flowing stream drainage density of the completely extended stream network for a British peatland catchment was 20 times greater than that of the fully retracted stream network (Goulsbra et al., 2014). In an agricultural catchment in Oregon the flowing drainage density increased by two orders of magnitude between dry summer periods and wet winter periods (Wigington et al., 2005).

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The expansion of the flowing stream network during wet periods increases the connectivity between hillslopes and streams. Wigington et al. (2005) argued that this increase in connectivity leads to ~~greater~~ higher nitrate exports because riparian buffer strips are largely bypassed, and travel times are shorter, when the flowing stream network is fully extended. Yet most catchment-scale solute transport studies assume static drainage networks, often derived from topographic maps that do not adequately represent intermittent streams. Even when intermittent streams are delineated as dashed lines on maps, their abundance is often greatly underrepresented (Ågren et al., 2015; Brooks and Colburn, 2011; Fritz et al., 2013). Inadequate representation of the stream network can significantly impact the modeled retention capacity of riparian buffer strips (Baker et al., 2007) and thus solute export.

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Travel time, i.e., the time it takes a raindrop to reach the catchment outlet, is an important control on the transport and fate of nutrients and contaminants, as well as mineral weathering. Because stream network expansion shortens the distances between hillslopes and flowing streams, it must also affect the distribution of travel times. However, most studies interpret temporal variations in travel time distributions in terms of the relative contributions of fast and slow flow pathways and changes in the residence times of different storage zones, ignoring the effects of changes in the flowing stream network on subsurface flowpath lengths (Benettin et al., 2015a; Harman, 2014; van der Velde et al., 2012; Yang et al., 2018). ~~The~~ ~~y~~Young water fractions ~~was~~ were correlated with the drainage densities~~y~~ across~~in~~ 22 Swiss catchments, suggesting that denser drainage networks, and thus shorter subsurface flowpaths, promote faster transport of recent precipitation (von Freyberg et al., 2018a). Hydrological modeling has similarly suggested a larger contribution of young water for lowland catchments with higher drainage densities and thus presumably shorter travel distances (Kaandorp et al., 2018).

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Here, using simple graphical analyses of field-mapped stream networks, we show that network extension and retraction not only change~~s~~ subsurface travel distances and thus catchment-scale travel times, but also change~~s~~ the shape of the travel time distribution. Our results imply that changes in the flowing stream network should be taken into account when modeling catchment-scale solute transport or interpreting travel time distributions.

## 2. Methods

### 2.1 Study site

For this study, we mapped flowing stream networks in a small headwater catchment in the Alptal, approximately 40 km southeast of Zurich. Mean annual precipitation is 2300 mm $y^{-1}$, with roughly a third falling as snow (Stähli and Gustafsson,

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2006). The wet climate and low-permeability Gleysols derived from Flysch bedrock (a sequence of sedimentary rocks, particularly argillite and bentonite schists, calcareous schists, marl and sandstone; Mohn et al., 2000; Schleppi et al., 1998) result in near-surface groundwater levels across much of the catchment (Rinderer et al., 2014). Streamflow generally responds very quickly (within tens of minutes) to rainfall. While most of the stormflow consists of pre-event water, event water contributions can be more than 50% (Fischer et al., 2017; von Freyberg et al., 2018b).

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Our 13 ha headwater study catchment is located in the upper parts of the Studibach catchment and ranges in elevation from 1421 to 1656 m above sea level. The lower half of the catchment is forested, while the upper part is dominated by grasslands and wetlands that are used as meadows in summer (Figure 1). The average slope is 22°. In the lower part of the catchment, the stream is incised and the streambed contains large boulders; in the upper part of the catchment the streams are narrow (<0.2 m wide) and barely incised. For more information on the Studibach study catchment, see van Meerveld et al. (2017).

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### 2.2 Stream networks used in this study

We manually surveyed the stream network by walking the entire catchment during different wetness conditions (including large events), using aerial photographs and GPS to ensure that the stream map included all streams. Our analysis uses the field-mapped flowing stream networks for three different dates with contrasting wetness conditions, as well as the complete network of all stream channels, which we assume represents the flowing stream network during extremely wet conditions. We mapped ~~any~~ stream reaches with dry streambeds, pools of standing (but not flowing) water, or trickling flow conditions (<< 1 liter per minute based on visual observation) as dry channels. Even though the study area is generally very wet, the 2018 summer was extremely dry, leading to one of the lowest ~~observed~~ measured streamflows since 1968 in the neighbouring Erlenbach catchment. Field mapping during this period allowed us to obtain information about the minimum flowing stream length (Table 1). We assumed that the entire mapped channel network would be flowing during extremely wet conditions, although we never documented this situation because the stream network is very dynamic during rainfall events and field mapping is too slow ~~during such conditions~~to capture the maximum extent of the flowing stream network. We also compared our field-mapped networks to the stream network shown on the standard Swisstopo map (Federal Office of Topography, Swisstopo Pixelkarte 25; National Map 1:25,000; Figure 1). Thus, in total we compared five different flowing stream networks (Figure 2; Table 1):

1. Extremely dry conditions (Aug 21, 2018)
2. Dry conditions (Nov 2, 2016)
3. Wetting-up conditions (Oct. 25, 2016 during a low intensity rainfall event; 20 mm in total)
4. Complete network (assumed to represent~~ting~~ the fully extended network during extremely wet conditions)
5. Topographic map (representing the stream network that would be assumed in the absence of field mapping)

The mapped flowing stream networks were significantly longer than the network shown on the Swisstopo map, except during the extremely dry conditions in August 2018 (Figure 2~~Figure 2~~; Table 1~~Table 1~~). The flowing stream networks during the dry and wetting-up conditions in fall 2016 contained multiple dry sections in the steep central part of the catchment, separating the upper parts of the flowing stream network from the outlet (Figure 2~~Figure 2~~b-c). Such discontinuities in the flowing stream network have been observed in other catchments as well (e.g., Godsey and Kirchner, 2014; Whiting and Godsey, 2016)

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## 2.3 Data analyses

Using the 2 m by 2 m LiDAR-derived digital elevation model for the catchment, we calculated the weighted mean length of all flow paths from each pixel to the nearest flowing stream pixel (with the weight based on the fraction of water taking each certain flowpath) based on the MD∞ algorithm (Seibert and McGlynn, 2007) (i.e., subsurface hillslope flow path length; $L_h$) and the travel distance through the flowing channel to the outlet ($L_s$) based on the D8 algorithm (O'Callaghan and Mark, 1984). For each pixel, we divided the average subsurface flow path length ($L_h$) by an assumed average subsurface velocity ($v_h$) to obtain an estimate of the subsurface travel time ($t_h$). We similarly divided the travel distance through the flowing stream channel ($L_s$) by an assumed average surface velocity ($v_s$) to obtain an estimate of the surface travel time ($t_s$). The subsurface and surface travel times were added to obtain an estimate of the total travel time to the catchment outlet (hereafter referred to as travel time; cf. Di Lazzaro (2009)~~)~~) for each pixel ($t_t$):

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$$t_t = t_h + t_s = \frac{L_h}{v_h} + \frac{L_s}{v_s} \qquad \text{eq. 1}$$

We then determined the frequency distribution of the travel times ($t_t$) for all pixels in the catchment. This was done for each of the five stream networks. For all of the analyses shown here, we used 0.5 m s$^{-1}$ for the surface velocity ($v_s$) and 5 10$^{-4}$ m s$^{-1}$ for the subsurface velocity ($v_h$). Different subsurface velocities and surface to subsurface velocity ratios (from 10 to 10 000) were also tested. We also mapped the spatial distribution of pixels for which the estimated travel time was less than one or two days, assuming that these have the potential to contribute to stormflow.

These calculations include several subjective decisions and simplifying assumptions (i.e., that velocities are constant in space and time, that all areas in the catchment contribute equally to discharge at the outlet, and that the flowing stream network remains stable for long enough so that travel times at the outlet can be expressed as a static transit time distribution). Our main objective is to illustrate the effects of changes in the flowing stream network on subsurface flow path lengths and thus the travel time distributions. These effects are best illustrated by keeping all other factors constant, using the simplifying assumptions outlined above. Previous work (Mutzner et al., 2016) has shown how different methods to extract the channel network affect hillslope-to-stream travel distances (i.e., rescaled width functions) and thus the derived geomorphological instantaneous unit hydrograph. Here, our focus is not on the effects of different stream network extraction methods, but rather on how changes in the flowing stream network affect subsurface travel distances and catchment-scale travel times.

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## 3. Results

Extension of the flowing stream network during wet conditions significantly shortens the subsurface flow pathways (shown in red for five selected locations A-E in Figure 3~~Figure 3~~). This not only shortens the average and median travel time to the outlet, but also changes the shape of the travel time distribution (Table 2~~Table 2~~ and Figure 4a-d). For the extended flowing stream networks typical of wet conditions, most subsurface travel distances (and thus travel times) are short, but for the retracted networks typical of dry conditions, the travel times are longer and more uniformly distributed. When the flowing stream network is greatly retracted during extremely dry periods, almost the entire catchment has travel times longer than two days and thus could not contribute to stormflow in response to a brief rainfall event. However, when the flowing stream network is fully extended, most of the catchment could contribute to stormflow at the outlet because the travel times are mainly short (Figure 4d). The correspondence between flowing stream networks and travel time distributions is not one to one, however. For example, even though the flowing stream network during the dry conditions in November 2016 is different from the network shown on the topographic map (Figure 2~~Figure 2~~b and e), the cumulative frequency distributions of the travel times are similar (Figure 5~~Figure 5~~).

The travel time distribution for the stream network during the wetting-up period (October 2016 mapping) is bimodal (Figure 4c) due to the large area with flowing streams that is disconnected from the outlet by the dry stream section in the steeper part of the catchment (Table 1~~Table 1~~ and Figure 2~~Figure 2~~c). For the selected subsurface velocity ($v_h$) of $5 \cdot 10^{-4}$ m s$^{-1}$, almost two days are required to cross the dry part of the channel as subsurface flow. A less ~~obvious~~ apparent bi-modal travel time distribution also results from disconnection of the flowing stream network during the extremely dry conditions of August 2018 (Figure 4a).

The chosen surface and subsurface velocities do not ~~greatly~~ substantially affect the shapes of the travel time distributions (Figure 6~~Figure 6~~). Changing the assumed subsurface velocity (and thus the ratio of the surface to subsurface velocities) by large factors has the effect of rescaling the travel time distributions but does not substantially change their shapes (Figure 6~~Figure 6~~). This is to be expected. The shapes of the travel time distributions will be mainly determined by the distribution of subsurface travel distances ($L_h$), whenever velocities are assumed to be constant in space and time, and slower in the subsurface than the surface. Under these assumptions, the subsurface travel times ($t_h$) will be much longer than the surface flow travel times ($t_s$), and thus will largely determine the travel time distribution. Reasonable ranges of assumed surface flow velocities have virtually no effect on the travel time distributions, due to the very small contribution of the surface flow travel times ($t_s$) to the total travel times ($t_t$).

## 4. Discussion

By only changing the flowing stream network and keeping all other variables (such as the velocities) constant, our analysis shows how the extension and retraction of the flowing stream network affect~~s~~ subsurface flowpath lengths and catchment-scale travel times. In practice, the effects of catchment wetness on travel time distributions will be larger than shown here, because subsurface flow velocities will be smaller during dry conditions, significantly increasing travel times when the stream network is most contracted. Subsurface flow velocities will also vary spatially, which will further broaden the travel time distributions. Furthermore, ~~The~~ subsurface flow directions may not follow the surface topography and may change depending on water table gradients and thus wetness conditions (Rodhe and Seibert, 2011; van Meerveld et al., 2015), and some areas of the catchment may not contribute to streamflow during dry conditions (Jencso et al., 2010; Zuecco et al., 2019). By excluding these confounding factors, we could isolate the effect of stream network geometry on travel times, and show that stream network extension and retraction significantly alters the mean and median travel times, as well as the shape of the travel time distribution.

Previous modeling studies have suggested that streamflow consists of a larger fraction of young water during wet conditions than during dry conditions. For example, Benettin *et al.* (2015b) calibrated a hydrological model for the Plynlimon catchment in Wales using both streamflow and stream chloride data, and suggested that the travel time distribution was much more skewed towards younger water during wet conditions. Visser *et al.* (2019) used a combination of isotope tracers to constrain a hydrological model for a Sierra Nevada catchment and inferred that the travel time distribution was skewed towards younger water during high-flow conditions but was nearly uniform during baseflow (although this was partly due to a lack of young water in storage due to drought conditions). This change in the streamflow travel time distribution (and the storage selection function) with catchment wetness conditions is generally attributed to a larger contribution from shallower and faster flow pathways during wetter conditions (Benettin et al., 2015b; Harman, 2014; Hrachowitz et al., 2016; van der Velde et al., 2012). ~~The~~ Although the travel times in these studies were much longer than we ~~have~~ calculated here, in part because we assumed that surface and subsurface flow velocities ~~were assumed to~~would not decrease during dry conditions ~~in our study did . Nevertheless~~, our results suggest that ~~even if the flow velocities are held constant,~~ the dynamics of the flowing stream network alone can lead to significant changes in travel time distributions. Therefore, these network dynamics and the associated changes in subsurface travel distances need to be taken into account when interpreting time-varying travel time distributions. Above all, more studies are needed where detailed tracer sampling is combined with detailed stream network mapping to determine how stream network extension affects travel time distributions. Our results also suggest the speculative possibility that the dynamics of stream network extension and retraction could potentially be inferred from the time-varying behaviour of travel time distributions.

Our results, furthermore, suggest that stream networks shown on the topographic maps may loosely approximate the flowing stream network during dry conditions, but not during wet conditions. When these static networks are used for modeling studies, the modeled flow pathways may be far longer than the real-world subsurface flowpaths, particularly during wet conditions (see also Zimmer and McGlynn, 2018). The resulting modeled transit time distributions would then be much less skewed than those in the real world. This would lead to much slower modeled transport of pollutants, unless compensated otherwise (e.g. via unrealistically high velocities ~~that are unrealistically high~~ or large areas with surface runoff, as for

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example shown for flow on the Greenland ice sheet by Yang et al. (2018)). Therefore, solute transport studies need to take the complexities of stream network extension and retraction into account, particularly in locations where (or at times when) the network may be very dynamic. This will require better knowledge of the processes and catchment characteristics that control flowing stream network extension and retraction, since it is impractical to map the dynamics of the flowing stream network in every catchment. As more field maps of network extension and retraction become available, empirical generalizations about stream network dynamics and their controlling factors will become more reliable. As an example of what may be possible, Prancevic and Kirchner (2019) have recently shown that topography may be a useful predictor of where the flowing stream network is highly dynamic and where it is more stable. Using either empirical generalizations from the limited available field studies, ~~or~~ predictive relationships like those suggested by Prancevic and Kirchner (2019), or modeled stream networks (Russell et al., 2015; Ward et al., 2018; Williamson et al., 2015)~~,~~ would be better than assuming that flowing stream networks are static.

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## 5. Conclusion

We estimated travel time distributions for different mapped stream networks by calculating the subsurface transport distance~~s~~ from each pixel to the nearest flowing stream and the surface transport distance along the stream network to the outlet for different flowing stream networks. Our results show that extension and retraction of flowing stream networks can significantly alter catchment travel time distributions, even if all other factors remain constant. When stream networks extend during wet conditions, travel times become shorter and their distributions become more skewed. Conversely, when stream networks retract during dry conditions, travel times become longer and more uniformly distributed. The effects of flowing stream network dynamics will be even ~~larger~~ more significant in the real world than calculated here, because we assumed that velocities did not change with wetness conditions, in order to isolate the effect of stream network geometry alone. Our simple graphical analysis implies that the dynamics of the flowing stream network need to be taken into account when interpreting travel time distributions or modeling solute transport. This will require better documentation of stream network extension and retraction in more diverse landscapes and climatic conditions, coupled with a better understanding of the processes and catchment characteristics that control flowing stream network dynamics.

## 6. Acknowledgements

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## 7. References

Ågren, A., Lidberg, W., and Ring, E.: Mapping Temporal Dynamics in a Forest Stream Network—Implications for Riparian Forest Management, Forests, 6, 2982, 2015.

Baker, M. E., Weller, D. E., and Jordan, T. E.: Effects of stream map resolution on measures of riparian buffer distribution and nutrient retention potential, Landscape Ecology, 22, 973-992, 10.1007/s10980-007-9080-z, 2007.

Benettin, P., Bailey, S. W., Campbell, J. L., Green, M. B., Rinaldo, A., Likens, G. E., McGuire, K. J., and Botter, G.: Linking water age and solute dynamics in streamflow at the Hubbard Brook Experimental Forest, NH, USA, Water Resources Research, 51, 9256-9272, 10.1002/2015wr017552, 2015a.

Benettin, P., Kirchner, J. W., Rinaldo, A., and Botter, G.: Modeling chloride transport using travel time distributions at Plynlimon, Wales, Water Resources Research, 51, 3259-3276, 10.1002/2014wr016600, 2015b.

Brooks, R. T., and Colburn, E. A.: Extent and Channel Morphology of Unmapped Headwater Stream Segments of the Quabbin Watershed, Massachusetts1, JAWRA Journal of the American Water Resources Association, 47, 158-168, 10.1111/j.1752-1688.2010.00499.x, 2011.

Day, D. G.: Drainage density changes during rainfall, Earth Surface Processes, 3, 319-326, 10.1002/esp.3290030310, 1978.

Di Lazzaro, M.: Regional analysis of storm hydrographs in the Rescaled Width Function framework, Journal of Hydrology, 373, 352-365, https://doi.org/10.1016/j.jhydrol.2009.04.027, 2009.

Fischer, B. M. C., Stähli, M., and Seibert, J.: Pre-event water contributions to runoff events of different magnitude in pre-alpine headwaters, Hydrol. Res., 48, 28-47, 10.2166/nh.2016.176, 2017.

Fritz, K. M., Hagenbuch, E., D'Amico, E., Reif, M., Wigington, P. J., Leibowitz, S. G., Comeleo, R. L., Ebersole, J. L., and Nadeau, T.-L.: Comparing the Extent and Permanence of Headwater Streams From Two Field Surveys to Values From Hydrographic Databases and Maps, JAWRA Journal of the American Water Resources Association, 49, 867-882, 10.1111/jawr.12040, 2013.

Godsey, S. E., and Kirchner, J. W.: Dynamic, discontinuous stream networks: hydrologically driven variations in active drainage density, flowing channels and stream order, Hydrological Processes, 28, 5791-5803, 10.1002/hyp.10310, 2014.

Goulsbra, C., Evans, M., and Lindsay, J.: Temporary streams in a peatland catchment: pattern, timing, and controls on stream network expansion and contraction, Earth Surface Processes and Landforms, 39, 790-803, 10.1002/esp.3533, 2014.

Gregory, K. J., and Walling, D. E.: The variation of drainage density within a catchment, International Association of Scientific Hydrology. Bulletin, 13, 61-68, 10.1080/02626666809493583, 1968.

Harman, C. J.: Time-variable transit time distributions and transport: Theory and application to storage-dependent transport of chloride in a watershed, Water Resources Research, 1-30, 10.1002/2014wr015707, 2014.

Hrachowitz, M., Benettin, P., van Breukelen, B. M., Fovet, O., Howden, N. J. K., Ruiz, L., van der Velde, Y., and Wade, A. J.: Transit times—the link between hydrology and water quality at the catchment scale, Wiley Interdisciplinary Reviews: Water, 3, 629-657, 10.1002/wat2.1155, 2016.

Jencso, K. G., McGlynn, B. L., Gooseff, M. N., Bencala, K. E., and Wondzell, S. M.: Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources, Water Resour. Res., 46, W10524, doi:10510.11029/12009WR008818, 2010.

Jensen, C. K., McGuire, K. J., and Prince, P. S.: Headwater stream length dynamics across four physiographic provinces of the Appalachian Highlands, Hydrological Processes, 31, 3350-3363, 10.1002/hyp.11259, 2017.

Kaandorp, V. P., de Louw, P. G. B., van der Velde, Y., and Broers, H. P.: Transient Groundwater Travel Time Distributions and Age-Ranked Storage-Discharge Relationships of Three Lowland Catchments, Water Resources Research, 54, 4519-4536, 10.1029/2017wr022461, 2018.

Mohn, J., Schürmann, A., Hagedorn, F., Schleppi, P., and Bachofen, R.: Increased rates of denitrification in nitrogen-treated forest soils, Forest Ecology and Management, 137, 113-119, http://dx.doi.org/10.1016/S0378-1127(99)00320-5, 2000.

Mutzner, R., Tarolli, P., Sofia, G., Parlange, M. B., and Rinaldo, A.: Field study on drainage densities and rescaled width functions in a high-altitude alpine catchment, Hydrological Processes, 30, 2138-2152, 10.1002/hyp.10783, 2016.

O'Callaghan, J. F., and Mark, D. M.: The extraction of drainage networks from digital elevation data, Computer Vision, Graphics, and Image Processing, 28, 323-344, https://doi.org/10.1016/S0734-189X(84)80011-0, 1984.

Peirce, S. E., and Lindsay, J. B.: Characterizing ephemeral streams in a southern Ontario watershed using electrical resistance sensors, Hydrological Processes, 29, 103-111, 10.1002/hyp.10136, 2015.

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Prancevic, J. P., and Kirchner, J. W.: Topographic Controls on the Extension and Retraction of Flowing Streams, Geophysical Research Letters, 46, 2084-2092, 10.1029/2018gl081799, 2019.

Rinderer, M., van Meerveld, H. J., and Seibert, J.: Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid?, Water Resources Research, 50, 6067-6080, 10.1002/2013wr015009, 2014.

Rodhe, A., and Seibert, J.: Groundwater dynamics in a till hillslope: flow directions, gradients and delay, Hydrological Processes, 25, 1899-1909, 10.1002/hyp.7946, 2011.

Russell, P. P., Gale, S. M., Muñoz, B., Dorney, J. R., and Rubino, M. J.: A Spatially Explicit Model for Mapping Headwater Streams, JAWRA Journal of the American Water Resources Association, 51, 226-239, 10.1111/jawr.12250, 2015.

Schleppi, P., Muller, N., Feyen, H., Papritz, A., Bucher, J. B., and Flühler, H.: Nitrogen budgets of two small experimental forested catchments at Alptal, Switzerland, Forest Ecology and Management, 101, 177-185, http://dx.doi.org/10.1016/S0378-1127(97)00134-5, 1998.

Seibert, J., and McGlynn, B. L.: A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models, Water Resources Research, 43, W04501, 10.1029/2006wr005128, 2007.

Shaw, S. B.: Investigating the linkage between streamflow recession rates and channel network contraction in a mesoscale catchment in New York state, Hydrological Processes, 30, 479-492, 10.1002/hyp.10626, 2016.

Stähli, M., and Gustafsson, D.: Long-term investigations of the snow cover in a subalpine semi-forested catchment, Hydrological Processes, 20, 411-428, 10.1002/hyp.6058, 2006.

van der Velde, Y., Torfs, P. J. J. F., van der Zee, S. E. A. T. M., and Uijlenhoet, R.: Quantifying catchment-scale mixing and its effect on time-varying travel time distributions, Water Resour. Res., 48, W06536, doi:06510.01029/02011WR011310, 2012.

van Meerveld, H. J., Seibert, J., and Peters, N. E.: Hillslope–riparian-stream connectivity and flow directions at the Panola Mountain Research Watershed, Hydrological Processes, 29, 3556-3574, 10.1002/hyp.10508, 2015.

van Meerveld, H. J. I., Fischer, B. M. C., Rinderer, M., Stähli, M., and Seibert, J.: Runoff generation in a pre-alpine catchment: A discussion between a tracer and a shallow groundwater hydrologist, https://publicaciones.unirioja.es/ojs/index.php/cig/article/view/3349, 10.18172/cig.3349, 2017.

Visser, A., Thaw, M., Deinhart, A., Bibby, R., Safeeq, M., Conklin, M., Esser, B., and Van der Velde, Y.: Cosmogenic Isotopes Unravel the Hydrochronology and Water Storage Dynamics of the Southern Sierra Critical Zone, Water Resources Research, 55, 1429-1450, 10.1029/2018wr023665, 2019.

von Freyberg, J., Allen, S. T., Seeger, S., Weiler, M., and Kirchner, J. W.: Sensitivity of young water fractions to hydro-climatic forcing and landscape properties across 22 Swiss catchments, Hydrol. Earth Syst. Sci., 22, 3841-3861, 10.5194/hess-22-3841-2018, 2018a.

von Freyberg, J., Studer, B., Rinderer, M., and Kirchner, J. W.: Studying catchment storm response using event- and pre-event-water volumes as fractions of precipitation rather than discharge, Hydrol. Earth Syst. Sci., 22, 5847-5865, 10.5194/hess-22-5847-2018, 2018b.

Ward, A. S., Schmadel, N. M., and Wondzell, S. M.: Simulation of dynamic expansion, contraction, and connectivity in a mountain stream network, Advances in Water Resources, 114, 64-82, https://doi.org/10.1016/j.advwatres.2018.01.018, 2018.

Whiting, J. A., and Godsey, S. E.: Discontinuous headwater stream networks with stable flowheads, Salmon River basin, Idaho, Hydrological Processes, 30, 2305-2316, 10.1002/hyp.10790, 2016.

Wigington, P. J., Moser, T. J., and Lindeman, D. R.: Stream network expansion: a riparian water quality factor, Hydrological Processes, 19, 1715-1721, 2005.

Williamson, T. N., Agouridis, C. T., Barton, C. D., Villines, J. A., and Lant, J. G.: Classification of Ephemeral, Intermittent, and Perennial Stream Reaches Using a TOPMODEL-Based Approach, JAWRA Journal of the American Water Resources Association, 51, 1739– 1759, 10.1111/1752-1688.12352, 2015.

Yang, J., Heidbüchel, I., Musolff, A., Reinstorf, F., and Fleckenstein, J. H.: Exploring the Dynamics of Transit Times and Subsurface Mixing in a Small Agricultural Catchment, Water Resources Research, 54, 2317-2335, doi:10.1002/2017WR021896, 2018.

Zimmer, M. A., and McGlynn, B. L.: Lateral, Vertical, and Longitudinal Source Area Connectivity Drive Runoff and Carbon Export Across Watershed Scales, Water Resources Research, 54, 1576-1598, doi:10.1002/2017WR021718, 2018.

Zuecco, G., Rinderer, M., Penna, D., Borga, M., and van Meerveld, H. J.: Quantification of subsurface hydrologic connectivity in four headwater catchments using graph theory, Science of The Total Environment, 646, 1265-1280, https://doi.org/10.1016/j.scitotenv.2018.07.269, 2019.

~~Ågren, A., Lidberg, W., and Ring, E.: Mapping Temporal Dynamics in a Forest Stream Network—Implications for Riparian Forest Management, Forests, 6, 2982, 2015.~~

~~Baker, M. E., Weller, D. E., and Jordan, T. E.: Effects of stream map resolution on measures of riparian buffer distribution and nutrient retention potential, Landscape Ecology, 22, 973-992, 10.1007/s10980-007-9080-z, 2007.~~

~~Benettin, P., Bailey, S. W., Campbell, J. L., Green, M. B., Rinaldo, A., Likens, G. E., McGuire, K. J., and Botter, G.: Linking water age and solute dynamics in streamflow at the Hubbard Brook Experimental Forest, NH, USA, Water Resources Research, 51, 9256-9272, 10.1002/2015wr017552, 2015a.~~

~~Benettin, P., Kirchner, J. W., Rinaldo, A., and Botter, G.: Modeling chloride transport using travel time distributions at Plynlimon, Wales, Water Resources Research, 51, 3259-3276, 10.1002/2014wr016600, 2015b.~~

~~Brooks, R. T., and Colburn, E. A.: Extent and Channel Morphology of Unmapped Headwater Stream Segments of the Quabbin Watershed, Massachusetts1, JAWRA Journal of the American Water Resources Association, 47, 158-168, 10.1111/j.1752-1688.2010.00499.x, 2011.~~

~~Day, D. G.: Drainage density changes during rainfall, Earth Surface Processes, 3, 319-326, 10.1002/esp.3290030310, 1978.~~

~~Di Lazzaro, M.: Regional analysis of storm hydrographs in the Rescaled Width Function framework, Journal of Hydrology, 373, 352-365, https://doi.org/10.1016/j.jhydrol.2009.04.027, 2009.~~

~~Fischer, B. M. C., Stähli, M., and Seibert, J.: Pre-event water contributions to runoff events of different magnitude in pre-alpine headwaters, Hydrol. Res., 48, 28-47, 10.2166/nh.2016.176, 2017.~~

~~Fritz, K. M., Hagenbuch, E., D'Amico, E., Reif, M., Wigington, P. J., Leibowitz, S. G., Comeleo, R. L., Ebersole, J. L., and Nadeau, T.-L.: Comparing the Extent and Permanence of Headwater Streams From Two Field Surveys to Values From Hydrographic Databases and Maps, JAWRA Journal of the American Water Resources Association, 49, 867-882, 10.1111/jawr.12040, 2013.~~

~~Godsey, S. E., and Kirchner, J. W.: Dynamic, discontinuous stream networks: hydrologically driven variations in active drainage density, flowing channels and stream order, Hydrological Processes, 28, 5791-5803, 10.1002/hyp.10310, 2014.~~

~~Goulsbra, C., Evans, M., and Lindsay, J.: Temporary streams in a peatland catchment: pattern, timing, and controls on stream network expansion and contraction, Earth Surface Processes and Landforms, 39, 790-803, 10.1002/esp.3533, 2014.~~

~~Gregory, K. J., and Walling, D. E.: The variation of drainage density within a catchment, International Association of Scientific Hydrology. Bulletin, 13, 61-68, 10.1080/02626666809493583, 1968.~~

~~Harman, C. J.: Time-variable transit time distributions and transport: Theory and application to storage-dependent transport of chloride in a watershed, Water Resources Research, 1-30, 10.1002/2014wr015707, 2014.~~

~~Hrachowitz, M., Benettin, P., van Breukelen, B. M., Fovet, O., Howden, N. J. K., Ruiz, L., van der Velde, Y., and Wade, A. J.: Transit times—the link between hydrology and water quality at the catchment scale, Wiley Interdisciplinary Reviews: Water, 3, 629-657, 10.1002/wat2.1155, 2016.~~

~~Jencso, K. G., McGlynn, B. L., Gooseff, M. N., Bencala, K. E., and Wondzell, S. M.: Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources, Water Resour. Res., 46, W10524, doi:10510.11029/12009WR008818, 2010.~~

~~Jensen, C. K., McGuire, K. J., and Prince, P. S.: Headwater stream length dynamics across four physiographic provinces of the Appalachian Highlands, Hydrological Processes, 31, 3350-3363, 10.1002/hyp.11259, 2017.~~

~~Kaandorp, V. P., de Louw, P. G. B., van der Velde, Y., and Broers, H. P.: Transient Groundwater Travel Time Distributions and Age-Ranked Storage-Discharge Relationships of Three Lowland Catchments, Water Resources Research, 54, 4519-4536, 10.1029/2017wr022461, 2018.~~

~~Mohn, J., Schürmann, A., Hagedorn, F., Schleppi, P., and Bachofen, R.: Increased rates of denitrification in nitrogen-treated forest soils, Forest Ecology and Management, 137, 113-119, http://dx.doi.org/10.1016/S0378-1127(99)00320-5, 2000.~~

~~Mutzner, R., Tarolli, P., Sofia, G., Parlange, M. B., and Rinaldo, A.: Field study on drainage densities and rescaled width functions in a high-altitude alpine catchment, Hydrological Processes, 30, 2138-2152, 10.1002/hyp.10783, 2016.~~

~~O'Callaghan, J. F., and Mark, D. M.: The extraction of drainage networks from digital elevation data, Computer Vision, Graphics, and Image Processing, 28, 323-344, https://doi.org/10.1016/S0734-189X(84)80011-0, 1984.~~

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~~Peirce, S. E., and Lindsay, J. B.: Characterizing ephemeral streams in a southern Ontario watershed using electrical resistance sensors, Hydrological Processes, 29, 103-111, 10.1002/hyp.10136, 2015.~~

~~Prancevic, J. P., and Kirchner, J. W.: Topographic Controls on the Extension and Retraction of Flowing Streams, Geophysical Research Letters, 46, 2084-2092, 10.1029/2018gl081799, 2019.~~

~~Rinderer, M., van Meerveld, H. J., and Seibert, J.: Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid?, Water Resources Research, 50, 6067-6080, 10.1002/2013wr015009, 2014.~~

~~Rodhe, A., and Seibert, J.: Groundwater dynamics in a till hillslope: flow directions, gradients and delay, Hydrological Processes, 25, 1899-1909, 10.1002/hyp.7946, 2011.~~

~~Russell, P. P., Gale, S. M., Muñoz, B., Dorney, J. R., and Rubino, M. J.: A Spatially Explicit Model for Mapping Headwater Streams, JAWRA Journal of the American Water Resources Association, 51, 226-239, 10.1111/jawr.12250, 2015.~~

~~Schleppi, P., Muller, N., Feyen, H., Papritz, A., Bucher, J. B., and Flühler, H.: Nitrogen budgets of two small experimental forested catchments at Alptal, Switzerland, Forest Ecology and Management, 101, 177-185, http://dx.doi.org/10.1016/S0378-1127(97)00134-5, 1998.~~

~~Seibert, J., and McGlynn, B. L.: A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models, Water Resources Research, 43, W04501, 10.1029/2006wr005128, 2007.~~

~~Shaw, S. B.: Investigating the linkage between streamflow recession rates and channel network contraction in a mesoscale catchment in New York state, Hydrological Processes, 30, 479-492, 10.1002/hyp.10626, 2016.~~

~~Stähli, M., and Gustafsson, D.: Long-term investigations of the snow cover in a subalpine semi-forested catchment, Hydrological Processes, 20, 411-428, 10.1002/hyp.6058, 2006.~~

~~van der Velde, Y., Torfs, P. J. J. F., van der Zee, S. E. A. T. M., and Uijlenhoet, R.: Quantifying catchment-scale mixing and its effect on time-varying travel time distributions, Water Resour. Res., 48, W06536, doi:06510.01029/02011WR011310, 2012.~~

~~van Meerveld, H. J., Seibert, J., and Peters, N. E.: Hillslope–riparian-stream connectivity and flow directions at the Panola Mountain Research Watershed, Hydrological Processes, 29, 3556-3574, 10.1002/hyp.10508, 2015.~~

~~van Meerveld, H. J. I., Fischer, B. M. C., Rinderer, M., Stähli, M., and Seibert, J.: Runoff generation in a pre-alpine catchment: A discussion between a tracer and a shallow groundwater hydrologist, https://publicaciones.unirioja.es/ojs/index.php/cig/article/view/3349, 10.18172/cig.3349, 2017.~~

~~Visser, A., Thaw, M., Deinhart, A., Bibby, R., Safeeq, M., Conklin, M., Esser, B., and Van der Velde, Y.: Cosmogenic Isotopes Unravel the Hydrochronology and Water Storage Dynamics of the Southern Sierra Critical Zone, Water Resources Research, 55, 1429-1450, 10.1029/2018wr023665, 2019.~~

~~von Freyberg, J., Allen, S. T., Seeger, S., Weiler, M., and Kirchner, J. W.: Sensitivity of young water fractions to hydro-climatic forcing and landscape properties across 22 Swiss catchments, Hydrol. Earth Syst. Sci., 22, 3841-3861, 10.5194/hess-22-3841-2018, 2018a.~~

~~von Freyberg, J., Studer, B., Rinderer, M., and Kirchner, J. W.: Studying catchment storm response using event- and pre-event-water volumes as fractions of precipitation rather than discharge, Hydrol. Earth Syst. Sci., 22, 5847-5865, 10.5194/hess-22-5847-2018, 2018b.~~

~~Ward, A. S., Schmadel, N. M., and Wondzell, S. M.: Simulation of dynamic expansion, contraction, and connectivity in a mountain stream network, Advances in Water Resources, 114, 64-82, https://doi.org/10.1016/j.advwatres.2018.01.018, 2018.~~

~~Whiting, J. A., and Godsey, S. E.: Discontinuous headwater stream networks with stable flowheads, Salmon River basin, Idaho, Hydrological Processes, 30, 2305-2316, 10.1002/hyp.10790, 2016.~~

~~Wigington, P. J., Moser, T. J., and Lindeman, D. R.: Stream network expansion: a riparian water quality factor, Hydrological Processes, 19, 1715-1721, 2005.~~

~~Williamson, T. N., Agouridis, C. T., Barton, C. D., Villines, J. A., and Lant, J. G.: Classification of Ephemeral, Intermittent, and Perennial Stream Reaches Using a TOPMODEL-Based Approach, JAWRA Journal of the American Water Resources Association, 51, 1739–1759, 10.1111/1752-1688.12352, 2015.~~

~~Yang, J., Heidbüchel, I., Musolff, A., Reinstorf, F., and Fleckenstein, J. H.: Exploring the Dynamics of Transit Times and Subsurface Mixing in a Small Agricultural Catchment, Water Resources Research, 54, 2317-2335, doi:10.1002/2017WR021896, 2018.~~

~~Zimmer, M. A., and McGlynn, B. L.: Lateral, Vertical, and Longitudinal Source Area Connectivity Drive Runoff and Carbon Export Across Watershed Scales, Water Resources Research, 54, 1576-1598, doi:10.1002/2017WR021718, 2018.~~

~~Zuecco, G., Rinderer, M., Penna, D., Borga, M., and van Meerveld, H. J.: Quantification of subsurface hydrologic connectivity in four headwater catchments using graph theory, Science of The Total Environment, 646, 1265-1280, https://doi.org/10.1016/j.scitotenv.2018.07.269, 2019.~~

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| | | Mapped networks | | | | Topographic map |
|---|---|---|---|---|---|---|
| | | Extremely dry | Dry | Wetting-up | Complete network | |
| **Streamflow** | **(mm d$^{-1}$)** | 0.2 | 0.5 | 8.1 | - | - |
| | **percentile** | 96 | 82 | 18 | - | - |
| **Flowing stream network length (km)** | | 0.63 | 1.11 | 3.11 | 3.77 | 0.68 |
| **Flowing stream network density (km km$^{-2}$)** | | 4.9 | 8.5 | 23.9 | 29 | 5.2 |
| **Connected flowing stream length (km)** | | 0.42 | 0.39 | 1.57 | 3.4 | 0.68 |
| **Fraction connected (-)** | | 0.65 | 0.35 | 0.50 | 0.90 | 1 |

**Table 1. ~~The f~~Flowing stream network length, flowing stream density, ~~the ~~flowing stream length that was connected to the outlet, and the fraction of the flowing stream length that was connected to the outlet for the five stream networks used in this study. Daily streamflow at the neighbouring 70 ha Erlenbach catchment~~,~~ and the percentile of flow based on the 1978-2018 flow record, are given for comparison of the wetness conditions as well. Note that we assume that during extremely wet conditions flow occurs throughout the complete network but that we did not survey the network during these conditions. For the 1978-2018 flow record, the average annual maximum daily flow for the Erlenbach catchment was 67 mm d$^{-1}$, and the average daily flow was 4.8 mm d$^{-1}$.**

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| | | **Mapped stream networks** | | | | **Topographic map** |
|---|---|---|---|---|---|---|
| | | **Extremely dry** | **Dry** | **Wetting-up** | **Complete network** | |
| **Travel time** | **Mean (days)** | 6.3 | 4.5 | 2.5 | 1.6 | 4.7 |
| | **Median (days)** | 6.5 | 4.1 | 2.5 | 1.0 | 4.5 |
| | **Interquartile range (days)** | 6.0 | 5.1 | 2.9 | 2.0 | 5.6 |
| | **Skewness** | -0.03 | 0.31 | 0.56 | 1.47 | 0.20 |
| **Subsurface travel time** | **Median (days)** | 6.5 | 4.1 | 2.4 | 1.0 | 4.5 |
| **Surface travel time** | **Median (days)** | 3.3 $10^{-3}$ | 5.7 $10^{-3}$ | 8.3 $10^{-3}$ | 9.3 $10^{-3}$ | 4.9 $10^{-3}$ |
| **Fraction of catchment with travel time** | **≤1 day (-)** | 0.09 | 0.13 | 0.27 | 0.51 | 0.16 |
| | **≤2 days (-)** | 0.15 | 0.26 | 0.43 | 0.71 | 0.26 |

**Table 2. Statistics for the travel time distributions ($t_t$), as well as the median subsurface ($t_h$) and surface ($t_s$) travel times, and the fraction of the catchment with travel times ~~less~~ shorter than or equal to one or two days, for the five different stream networks using ~~a surface velocity ($v_s$) of 0.5 m s$^{-1}$ and~~ a subsurface velocity ($v_h$) of ~~5~~ 5·10$^{-4}$ m s$^{-1}$~~.~~ and surface velocity ($v_s$) of 0.5 m s$^{-1}$. See Figure 2 for the maps with the stream networks and Figure 4 for the travel time distributions and maps of the areas with travel times ~~smaller~~ shorter than one and two days.**

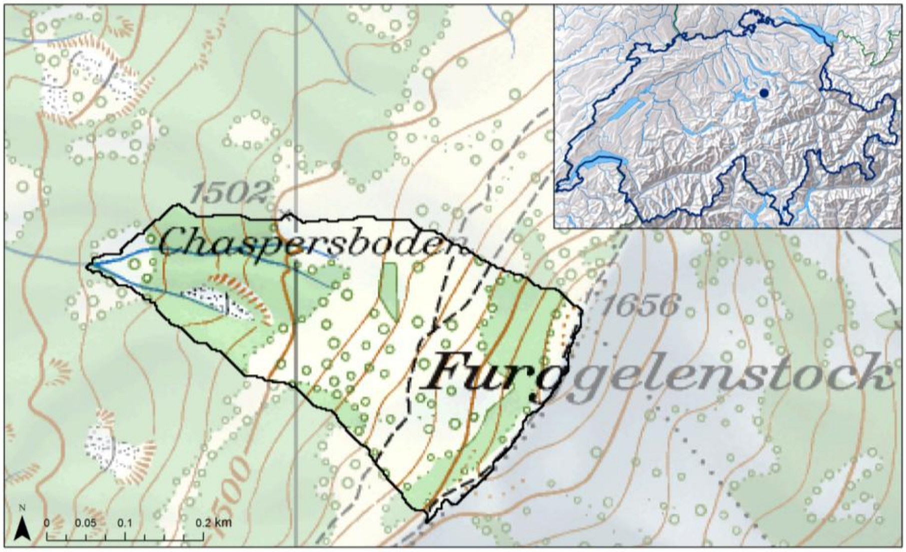
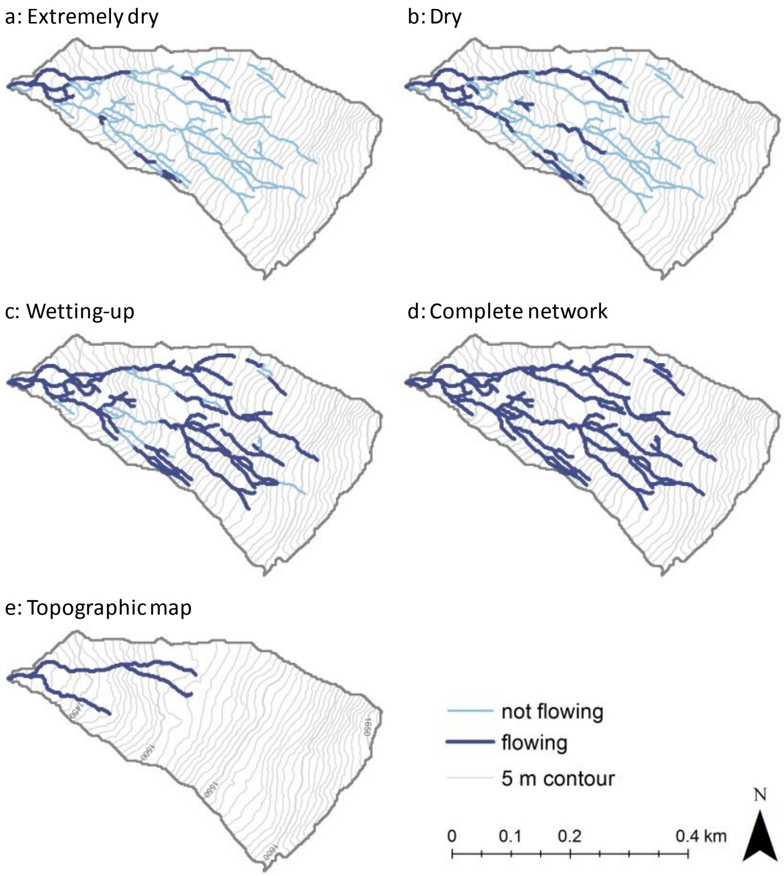


**Figure 1. Map of the upper Studibach study catchment and its location in Switzerland (inset). Source: Federal Office of Topography (Swisstopo) National Map 1:25,000 (Pixelkarte 25) and Reliefkarte 1:2,000,000.**



a: Extremely dry

b: Dry

c: Wetting-up

d: Complete network

e: Topographic map

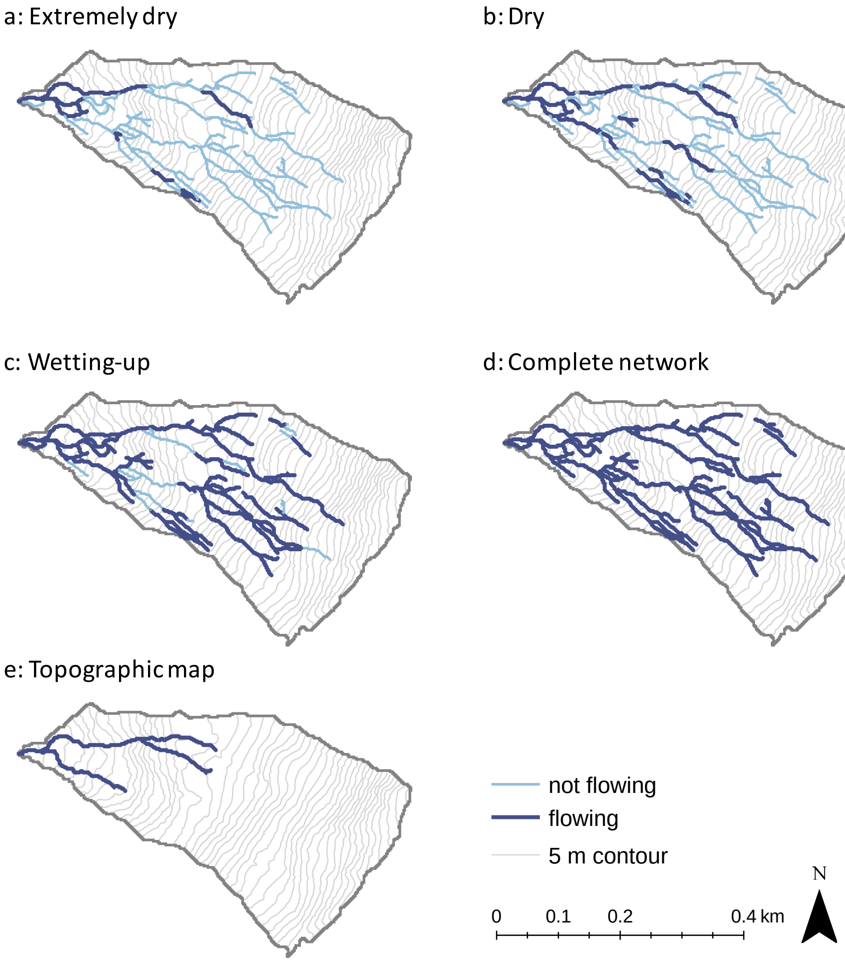
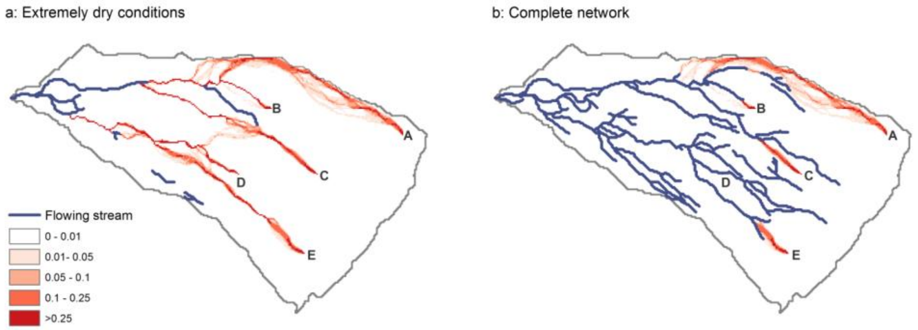


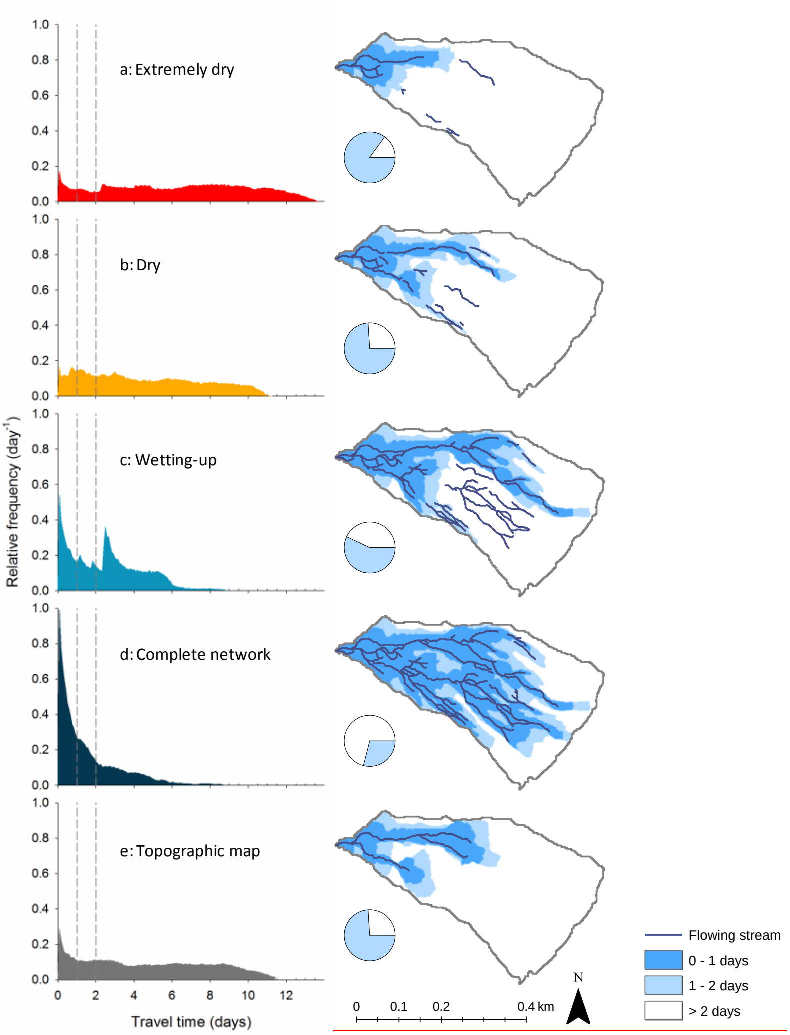
**Figure 2. Maps of the five stream networks (flowing in dark blue and not flowing in light blue) used in this study. a: extremely dry conditions observed on 21 August 2018; b: dry conditions observed on 2 November 2016; c: wetting-up conditions observed during a rainfall event on 25 October 2016; d: the complete stream network assumed to represent the flowing stream network during extremely wet conditions; e: the stream network shown on the 1:25,000 topographic map (see Figure 1). The length of the flowing stream network changes dramatically with wetness conditions and is significantly underrepresented by the stream network shown on the topographic map.**



a: Extremely dry conditions

b: Complete network

**Figure 3. Maps showing subsurface flow pathways starting from five selected pixels (in red; A-E) and the flowing stream network (in blue) observed during extremely dry conditions and for the complete network (assumed to represent extremely wet conditions). Darker colors indicate a larger fraction of the flow. The shorter flowing stream network under dry conditions implies much longer subsurface flow pathways from most points on the landscape. The subsurface fractions of the total travel distance to the outlet ($L_h/L_t$, m/m) for the extremely dry and complete network are: A: 0.66 and 0.44; B: 0.48 and 0.07; C: 0.59 and 0.15; D: 0.74 and 0.01; E: 0.81 and 0.11, respectively.**


a: Extremely dry
b: Dry
c: Wetting-up
d: Complete network
e: Topographic map
Relative frequency (day$^{-1}$)
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
Travel time (days)
0
0.1
0.2
0.4 km
N
Flowing stream
0 - 1 days
1 - 2 days
> 2 days

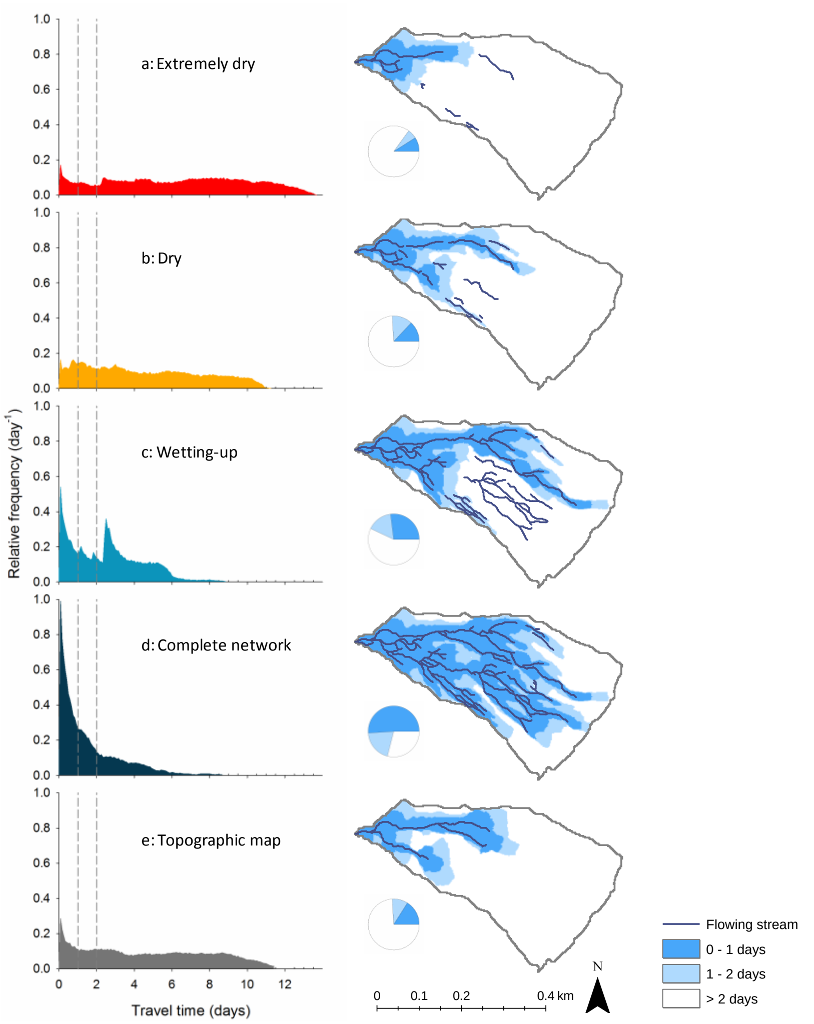


**Figure 4. Effects of flowing stream network extension and retraction on the travel time distributions. The left hand column shows the distributions of travel times ($t_t$) to the catchment outlet for the five flowing stream networks. The right hand column shows the networks themselves, as well as the locations in the catchment with travel times ≤ 1 and 1-2 days (dark blue and light blue, respectively, corresponding to the fractions of catchment area shown in the pie charts). Travel times were calculated assuming a ~~surface velocity ($v_s$) of 0.5 m s$^{-1}$ and a~~ subsurface velocity ($v_h$) of $5 \cdot 10^{-4}$ m s$^{-1}$~~.~~ and a surface velocity ($v_s$) of 0.5 m s$^{-1}$. See Table 2 for the main descriptive statistics of the travel time distributions. Under wetter conditions, more of the catchment area lies close to flowing streams; thus travel times are shorter and their distribution is more skewed.**

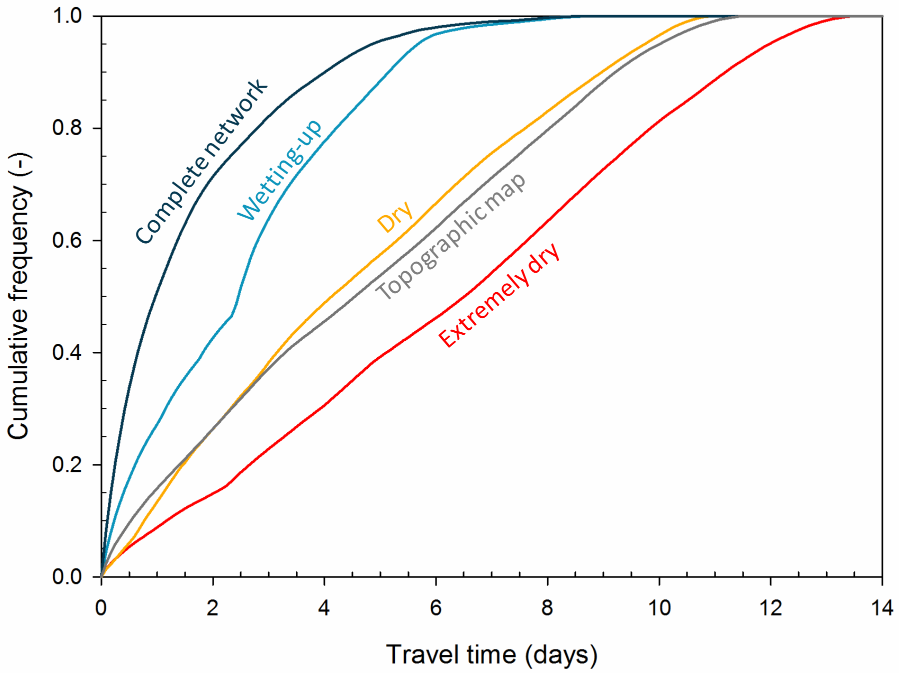


**Figure 5. Cumulative frequency distributions of the travel time ($t_t$) to the catchment outlet for the five flowing stream networks shown in Figures 2 and 4. See Table 2 for the main descriptive statistics of the travel time distributions.**

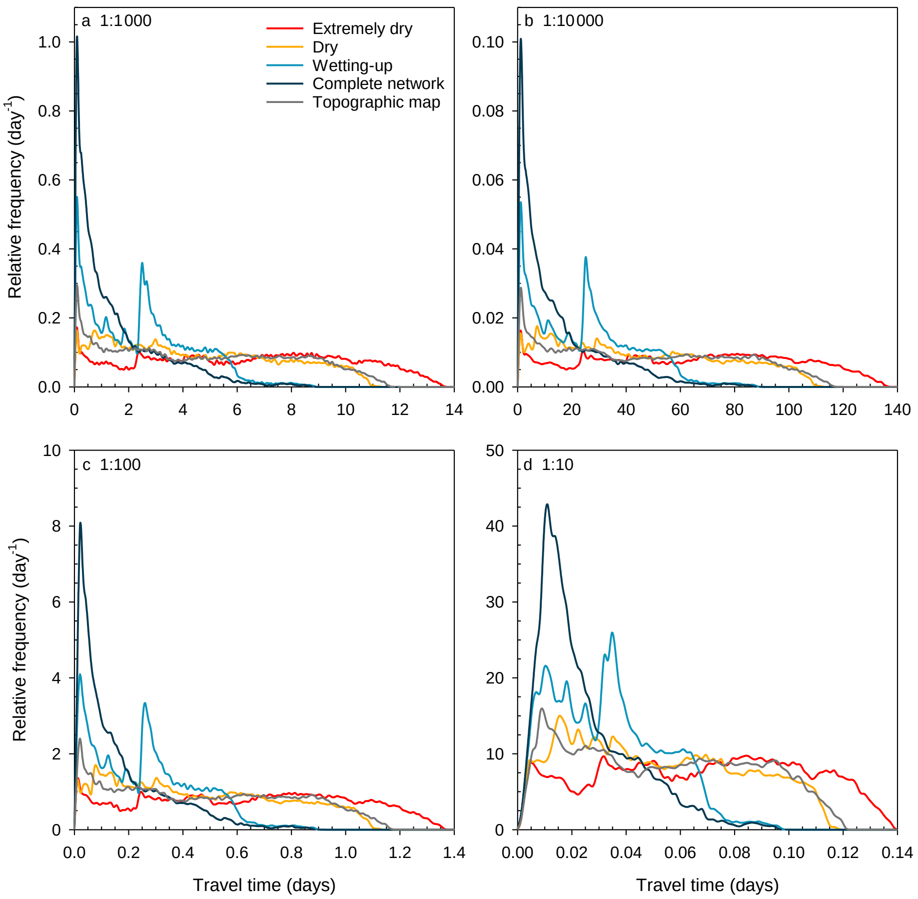


**Figure 6. Different assumed subsurface flow velocities change the travel times but not the shapes of their distributions. The panels show the travel time distributions for the five flowing stream networks, assuming a surface velocity ($v_s$) of 0.5 m s$^{-1}$ and subsurface velocities ($v_h$) of a: $5\cdot10^{-4}$ m s$^{-1}$ (as used in Figure 4), b: $5\cdot10^{-5}$ m s$^{-1}$, c: $5\cdot10^{-3}$ m s$^{-1}$, and d: $5\cdot10^{-2}$ m s$^{-1}$. The value shown in the upper left corner of each panel represents the ratio of the subsurface to surface velocities ($v_h : v_s$).**