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Identifying Subsurface Connectivity From Observations: Experimentation With Equifinality Defines Both Challenges and Pathways to Progress

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ABSTRACT

Linkages between landscapes and streams are increasingly described in terms of hydrological connectivity. The ability to effectively distinguish different patterns of water movement through catchments makes connectivity particularly interesting to both scientists and practical water managers. Hydrometric data (groundwater levels, soil moisture and streamflow) are often employed to infer the connection between the landscape and its drainage network. Such observational data, however, are insufficient to infer subsurface connectivity in humid settings with perennial stream flow, due to the risk of equifinality. To quantify how much subsurface flow patterns can differ and still be consistent (equifinal) with comprehensive observations of hillslope groundwater levels and stream runoff (the hydrometric data), this study used a modelling experiment based on a well-characterised field site. Particle-tracking simulations at different flow rates defined the water flow paths and transit times of two virtual hillslopes that differed profoundly in the vertical distribution of the saturated hydraulic conductivity. Even though the simulated weekly stream flows and groundwater levels were similar (i.e., the hillslopes were hydrometrically equifinal) particle velocities and water ages at specific locations along these hillslopes differed by orders of magnitude. Flow path lengths and catchment transit times varied up to several 100%. The hillslope- and stream-based metrics used to describe connectivity also varied with stream flow rates. These results underline the need to recognise the risks for equifinality when inferring subsurface connectivity from hydrometric observations alone, even when those observations are comprehensive. The results also highlight the value of model simulations for quantifying the uncertainty in the inferred connectivity, targeting the best sampling locations/times to reduce this uncertainty with tracer data and better understanding the way connectivity influences stream chemistry.

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1 | Introduction

Much of the effort to understand and manage human impacts on the amount and quality of surface water is based on the axiom that water is a mirror of the landscape. However, water is a distorted mirror at best. The landscape 'seen' in surface water depends on what source areas (and depths) in the landscape contribute to surface water, when those contributions occur and how the chemistry of water in the source areas change along different flow pathways to the stream.

A popular way of discerning the imprint of a landscape on surface waters is to characterise hydrological connectivity. Use of the term 'hydrological connectivity' in the scientific literature has grown from 32 occurrences between 1993 and 2002, to 286 in the period 2003–2012 and 1192 in the period 2013–2022 (Web of Science, accessed 2023-04-29). A major impetus for the increasing interest in connectivity is that it provides a way for science to inform policy, since the term concisely summarises where and when what happens on land will influence receiving waters. The United States Supreme Court recognised this in its 2006 decision tying implementation of the U.S. Clean Water Act to a 'significant nexus' linking waters to catchments (Downing, Winer and Wood 2003). The subsequent ruling by the same court in 2023, 'Sackett vs EPA' keeps the issue of legally defining connectivity a matter of not only scientific but also practical interest (McElfish et al. 2023).

The increasing use of the term hydrological connectivity means that it is applied to hydrological situations with many different types of runoff generation mechanisms, not just surface flows where it is simplest to apply. As a result, there is now considerable divergence in the literature defining 'hydrological connectivity' and quantifying it with different metrics (Ali et al. 2018; Bracken et al. 2013; Goodwell et al. 2018; Michaelides and Chappell 2009). Despite the multiplicity of meanings, the succinct definition by Bracken and Croke (2007), 'the movement of water from one part of the landscape to the other', captures the fundamental nature of connectivity. Regarding the multitude of connectivity metrics, the ultimate usefulness of any metric depends on how well it characterises water movement through catchments.

The potential power of metrics to infer connectivity is most evident in surface connectivity via overland flow where precipitation enters the stream quickly from spatially delimited areas of the catchment. For surface flows, a binary separation of landscapes is based on where water flows overland in a particular time-perspective (e.g., Coles and McDonnell 2018; Silasari et al. 2017). Overland flow can result from the exceedance of infiltration capacity by precipitation/snowmelt (Horton 1933), return-flow to the soil surface, or inputs on saturated areas (Dunne and Black 1970). More recent studies have focused on the filling of surface depressions that then 'spill' to generate substantial overland flow in arid regions (e.g., Lazaro et al. 2015; Wolstenholme et al. 2020), agricultural landscapes (e.g., Peñuela et al. 2016) and on frozen soils (Coles and McDonnell 2018). A number of models can now simulate this type of surface connectivity (e.g., Appels, Bogaart and van der Zee 2011; Kirkby 2014; Masselink et al. 2017; Peñuela et al. 2016).

In many boreal and temperate catchments, though, overland flow is not a major runoff generation mechanism, if it is present at all. Instead, subsurface flow provides the preponderance of water that reaches the streams. Prominent types of subsurface flow include interflow (Weiler et al. 2006), preferential flow (Buttle and McDonald 2002), transmissivity feedback (TF) (Bishop 1991; Seibert et al. 2011) and groundwater inputs (Carlier et al. 2018). Even for catchments where overland flow occurs during periods of high rainfall or snowmelt, subsurface flows can sustain stream baseflow for extended periods. This baseflow can be of great importance for life in the streams and for society.

Characterising and measuring subsurface connectivity is more challenging since connections can be more persistent and are not visible on the ground surface (Ameli and Creed 2017). Thus, connectivity created by subsurface flows is more difficult to characterise with metrics for the obvious reason that there is a vertical dimension of flow hidden from view. Subsurface flows are also more sustained, extending beyond stream flow events generated by temporally discrete inputs of precipitation or snowmelt. This requires moving beyond a binary conceptualization of connectivity to ones where the strength of connection between different catchment locations varies continually. In humid landscapes with perennial streamflow fed by subsurface flows, a considerable proportion of the landscape is persistently 'connected'. For instance, a simulation of a steep (35% average slope), pre-Alpine catchment based on measured groundwater levels suggested that 9% of the catchment was always connected to the stream and 18% was never connected (Rinderer, Van Meerveld and McGlynn 2019). For a more arid catchment in Montana, model simulations suggested that 10% was never connected (Nippgen et al. 2015) and large parts of the Canadian Prairies do not contribute streamflow during events with a 2 years return interval (Dumanski et al. 2015).

Despite the challenges of inferring connectivity for subsurface flows, hydrological connectivity has become a popular way of representing the relationship of catchments to stream water amount and chemistry. There is a growing body of literature on the inference of subsurface hydrological connectivity (e.g., Blume and van Meerveld 2015; Devito, Hill and Roulet 1996; Ocampo, Sivapalan and Oldham 2006; Rinderer, Van Meerveld and Seibert 2014). These inferences can be based largely on catchment hydrometric data (groundwater levels, soil moisture) or the chemical and isotopic composition of the streamwater itself (Barthold et al. 2010; Capell et al. 2011). Conservative tracers, such as the isotopes of deuterium and oxygen in the water molecule are particularly powerful since they can help establish the source areas of stream runoff within a catchment (e.g., Laudon et al. 2004). It is becoming increasingly common to complement groundwater levels with tracer observations when assessing connectivity, but the degree to which specific tracers can constrain the subsurface connectivity varies (Ameli et al. 2021). Hydrometric data also continues to be the primary basis for some efforts to characterise subsurface connectivity (e.g., Beiter, Weiler and Blume 2020; Blaurock et al. 2021; Rinderer, Van Meerveld and McGlynn 2019). This often involves interpolation between observations (e.g., van Meerveld, Seibert and

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Peters 2015) or relationships between the occurrence of soil saturation and topography to determine the subsurface saturated area (e.g., Jencso et al. 2009; Rinderer, Van Meerveld and McGlynn 2019). Jencso and McGlynn (2011), for example, used groundwater level data together with information on the accumulated area to construct connectivity duration curves defining where and when different parts of catchments were connected, from the largest events to extended periods of baseflow with low streamflow rates.

There are, however, reports of difficulties when extensive hydrometric observations are consistent with a range of possible subsurface connections (Ali and Roy 2010; James and Roulet 2007). The difficulty of inferring subsurface connectivity from hydrometric data is an example of equifinality, that is, when the observations are not sufficient to constrain the process of interest (Beven 2006). Furthermore, even where there is a continuous saturated zone extending to a stream (a situation commonly interpreted as subsurface connectivity), this does not unequivocally define water flow pathways. Water can still percolate downwards rather than continuing to the stream if that saturated zone is perched above an unsaturated zone (Ameli, Craig and McDonnell 2015; Klaus and Jackson 2018), or where there are local reversals in hydraulic gradients (e.g., Zimmer and McGlynn 2017).

While questions have been raised about the adequacy of hydrometric data for inferring subsurface connectivity, it is not easy to quantify these concerns. In observational studies, there is always the chance that more data can result in a better-constrained system description. In this paper, we use a virtual modelling experiment to quantify the implications of hydrometric equifinality on the inference of subsurface connectivity. We do this by taking advantage of the well-studied 'S-transect' hillslope in the Krycklan Catchment Study where subsurface connectivity has been quantified using a suite of measurements. These include hydrometric data stream flow, groundwater levels at different distances from the stream to the water divide (Amvrosiadi et al. 2017b; Stahli et al. 2001), conservative tracers (i.e., the oxygen-18 and deuterium of water molecules (Laudon et al. 2004)) and nearby measurements of the soil physical properties (Bishop 1991). Despite how well these data, when taken together, define the spatial and temporal extent of subsurface connectivity, there is a profound problem of equifinality when only the hydrometric data are used. Ameli et al. (2021) demonstrated that a range of hillslope permeability architectures, differing only with respect to the vertical distribution of saturated hydrological connectivity (K_{sat}), are consistent with the stream flow and groundwater levels at different distances from the stream.

In this study we use two extreme scenarios of the hydrometric equifinality on that hillslope: exponential decline in K_{sat} with depth (the current understanding of the actual situation) and a hillslope where K_{sat} is uniform across the hillslope. While the uniform K_{sat} scenario is counterfactual when using all available information, the two scenarios provide an opportunity to explore the potential consequences of relying on only hydrometric data when characterising subsurface connectivity in a setting with perennial streamflow. The two hillslope modelling scenarios conserve mass, produce almost identical stream flows and reproduce the available water table measurements equally well at a weekly time scale (Ameli et al. 2021 and Figure 1). Nonetheless, the patterns of water movement through the hillslopes and thus connectivity, are very different. We quantify these differences with three metrics of subsurface connectivity synthesised from the particle-tracking model of flow through the two virtual hillslopes presented by Ameli et al. (2021):

(1) The flow path length of water particles moving through the hillslope to the stream.

(2) The cross-sectional area from which the particles in the stream originate.

(3) The transit time of water through the hillslope to the stream.

Each of these modelled features of connectivity are presented for high and low flow conditions, as well as integrated over the course of a decade of simulations based on observed climate data. The novel cross-sectional area indicator was created to exploit the potential of the particle-tracking model to localise source areas for streamwater.

2 | Methods

2.1 | Field Site and Measurements

The forested study hillslope that serves as the basis for this virtual experiment is located in northern Sweden (64°14′ N, 19°46′E; (Laudon et al. 2021; Nyberg, Rodhe and Bishop 1999)). The topography is characterised by gentle slopes (2%–10%). The dominant forest vegetation is Norway spruce (*Picea abies*) on the lower slopes and Scots pine (*Pinus sylvestris*) on the upper slopes. The geological parent material is unconsolidated glacial till, with a depth to bedrock of at least 5 m in most places. The dominant soils are well-developed podzols (spodosols), except at the toe of the slope where paludification since the last ice age has generated organogenic soils. Soil properties, including porosity and hydraulic conductivity (Bishop 1991; Nyberg et al. 2001) have been characterised and revealed a strong vertical decrease in K_{sat} that focuses lateral flows in transiently saturated soil layers. The conclusions about flow paths based on soil physical data, complemented by hydrometric data and conservative hydrological tracers, led to coining of the term 'TF' to characterise the subsurface flow mechanism (Bishop 1991). Determination of subsurface connectivity has been the common starting point for explaining the vulnerability of streams to anthropogenic perturbations, such as pollutants in precipitation for example, lead (Klaminder et al. 2006), mercury (Lee, Bishop and Munthe 2000) and nitrogen (Petrone, Buffam and Laudon 2007), as well as climate change (Tiwari, Sponseller and Laudon 2019).

In 1996, the 'S-transect' used in the present study was established parallel to the assumed groundwater flow direction along a hillslope (Figure S1, (Nyberg et al. 2001)). Groundwater wells were installed at distances 4, 12 and 22 m from the stream along the topographic fall line. In 2013, an additional well near the water divide was installed 140 m from the stream. A V-notch weir was established in 1985 to monitor streamflow at the outlet of the forested 12 ha Västrabäcken

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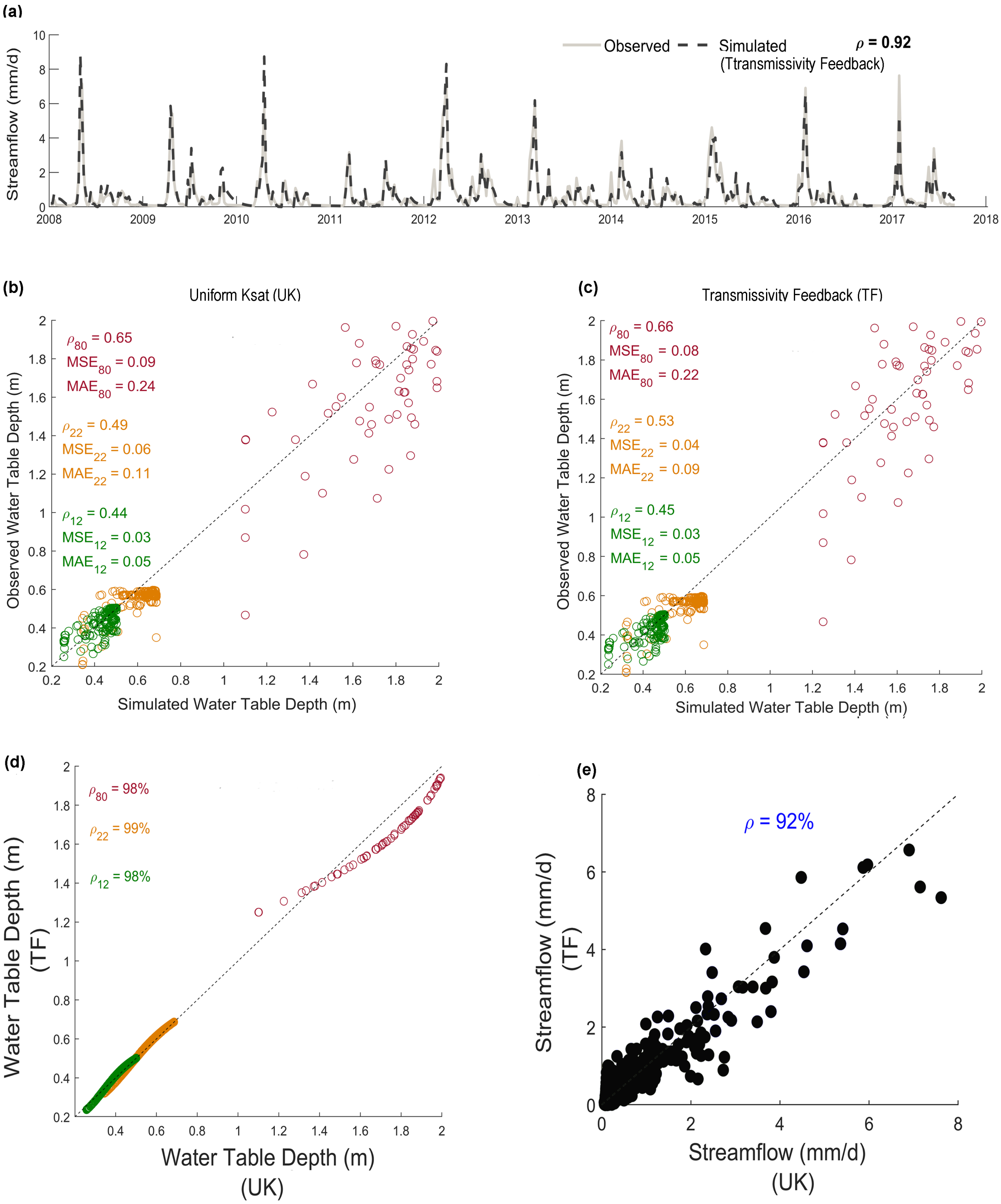

FIGURE 1 | (Panel a) Time-series of weekly observed streamflow values and simulated streamflow for the Transmissivity Feedback (TF) scenario. Since the correlation between the weekly Uniform K_{sat} (UK) and TF scenarios were as good as the correlation between TF and observed streamflows (correlation coefficient of 0.92, cf. panel (e)) only the TF simulation is plotted here against the observed values. (Panels b. and c.) Correlation between observed and simulated water table depths at distances of 12, 22 and 140 m from the stream for the UK and TF hillslopes respectively. Goodness of fit was evaluated using the correlation coefficient (ρ), mean squared error (MSE) and mean absolute error (MAE). The subscripts and colours correspond to the distance of the groundwater well from the stream as measured along the hillslope. (For the location of both the stream gauging in panel a and the water table measurements in panels b and c, see SI Figure S1). (Panel d.) Correlations between the water table depths along the hillslope in the UK and TF scenarios at distances of 12, 22 and 140 m from the stream for the range of weekly average conditions observed during the decade of observations used in this study (2008–2017). (Panel e.) Correlation between the simulated weekly stream flows for the UK and TF scenarios 2008–2017. The figures highlight the equifinality of the scenarios with respect to measured streamflow and groundwater depths. The TF scenario represents the situation used in many studies of flow and chemistry at this site. These figures were adapted from Ameli et al. (2021). Flow paths: High flow (90th percentile flow).

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sub-catchment in which the S-transect is located. This catchment is referred to as 'C2' in the Krycklan Catchment Study (Laudon et al. 2013).

For this study, we used the streamflow and groundwater hydrometric data for the decade from 2008 to 2017. The mean annual temperature, precipitation and runoff during this period were 2.3°C, 632 mm and 243 mm respectively. The 10th percentile, median, average and 90th percentile of daily runoff were 0.06, 0.30, 0.67 and 1.80 mm d^{-1}, respectively. An example of the daily runoff response to precipitation, together with groundwater levels on the S-transect, are presented in the Supporting Information (Figure S1e). Amvrosiadi et al. (2017b) used the observations of groundwater, rainfall, runoff and soil properties to define water flow patterns and storages along the entire S-transect up to the water divide.

2.2 | Flow and Particle Tracking Transport Model

We employed a physically-based, grid-free, hillslope flow model built on a 2-D Richards Equation with continuous velocity field for water flow in both saturated and unsaturated zones at steady state conditions (Ameli et al. 2021). This quasi-semi state approach of the model allows it to overcome the numerical instabilities faced when applying the Richards Equation to hillslopes where the saturated hydraulic conductivity changes rapidly with depth. The rapid decline in K_{sat} from the soil surface downwards is a key feature responsible for the TF mechanism of runoff generation characteristic of glacial till catchments such as the 'S-Transect' field site (Figure S1) on which this virtual experiment is based (Ameli et al. 2016a; Ameli, McDonnell and Bishop 2016b). The quasi-steady state model comprises thousands of successive steady states, each corresponding to weekly-averaged streamflow, assuming the hillslope reaches steady state at a weekly-scale.

A random walk particle-tracking routine takes advantage of the continuous velocity field in the entire domain. This approach efficiently tracks particles from when they enter the catchment at the land surface to their exit into the stream. Tracking of water particles allows the calculation of water particle 'backward' residence time for each point within the hillslope (i.e., time since that particle entered the soil), as well as 'forward' water transit time from each point until entering the stream. Based on extensive field observations and the high hydraulic conductivity of near surface soils, overland flow is not included in the model.

Weekly steady state models were successively linked together for the 10-year study period 2008–2017 after a 27-year spin-up period. The duration of the spin-up was chosen to allow particles entering the hillslope at the water divide to reach the stream (Ameli et al. 2021). Each water particle moved through the hillslope using the saturated and unsaturated Richards-based velocity calculated at the starting location for that particle by the steady state model for the weekly-averaged streamflow of the corresponding calendar week. The model assumes that hillslope flow is represented by the steady state condition where net water input and streamflow are identical during that week. The amount of water entering the soils each week is the 'hydrologically effective rainfall' calculated by the HBV model, which accounts for both snowmelt and the proportion of precipitation returned to the atmosphere as evapotranspiration that week (Teutschbein et al. 2015). The weekly input correlated well with the measured weekly average discharge rate during the study period (correlation coefficient of 0.87), indicating the adequacy of the weekly steady state assumption (Ameli et al. 2021). Since evapotranspiration is removed from precipitation before water inputs to the soil are calculated, all water in the hillslope at the start of the week will either stay in the hillslope or enter the stream. Other features of the model are described in the Supporting Information (SI), Section B.

2.3 | Hillslope Scenarios and Visualisations of Subsurface Flow

Using this modelling approach, Ameli et al. (2021) showed that weekly runoff and groundwater levels at different distances from the stream on the S-transect could be equally well simulated using a range of different vertical profiles of K_{sat} (i.e., soil permeability architectures). Thus, weekly runoff and groundwater levels along the hillslope are equifinal as a metric for distinguishing between different hillslope permeability architectures (Figure 1b–e). Another study demonstrated that the soil moisture in the vadose zone was correlated to the groundwater levels (Amvrosiadi, Bishop and Seibert 2017a). We assume from this finding that the distributed soil moisture values would be similarly equifinal concerning streamflow.

For the present study, we used two extremes of the studied K_{sat} profiles previously modelled by Ameli et al. (2021). One extreme has a uniform K_{sat} with depth. Contrasting to this, the exponent of an exponential K_{sat} decline term was set to a value of 2.5. Increasing the exponent above zero (the uniform K_{sat} situation), yields increasing rates of K_{sat} decrease with depth below the ground surface. This promotes the TF mechanism of runoff generation (Bishop 1991; Seibert et al. 2009). The scenario with uniform K_{sat} across the hillslope was termed the UK scenario and the scenario with 2.5 as the exponent for K_{sat} decline was termed the TF scenario (TF). In all other respects, the scenarios were identical, including the mean K_{sat} of the entire hillslope, 12.4 m d^{-1}. The contrasting hillslope permeability architectures of the UK and TF scenarios are visualised in Figure 2a,b.

The decade of observed temperature and precipitation used for the simulations captured much of the variation in the regional weather observed over the last half century. The two virtual hillslopes generated similar weekly runoff rates (correlation coefficient $\rho = 0.92$; Figure 1e) and groundwater levels along the hillslope ($\rho = 0.98$–0.99; Figure 1d). These simulated values of runoff and groundwater were also similar in how well they matched the observations ($\rho = 0.92$ for streamflows and from 0.44–0.66 for groundwater levels at different distances from the stream, Figure 1a–c).

For the two scenarios, the flow of the water through the hillslope is visualised as the pathways (Figure 2c–f), particle velocities (Figure 3) and forward transit time from the point of interest to

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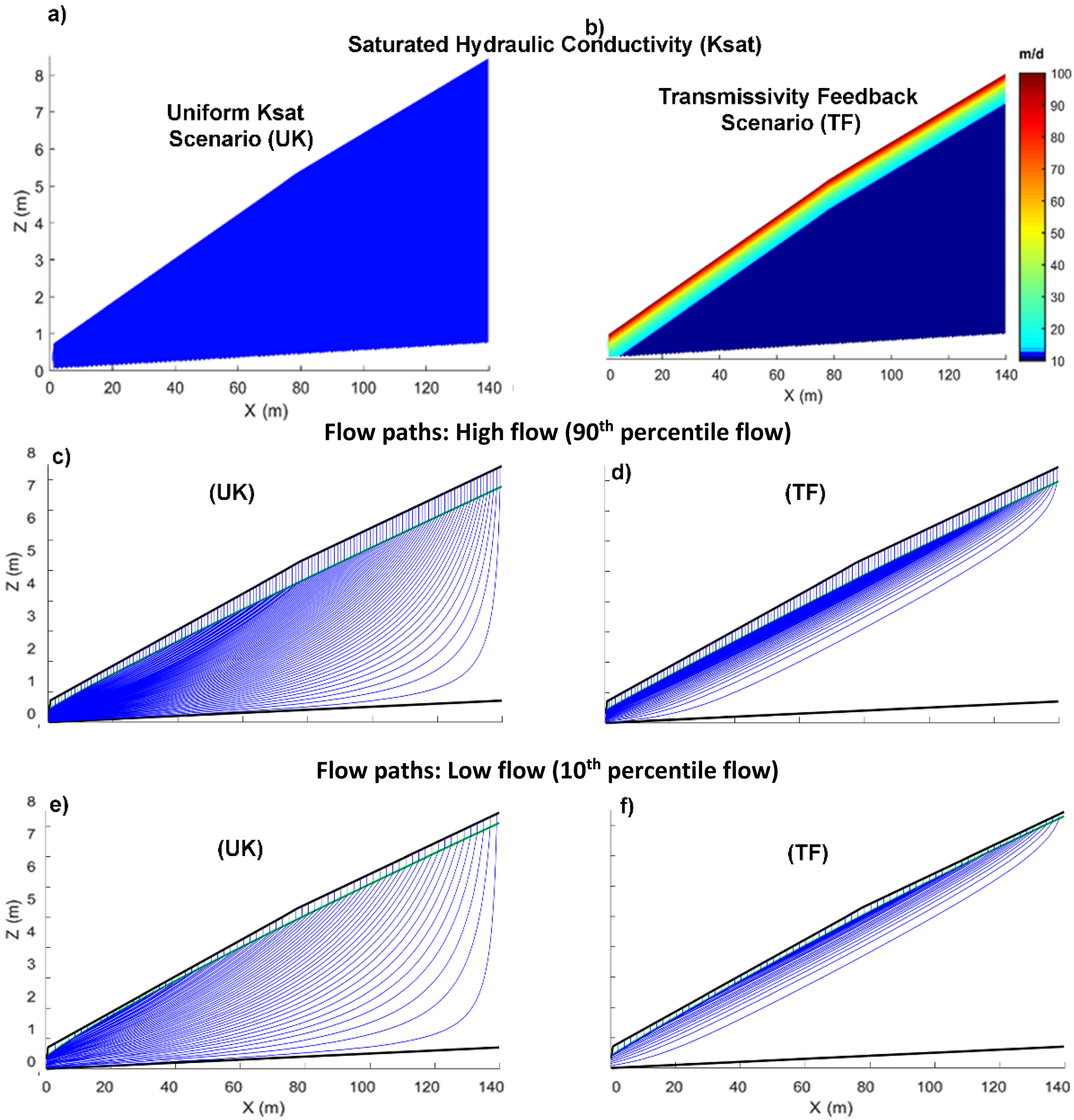

FIGURE 2 | Upper panels a, b: The permeability architecture of the saturated hydraulic conductivity (K_{sat} m d^{-1}) across the hillslope. To the left (a) the scenario with uniform K_{sat} (UK scenario) where $K_{sat} = 12.4$ m d^{-1} throughout the entire hillslope and to the right (b) the transmissivity feedback scenario (TF scenario) where K_{sat} declines exponentially with depth below the ground surface ($z-z_t$) toward the no-flow boundary at the bottom of the hillslope, ($k_{sat}(x,z) = 100e^{2.5(z-z_t)}\,\frac{\text{m}}{\text{d}}$). Middle panels c, d: The flow paths of water particles falling on the hillslope at different distances from the stream (x-axis) when the flow rate is the 90th percentile for the 10-year study period ('high flow', 1.80 mm d^{-1}). To the left for the UK scenario (c) and to the right for the TF scenario (d). The water table is the green line located at the bottom of the vertical lines where downward infiltration through the unsaturated zone ends. Lower panels e, f: The flow paths when the flow rate is at the 10th percentile for the 10-year study period ('low flow', 0.06 mm d^{-1}). To the left (e) the UK scenario and to the right (f) the TF scenario. N.B. To avoid using space in the figure to duplicate information, the axis labels for some panels have been omitted where they repeat information on nearby panels.

the stream (SI Figure S2) and residence time back to precipitation entering the soil (as rainfall or snowmelt, SI Figure S3). This was done on a weekly time-step over the 10-year study period. In the figures and Table 1 we highlight the results for a high flow week (90th percentile) and a low flow week (10th percentile), as well as the median for the entire study period. Since the water that will be transpired never enters the hillslope, the residence time of the transpired water is not included in the estimate of water residence time in the hillslope. This affects both the UK and TF scenarios in similar ways and, therefore, this should not alter the

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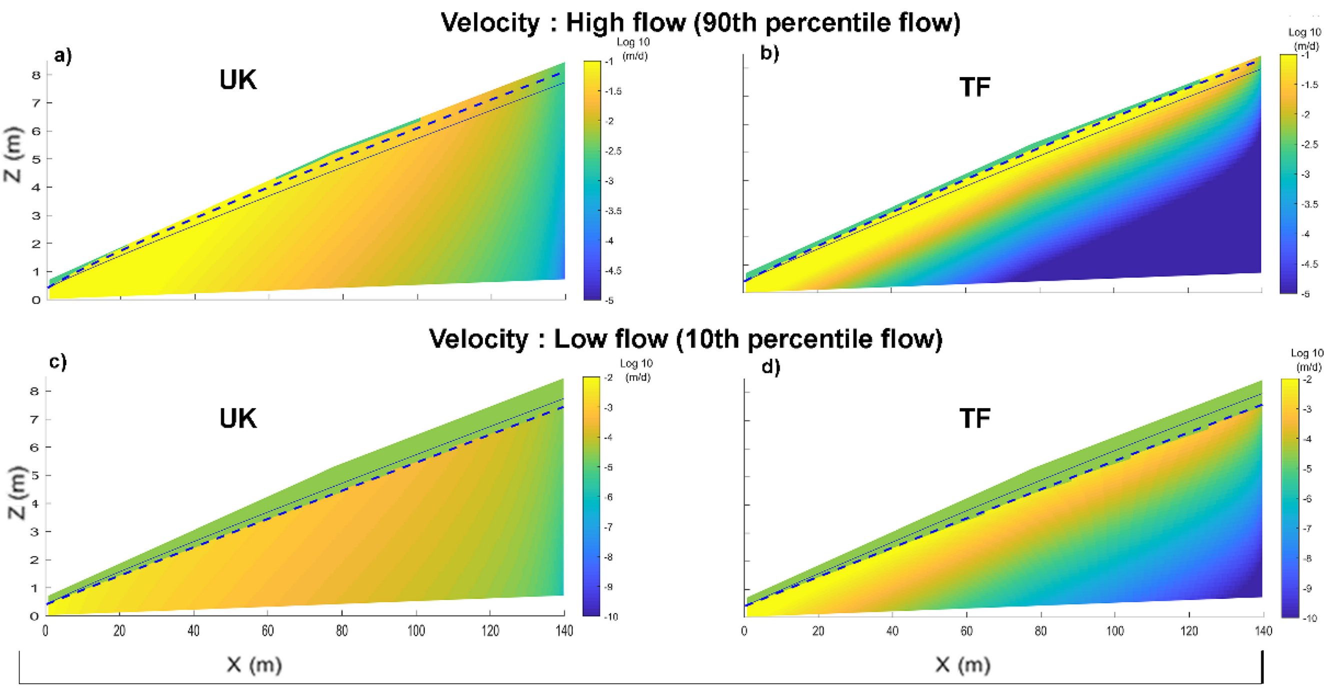

FIGURE 3 | A snapshot of simulated particle velocities for the Uniform K_{sat} hillslope (UK to the left, panels a and c) and the Transmissivity Feedback hillslope with the exponential decline in K_{sat} (TF to the right, panels b and d) for the 90th percentile high flow conditions of 1.8 mm d^{-1} (for panels a and b) and the 10th percentile low flow conditions of 0.06 mm d^{-1} (panels c and d). The water table for the flow percentile depicted in the panel is shown as a thick dashed blue line; the water table for the flow percentile not depicted in the panel (e.g., in panel a, the 10th percentile flow) is shown as a thin, finely dotted line for easier comparison between the water table for high and low flow situations. N.B. the logarithmic colour scales are different for the high flow and low flow conditions depicted in the upper and lower panels, respectively. For the high flow conditions (90th percentile flows), the maximum velocity (yellow) is 0.1 m d^{-1} and the minimum (dark blue) is 10^{-5} m d^{-1}. For the low flow conditions (10th percentile flows), the maximum velocity (yellow) is 0.01 m d^{-1} and the minimum (dark blue) is 10^{-10} m d^{-1}. Furthermore, to avoid using space in the figure to duplicate information, the axis labels for some panels have been omitted where they repeat information on nearby panels.

comparison of permeability architectures, which is the focus of this paper.

2.4 | Metrics of Subsurface Connectivity

The connectivity of the subsurface flows in the different model simulations was quantitatively summarised with three metrics. One was stream-based: the distribution of stream water ages calculated from transit times through the catchment (Figure 6). The other two metrics are hillslope-based: the median flow path length to the stream and the total cross-sectional area of the hillslope contributing particles to the stream (Figure 5a,b). These metrics are calculated from the history of the particles reaching the stream during each week of the 10-year simulation.

For the connected hillslope cross-sectional area, we determined the locations on the hillslope that contribute particles with ages that are shorter than the median age of water in the stream during the period of integration. For the 10 years between 2008 and 2017, these histories were integrated over all consecutive weekly sequences ranging from 10 to 50 weeks. This yields a distribution of values for each indicator, since different sequences of weekly stream flow rates will yield different values for the indicator.

For the stream-based indicator, the median and quartiles of the particle transit times are presented as a function of the flow percentiles: moderately low flow (1st quartile), median flow and moderately high flow (3rd quartile). For the hillslope-based metrics, the values for the median and quartiles are shown for each integration period. Integration periods shorter than 10 weeks did not have enough particles to represent the metrics adequately and are therefore not reported.

3 | Results

3.1 | Hillslope Subsurface Connectivity at High and Low Flow

To explore the differences between the subsurface connectivity predicted by the two scenarios of hillslope permeability architecture, we start with the flow pathways for the 90th and 10th percentiles of daily flow from 2008 to 2017. For the Uniform K_{sat} (UK) hillslope scenario (Figure 2c,e), the flow pathways are spread from the top to the bottom of the hillslope along its entire length. The flow paths converged toward the stream as the vertical extent of the hillslope narrows. For the TF hillslope scenarios (Figure 2d,f), the pathways were markedly more superficial along the entire length of the hillslope.

There were also distinct differences between the UK and TF scenarios with respect to the distribution of particle (Darcy) velocities (Figure 3). The velocity distributions across the two hillslope scenarios are relatively consistent between high and low flows. In the Uniform K_{sat} (UK) hillslope scenario (Figure 3a,c) there is less

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TABLE 1 | Differences in subsurface connectivity between the UK and TF scenarios at specific locations on the hillslope.

		Downslope				Upslope		
		25 m from stream				120 m from stream		
		Scenario		Ratio		Scenario		Ratio
	Depth (m)	UK	TF	TF/UK	Depth (m)	UK	TF	TF/UK
Median decadal catchment	0.75	1.4	0.8	0.59	1.5	56	64	1.15
Transit time to stream (yrs)	1.75	1.6	4.4	2.82	6.0	99	688 188	6918
	Depth (m)				Depth (m)			
Median decadal	0.75	11.0	17.5	1.58	1.5	0.80	0.82	1.02
Particle velocity ($m\,yr^{-1}$)	1.75	8.2	1.8	0.22	6.0	0.26	0.000017	0.00006
	Depth (m)				Depth (m)			
High flow (90th percentile)	0.75	50.4	44.9	0.89	1.5	4.1	2.3	0.55
Particle velocity ($m\,yr^{-1}$)	1.75	38.2	4.6	0.12	6.0	1.3	0.000050	0.00004
	Depth (m)				Depth (m)			
Low flow (10th percentile)	0.75	0.8	2.8	3.55	1.5	0.06	0.11	1.91
Particle velocity ($m\,yr^{-1}$)	1.75	0.6	0.2	0.35	6.0	0.02	0.000004	0.00020
	Depth (m)				Depth (m)			
Saturated hyd. conductivity	0.75	12.4	17.6	1.42	1.5	12.4	3.05	0.25
Ksat ($m\,d^{-1}$)	1.75	12.4	1.45	0.12	6.0	12.4	0.00006	0.00000

variation in velocity across the hillslope than for the TF hillslope scenario (Figure 3b,d). The velocities are higher in most areas of the UK hillslope compared to the TF, except for the superficial soil layers (i.e., in the uppermost metre of the saturated soils; Table 1). The principle variation in velocity across the UK hillslope occurs with distance from the stream. Velocities increase by an order of magnitude from the catchment divide, where they are lowest, toward the stream due to the accumulation of water in the hillslope closer to the stream, where there is less hillslope depth to transmit that water. For the TF scenarios, the differences in velocities within the hillslope are even more marked. The velocities in the deeper soils furthest from the stream are over five orders of magnitude lower than the fastest flows in the hillslope. While velocities also increase toward the stream for the deeper layers, the highest velocities are in the upper 2 m of the soil in a band that extends along the entire length of the hillslope. In much of the deeper TF soils though, the particle velocities are lower than at the corresponding depths in the UK soils, often by orders of magnitude (Table 1). These differences in velocities are reflected in the 'forward' transit time from a point in the hillslope to the stream and the 'backward' residence times defining how long a water particle has been in the hillslope (Figures S2 and S3).

3.2 | A Decade of Subsurface Connectivity

The decade of simulated particle-tracking makes it possible to look at the median flow conditions in the hillslope during a period long enough to capture much of the variation in local weather. The median particle velocities below the water table (Figure 4a,b) are more uniform and generally higher across the hillslope in the UK scenario than for the TF scenario. For the TF hillslope, higher velocities in the saturated zone are restricted to the uppermost soil layers, where almost all the flow is focused. The deeper soils in TF scenario have much lower velocities, especially further from the stream, where the difference is four orders of magnitude (Table 1).

The presence of water in the hillslope that is more than decades old would seem surprising if one looks at some of the papers from this area based on the Oxygen-18 of rainfall/runoff. These report mean transit times in the stream of just a few years (e.g., Peralta-Tapia et al. 2016). Two recent papers from this area, however, reported water in the hillslope and or stream that was well over a decade old. Kolbe et al. (2020) reports shallow groundwater less than 5 m below the water table where CFC age dating indicated three to four decades of residence time. Sterte et al. (2021) reports

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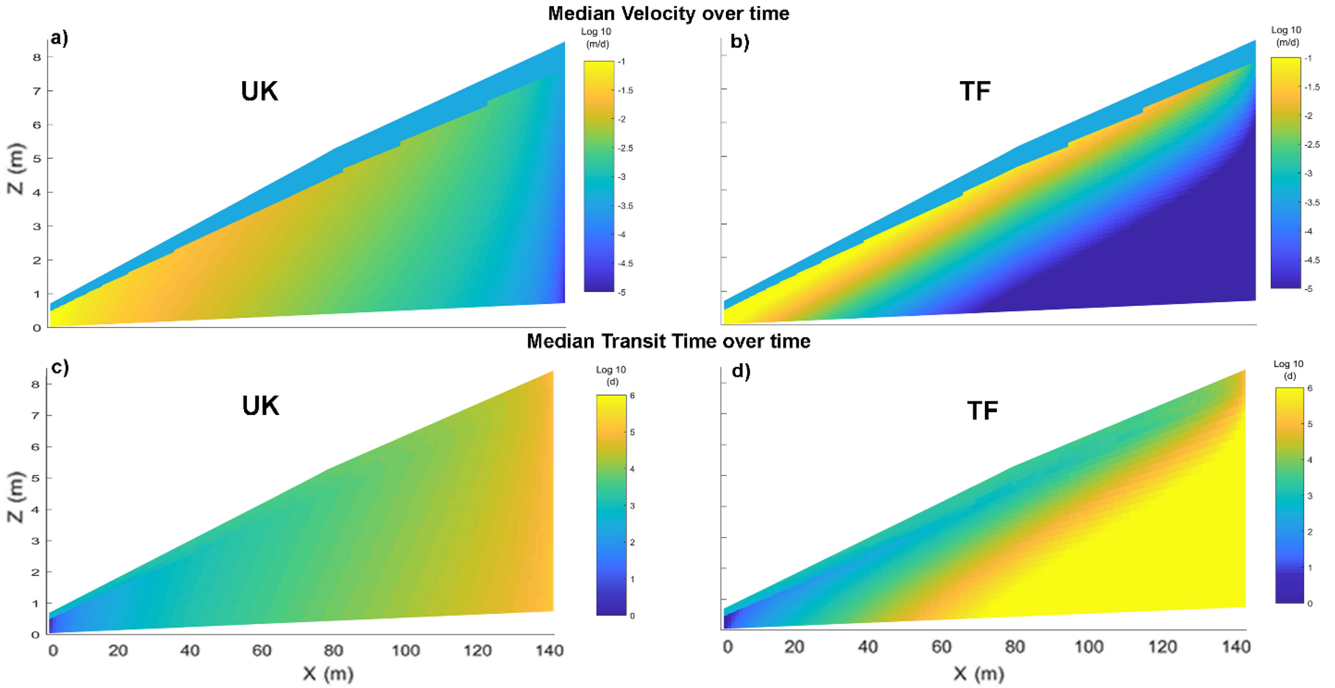

FIGURE 4 | Simulated median flow velocity (upper panels a, b) and forward transit time from any point to the stream (lower panels c, d) for each point in the hillslope-based on 10 years (2008–2017) of simulation. The Uniform K_{sat} hillslope is to the left (UK, panels a and c), while the Transmissivity Feedback hillslope is to the right (TF, panels b and d). N.B. To avoid using space in the figure to duplicate information, the axis labels for some panels have been omitted where they repeat information on nearby panels.

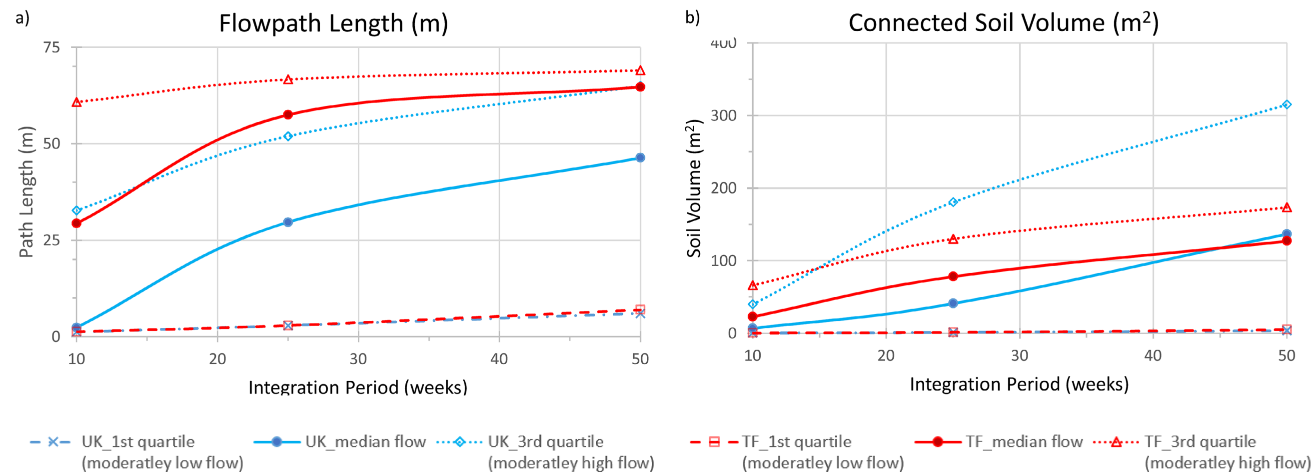

FIGURE 5 | (a) Simulated path lengths for water moving through the catchment to the stream and (b) the simulated cross-sectional area of soil contributing particles to the stream. The connectivity metrics are expressed as the median and quartiles integrated over periods between 10 and 50 consecutive weeks (indicated on the x-axis). The periods of integration are all possible sequences of consecutive weeks from within the decade of simulated hillslope flows driven by observed weather variables 2008–2017.

an application of the MIKE-SHE model that had a long tail in the transit time distribution of streamwater that stretched to decades in age, with some water as much as 100 years old.

For the median transit time from a given point on the hillslope to the stream (Figure 4c,d), the differences across the hillslope are smaller in the UK scenario compared to the TF scenario (one as opposed to five orders of magnitude at specific locations in the hillslope, Table 1). The changes in the UK scenario occur primarily with distance from the stream at all depths (Figure 4c).

For the TF scenario, the transit time is distinctly shorter in the superficial band of more permeable soils, below which the transit times are up to four orders of magnitude longer (Figure 4d, Table 1). In the deeper soils of the TF scenario, there is also a five order of magnitude increase in transit time with distance to the stream. Thus, the differences in subsurface connectivity, as measured by time remaining to reach the stream, are more spatially variable in the TF hillslope, where the zone of rapid connectivity is concentrated in the superficial soils. The median residence time is depicted in the SI, Figure S4 and accompanying text.

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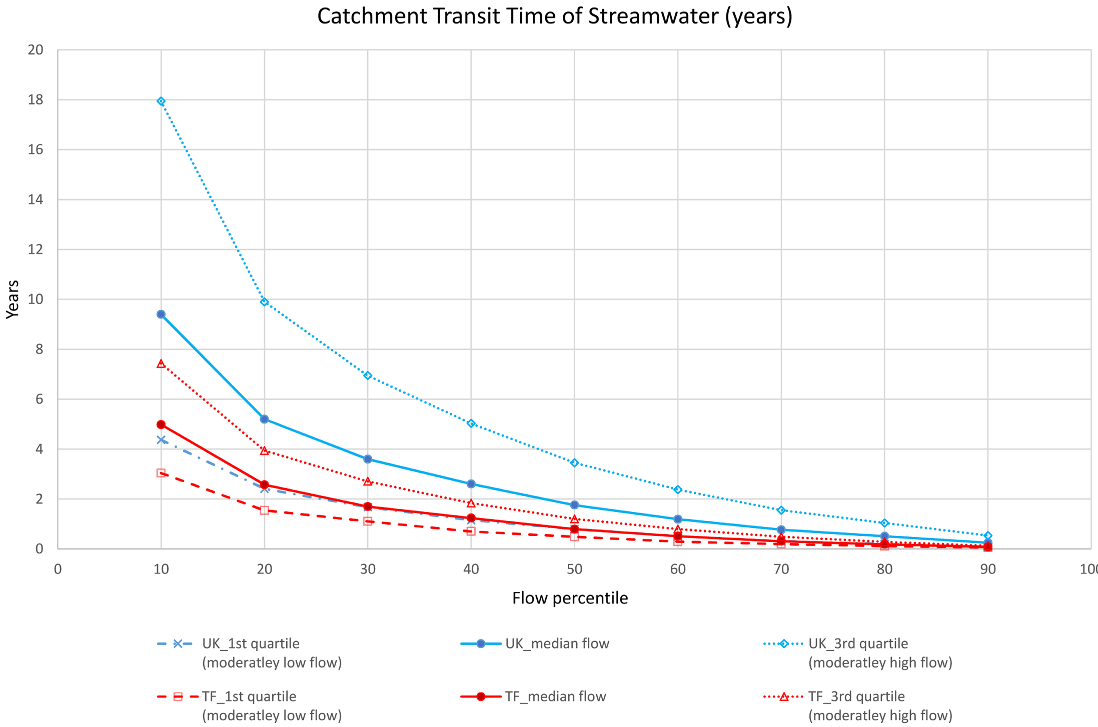

FIGURE 6 | Transit time through the catchment of water in the stream expressed as the median and interquartile range (IQR) at the different flow percentiles. The periods of aggregation are all possible sequences of consecutive weeks from within the decade of simulated hillslope flows driven by observed weather variables 2008–2017.

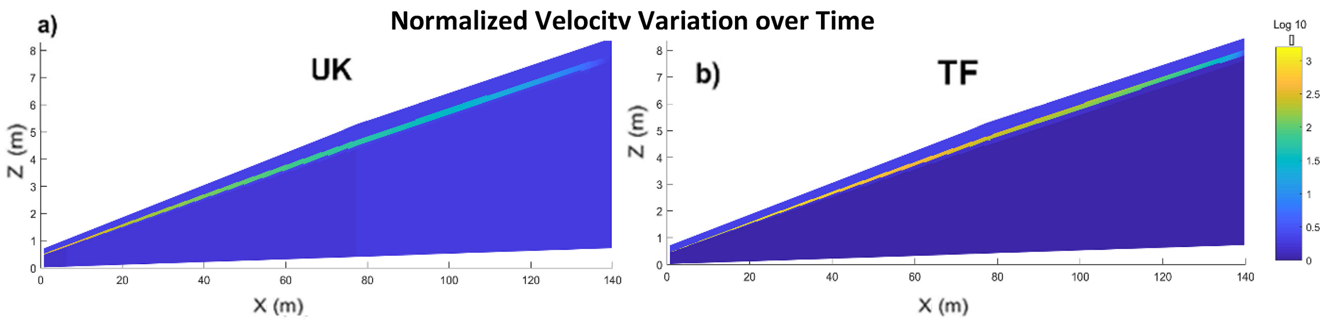

FIGURE 7 | Variation in lateral particle velocities at each point in the hillslope over the course of a decade (2008–2017, panels a, b) for the Uniform Ksat hillslope to the left (UK) and the Transmissivity Feedback hillslope (TF) to the right. The variation in lateral velocity is calculated as the difference between the 75th and 25th percentiles, normalised with respect to median velocity at that point.

3.3 | Hillslope and Stream Based Metrics of Subsurface Connectivity

From the decade of particle-tracking flow simulation, two hillslope-based connectivity metrics were quantified, the median path length and cross-sectional area of connected hillslope soils. The path lengths increase with the period of integration at a rate that declines as the integration period gets longer (Figure 5a). For the UK hillslope, the median path length starts at 2 m for 10 weeks of time integration, increasing to 45 m at 50 weeks of integration (Figure 5a). The TF hillslope has consistently longer median path lengths, starting at 30 m, extending up to 65 m as the integration period increases from 10 weeks to 50 weeks. For the UK hillslope, the interquartile range (IQR) of the path lengths increases from 30 m at 10 weeks of integration to 60 m at 50 weeks of flow integration. The IQR of the path lengths is ca 60 m for the TF for all periods of flow integration. The transit times skew as integration time increases for both the TF and UK scenarios, but more so for the TF scenario.

The cross-sectional area of the hillslope from which particles enter the stream increases with the integration time as well (Figure 5b). Unlike the other metrics, though, the differences between the median values for the UK and TF scenarios are small, even though the IQRs still differ markedly. For the TF hillslope, the median value of soil cross-sectional contributing area increases from 23 to 130 m^2 between 10 weeks and 50 weeks of flow integration. For the UK hillslope, the area starts a bit smaller (7 m^2 at 10 weeks of integration), but increases to a slightly larger area at 50 weeks of flow integration (140 m^2). The IQR is smaller for the TF scenario (20–120 m^2 between 10 and 50 weeks of integration) than for the UK scenario (40–310 m^2).

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The transit times through the hillslope are a stream-based connectivity metric (Figure 6). The median transit times (i.e., the time between particles entering the hillslope and exiting to the stream) decrease as flow increases. At the 10th percentile of flow (0.06 mm d^{-1}), the median particle transit time for the TF scenario is 5 years. This decreases to ca 30 days at the 90th flow percentile (1.8 mm d^{-1}). The UK scenario has longer median transit times, starting at 9.4 years for the 10th flow percentile, decreasing to 70 days at the 90th flow percentile. This means that the absolute differences between the UK and TF scenarios in terms of median catchment transit time of streamwater also decrease as stream flow rates increase—from years at low flow, to tens of days at high flows, even though relative differences between the TF and UK scenarios remain. The IQR of these catchment transit times for water particles also declines in absolute terms as the flow increases. The span of the IQR is several times larger for the UK scenario than the TF scenario.

For both hillslope scenarios, the particle velocities changed relatively little at a particular point on the hillslope, which is to be expected when lateral hydraulic gradients are rather constant in the saturated zone. There was, however, one narrow band (ca 1 m in vertical extent) along the entire hillslope where the lateral particle velocities changed markedly (Figure 7).

4 | Discussion

4.1 | Equifinality of Inferred Subsurface Connectivity When Only Hydrometric Data Are Available

The promise of effectively distinguishing catchment sources of streamwater makes the hydrological connectivity concept particularly interesting for practical water management and understanding catchment sources of solutes, such as organic carbon (Zimmer and McGlynn 2018). The concern that hydrometric measurements may not constrain connectivity well in some settings motivated this modelling experiment with two scenarios for the hillslope permeability architecture, uniform K_{sat} (UK) and exponential K_{sat} decline with depth (TF). The modelled equifinality with respect to the weekly streamflow and groundwater tables of these two 'virtual' hillslopes (Figure 1) enabled us to quantify how little the subsurface connectivity was constrained by groundwater level measurements along the 140 m hillslope.

Although the simulated weekly streamflows emerging from the two virtual hillslopes were almost identical (Figure 1e), large differences in the journey of water particles through the two virtual hillslopes were readily apparent in the visualisation of flow paths for both high flow and low flow conditions (Figure 2c–f), particle velocities (Figure 3), forward transit times to the stream (SI Figure S2) and backward residence times since entering the hillslope (SI Figure S4). These differences were pronounced at both high and low flow conditions and persisted even when considering the flow patterns over a decade (Figure 4). In particular, the particle velocities and water age of subsurface flow at specific locations within the hillslope could differ by orders of magnitude for the UK and TF scenarios (Table 1).

The simulated groundwater tables from the riparian zone to the water divide (Figure 1) suggest that more groundwater observation points along the hillslope would not have been able to better identify the differences in connectivity associated with the different permeability architectures. Because soil moisture is predictable from the groundwater table on this hillslope (Amvrosiadi, Bishop and Seibert 2017a), distributed soil moisture measurements are also unlikely to be a valuable metric for defining subsurface connectivity in the type of hydrogeological setting represented by this study. This confirms suggestions from earlier field studies (Ali and Roy 2010; James and Roulet 2007) that not even extensive hydrometric observations (i.e., distributed groundwater level or soil moisture measurements) in a catchment with perennial streamflow will constrain subsurface connectivity sufficiently to be helpful for water management.

When using connectivity metrics to quantitatively summarise the differences between the UK and TF scenarios over the course of a decade, the medians are still distinctly different for two of the three metrics investigated. However, instead of the orders of magnitude difference seen at some discrete locations on the hillslope, (especially upslope at deeper depths, Table 1), median values of these metrics differed by factors of two to three for the transit times of particles to the stream (Figure 6), as well as for the flow path distance (Figure 5a). The median cross-sectional areas of the hillslope contributing to the stream, on the other hand, were more similar (Figure 5b).

Skewness around the median values for the connectivity metrics (as indicated in Figures 5 and 6 by the vertical position of the median in relation to the upper and lower quartiles) reflects the larger differences in the more complete representations of particle movement along the hillslope (Figures 2–4). For instance, even though the median connected soil cross-sectional areas were similar (Figure 5b), the location of the median values in relation to the quartiles differs between the UK and TF scenarios, due to differences in the spatial distribution of connected soil volumes along the hillslope that are evident from the flow paths in Figure 2. For the TF permeability architecture, the major flow pathways are superficial layers extending far up the slope. In contrast, for the UK architecture, the full depth of the hillslope is 'connected' to the stream, but this connection extends a shorter distance up the hillslope for different periods of integration. While this can be understood when interpreting the metrics of connectivity with the help of the flow paths mapped out by the particles, it is also an example of how simplifications of subsurface connectivity into numeric metrics (e.g., Figures 5 and 6) lose valuable information about water flow through the catchment.

While it is a discouraging message that hydrometric data are insufficient to infer subsurface connectivity in some situations, this problem can be overcome with measurements that are more informative. Measurements of soil physical properties provide information about which permeability architecture is correct (Amvrosiadi et al. 2017b; Bishop 1991). The increasing use of age tracer data in hydrological studies has great potential in this regard (Kirchner, Benettin and van Meerveld 2023; McMillan et al. 2012), especially when multiple tracers are used to cover different age ranges (Kolbe et al. 2020; Thiros, Gardner and Kuhlman 2021). However,

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inferring hydrological connectivity from age tracer data has its own challenges either because of non-ideal tracer behaviour (Svensson et al. 2021) or the mismatch between the range of water ages in catchments relative to the information provided by a particular tracer (Kirchner 2016). Changes in stream water composition with increasing discharge and connectivity are smaller for catchments with many source areas (Abbott et al. 2018), which also hinders interpretation of connectivity based on tracer data when there are many different source areas that become connected. The value of a particular tracer, furthermore, depends on where and when the tracer is sampled. Ameli et al. (2021) showed that measurements of the oxygen isotopes in water made it possible to discriminate between the UK and TF permeability architectures. Nevertheless, while several years of biweekly tracer samples from the stream were useful in distinguishing between the two permeability architectures, a few dozen hillslope groundwater samples were even more informative.

Since connectivity of subsurface flows is of interest because of its great influence on the chemistry of surface waters, non-conservative chemical constituents have also been used to discern the subsurface flow pathways. An example of this is the use of weathering products to identify water inputs from slower, deeper flow paths (Tiwari et al. 2017). For such applications, though, it is necessary to sample both hillslope groundwater and stream runoff to test assumptions about where the sources are and how conservative these tracers actually are in the subsurface. For instance, when overland flow was assumed to be the source of chemical elements such as methylmercury that reach the forest floor via throughfall, it required measurements of water chemistry and groundwater levels to disprove that hypothesis (Bishop et al. 1995). It is, however, common that only the stream or the hillslope is included in a study (Burns et al. 2019).

When using information on chemical constituents that are not ideal hydrological tracers to infer flow paths (e.g., chloride Nyberg, Rodhe and Bishop 1999; Svensson et al. 2021), there is also a trade-off between what one learns about chemistry and hydrology. If one does not have to use a potentially reactive chemical substance as a tracer to identify connectivity, but still had information about connectivity, more could be learned about how biogeochemical processes alter these substances as they move through the catchment (Li et al. 2021). Even when the overall picture of shallow and deep pathways is correct, there are details such as reaction rates that depend on the accuracy of the flow rates along specific pathways, as in the case of chemical weathering (Erlandsson Lampa et al. 2020; Maher 2011).

4.2 | Utility of Virtual Modelling Experiments—Including Counterfactual Cases

The results in this study are from a hillslope setting that is common in unconsolidated glacial till soils of high-latitude areas. There is a range of possible hillslope permeability architectures for this setting and this study explores just two contrasting ones. The preponderance of evidence suggests that the TF architecture represents this setting much better than the UK scenario (Ameli et al. 2021). Nonetheless the counterfactual model for the UK soil permeability architecture is useful, even though it is known be wrong, because saturated matrix flow through the UK hillslope reproduces observed weekly streamflow and groundwater levels along the slope as well as the model based on the TF architecture.

Hydrometric data may better constrain the range of possible patterns in hillslope flow at time scales shorter than weekly averages. Preferential flow structures other than the superficial TF pathways of the TF scenario, such as the preferential flow associated with macropores, were also not explored. Despite these limitations, the two scenarios are sufficient to demonstrate the value of leveraging knowledge about a site to create a virtual observatory as suggested by Thomas et al. (2016). More specifically, applying the particle-tracking model to the two contrasting hillslope permeability architectures defined the large range of flow patterns and thus subsurface connectivity that could be consistent with the hydrometric information (groundwater levels and streamflow).

The exhaustive representation of connectivity by a particle-tracking model also provides clues about features that merit further investigation. An example of this emerged from our analysis of the virtual modelling experiment that would be hard to discern even by direct observation, much less a simplified metric. This feature was the degree to which lateral flow velocities changed along the hillslope. While the particle velocities were relatively constant across most of the hillslope for both hillslopes, the modelling identified a narrow band across the entire hillslope where there were clear changes (Figure 7). That ca 1 m deep band coincides with the zone of water table variation, discernible in Figure 3 as the difference between the groundwater levels at the 10th and 90th flow percentiles. This variation in lateral particle velocities is caused by changes in the soil hydraulic conductivity as superficial soil layers alternated between saturation (with no air-filled pores) and unsaturated conditions when the water table fell below that particular soil layer. Recognising this zone can be of value where sequences of water movement rates and changes in redox potential are essential for chemical transformations for example, for different species of nitrogen and phosphorus (Kolbe et al. 2019), the chemodynamic behaviour of iron and manganese in streamwater (Herndon et al. 2018) or weathering rates (Erlandsson Lampa et al. 2020). The location of this zone depends on the climate and vegetation (precipitation inputs and potential evapotranspiration) and the permeability architecture of the hillslope. Given that the location of the zone is identifiable from groundwater level observations, we highlight the value of targeting data acquisition efforts here. This is due both to its importance for biogeochemical processes and the susceptibility of this zone to variation in weather patterns on the short term and climate change on the longer term (Li et al. 2021).

5 | Conclusions

Connectivity is widely used to understand and describe how surface waters mirror the landscape, even when that connectivity is hidden below the soil surface. A virtual exploration of two hillslopes with different hillslope permeability architectures

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revealed how imprecise the characterisation of subsurface connectivity can be when it is based only on comprehensive groundwater level data. Measurements of water age tracers, soil properties and chemical indicators of catchment source areas are, therefore, of particular value in developing more precise characterizations of subsurface connectivity or the soil permeability architecture that shapes hillslope-stream connectivity. This will bring us closer to knowing which parts of the landscape are mirrored in surface waters at different times.

Above all, the results highlight that when analysing hydrometric observations, the possibility of applying spatially and temporally resolved flow models should be considered. Models are becoming easier to apply and can help define the degree of equifinality consistent with the available data. Where it is clear that more precision is needed to resolve features of subsurface flow to answer a specific scientific or management question than the existing data allow for, model simulations can guide the collection of additional field data. The key to using models proactively is to identify the degree of dissimilarity between model scenarios (Ameli et al. 2021). The greater the dissimilarity at a potential sampling point in space and time, the greater the value of sampling just there and then.

Finally, we would like to emphasise that in the search for critical information about catchment hydrology, it is essential to confront the potential for equifinality. When recognised, that equifinality can even be embraced as something to learn from—as we have tried to do in this study. Until equifinality has been addressed, the possibility that alternative process explanations can match a set of observations will cloud the use of hydrological connectivity to understand hydrological systems better so that we can manage them sustainably. We hope this study's spatially and temporally explicit quantification of hydrometric equifinality in modelling subsurface water flow paths and transit times will serve as an incentive to all who seek to constrain subsurface connectivity as effectively as possible with well-designed observations.

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

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