AGU PUBLICATIONS

Water Resources Research

REVIEW ARTICLE

10.1002/2017WR020707

Key Points:
- Connectivity exists when water, sediment, or a chemical mobilized at a source exceeds losses incurred during travel to a receptor point
- Quantification of process Time scales, Thresholds, Excesses and Losses (T-TEL) is needed to characterize water and material connectivity
- The T-TEL method, based on a literature consensus, is proposed as a robust quantitative tool for standardizing connectivity assessments

Correspondence to:
G. Ali,
genevieve.ali@umanitoba.ca

Citation:
Ali, G., Oswald, C., Spence, C., & Wellen, C. (2018). The T-TEL method for assessing water, sediment, and chemical connectivity. *Water Resources Research*, *54*. https://doi.org/10.1002/2017WR020707

Received 5 MAR 2017
Accepted 23 DEC 2017
Accepted article online 8 JAN 2018

The T-TEL Method for Assessing Water, Sediment, and Chemical Connectivity

Genevieve Ali[1,2,3], Claire Oswald[4], Christopher Spence[5], and Christopher Wellen[4]

[1]Department of Geological Sciences, University of Manitoba, Winnipeg, MB, Canada, [2]Manitoba's Watershed Systems Research Program, University of Manitoba, Winnipeg, MB, Canada, [3]Center for Earth Observation Science, University of Manitoba, Winnipeg, MB, Canada, [4]Department of Geography and Environmental Studies, Ryerson University, Toronto, ON, Canada, [5]Environment and Climate Change Canada, Saskatoon, SK, Canada

Abstract The concept of connectivity has been the subject of a great deal of recent research and provided new insights and breakthroughs on runoff generation processes and watershed biogeochemistry. However, a consensus definition and cohesive mathematical framework that would permit the consistent quantification of hydrologic connectivity, the examination of the interrelationships between water and material (e.g., sediment and chemicals) connectivity, or rigorous study intercomparison, have not been presented by the water resource community. Building on previous conceptualizations and site-specific or process-specific metrics, this paper aimed to review the current state of science on hydrologic connectivity and its role in water-mediated connectivity of material such as solutes and sediment before introducing a conceptual and a mathematical connectivity assessment framework. These frameworks rely on the quantification of Time scales, Thresholds, Excesses and Losses related to water and water-mediated material transport dynamics and are referred to as the T-TEL method. Through a small case study, we show how the T-TEL method allows a wide range of properties to be quantified, namely the occurrence, frequency, duration, magnitude, and spatial extent of water and water-mediated material connectivity. We also propose a research agenda to refine the T-TEL method and ensure its usefulness for facilitating the research and management of connectivity in pristine and human-impacted landscapes.

1. Introduction: Connectivity Is a Useful Concept But . . .

Many hydrologists have highlighted the need for concepts and tools that unify analysis of common emergent hillslope and catchment behavior across different hydroclimatic regimes, topographies, and geologies (Bracken & Croke, 2007; McDonnell et al., 2007; Tetzlaff et al., 2007). Calls to action have encouraged hydrologists not to solely focus on site-specific complex hydrological dynamics but also seek to understand "*the set of organizing principles that might underlie the heterogeneity and complexity*" (McDonnell et al., 2007, p. 1). The concept of connectivity has the potential for allowing such organizing principles to be uncovered and thus help hydrology move forward. In broad terms, connectivity describes flows of matter, organisms, or energy between landscape components (Pringle, 2001). In relation to water, connectivity can be used to evaluate when and where flow is transmitted across the landscape, regardless of generating and transport processes (Ambroise, 2004; Bracken & Croke, 2007). The phrases "sediment connectivity," "nutrient connectivity," "chemical connectivity," and "biogeochemical connectivity" are also used to refer to situations in which a high source strength and/or a high transport potential can lead to the movement of constituents with water (Lane et al., 2003).

One current and puzzling paradox in hydrology is the great enthusiasm for the concept of connectivity and the lack of a single conceptual framework to quantitatively characterize it in a robust manner. For instance, definitions of "water connectivity" are sometimes ambiguous and field assessment methodologies site specific (Antoine et al., 2009; Bracken et al., 2013). Different runoff processes have been categorized as creating different types of water connectivity, such as overland flow connectivity (Gomi et al., 2008), shallow subsurface matrix flow connectivity (Detty & McGuire, 2010b; Jencso et al., 2009; McGuire & McDonnell, 2010), preferential flow connectivity (Tromp-van Meerveld & McDonnell, 2006b), and deep groundwater flow connectivity (Knudby & Carrera, 2005). Sediment connectivity studies have been performed using a variety of direct or surrogate measures (Croke et al., 2005; Fryirs et al., 2007a, 2007b; Hooke, 2003; Lexartza-Artza &

Wainwright, 2011). Biogeochemical connectivity has been implicitly examined via tracer studies to determine active flow paths from sources to outlets but rarely has it been explicitly quantified (Ocampo et al., 2006; Stieglitz et al., 2003). Hydrologists have applied connectivity as an abstract concept (Ali & Roy, 2009; Renard & Allard, 2013), a conceptual framework to advance process understanding (Bracken & Croke, 2007), a hydrologic state variable (i.e., a variable representing the coupling relationships between elementary units within a larger system; Phillips et al., 2011), and an emergent property of hydrosystems (i.e., a property only seen at large scales and created by the interaction and feedbacks between small-scale processes; Antoine et al., 2009; Bracken et al., 2013). There is also ambiguity regarding whether connectivity can be assessed between any two points or between a source point and a catchment outlet, and whether it should be seen as a binary or a continuous variable (Cohen et al., 2016). This high level of uncertainty associated with the applicability of connectivity in hydrology is in contrast to its application in the field of ecology where it is a more mature concept: the organism-based definition of connectivity is largely agreed upon, its quantification from field data is coded in the literature, and its practical use to guide the management of biological reserves is unchallenged (Amoros & Bornette, 2002; Calabrese & Fagan, 2004; Pringle, 2001, 2003a). Hydrologic connectivity has also been suggested as a critical property for scaling hydrological behavior and calibrating and validating numerical models (Jencso et al., 2009; Smith et al., 2013), although the particulars of how to do so across a wide range of catchments have not been put forward.

Watershed scientists and practitioners have yet to build upon the aforementioned diversity in the application of the connectivity concept to effectively link hydrologic, sediment, and biogeochemical dynamics. Specifically, integrating water and material (i.e., particulate and dissolved constituents) connectivity is necessary as some jurisdictions are required, by law, to use standardized connectivity assessments to assist with policy/management decisions (Leibowitz et al., 2008; U.S. Army Corps of Engineers et al., 2015). For example, critical connectivity regimes need to be quantified—in terms of magnitude, frequency, and duration—when assessing water body protection under the United States Clean Water Act (Freeman et al., 2007). Those critical regimes, however, are often identified through political and legal procedures (Freeman et al., 2007) in the absence of consensus scientific methods. Robust science-based policy and management decisions will remain elusive until the scientific community can streamline the knowledge on water, sediment, and biogeochemical connectivity and develop a standardized framework to quantify those connectivities. With that in mind, we initiated the current literature review to identify a consensus definition of connectivity, establish a cohesive mathematical framework, and allow the consistent quantification of water and material connectivity. Four specific research objectives were pursued:

1. Identify the definitions of water and material (i.e., sediment and biogeochemical) connectivity that are the easiest to operationalize (i.e., translate into quantitative measures).
2. Review the primary components of a conceptual model of water and water-mediated material connectivity.
3. Suggest a mathematical framework for quantifying the occurrence, frequency, duration, magnitude, and spatial extent of water and water-mediated material connectivity.
4. Provide a case study using observational data to evaluate the viability and limitations of the framework and inform recommendations for its future application in a range of landscape and climatic conditions.

2. Disentangling Connectivity Definitions and Metrics in Search of Practicality

2.1. Hydrologic Connectivity

Previous literature reviews argued that one of the main impediments to operationalizing the hydrologic connectivity concept has been the lack of a consistent definition (Ali & Roy, 2009; Bracken et al., 2013). Several system-specific definitions of water (or hydrologic) connectivity exist that either focus on components of the water cycle (Pringle, 2003b), the physical coupling of landscape units via water (Antoine et al., 2011; Bracken & Croke, 2007), spatial patterns of watershed properties or hydrologic state variables (Knudby & Carrera, 2005; Western et al., 2001) or flow processes (Jencso et al., 2009; Jencso & McGlynn, 2011; Ocampo et al., 2006; Vidon & Hill, 2004). The definition proposed by Pringle (2003b), i.e., the water-mediated transfer of matter, energy and/or organisms within or between elements of the hydrologic cycle, is the broadest and least process-specific as it focuses on the presence (or absence) of water movement within the water cycle. It does not explicitly state how to identify and measure hydrologic connectivity. Conversely, the

10.1002/2017WR020707

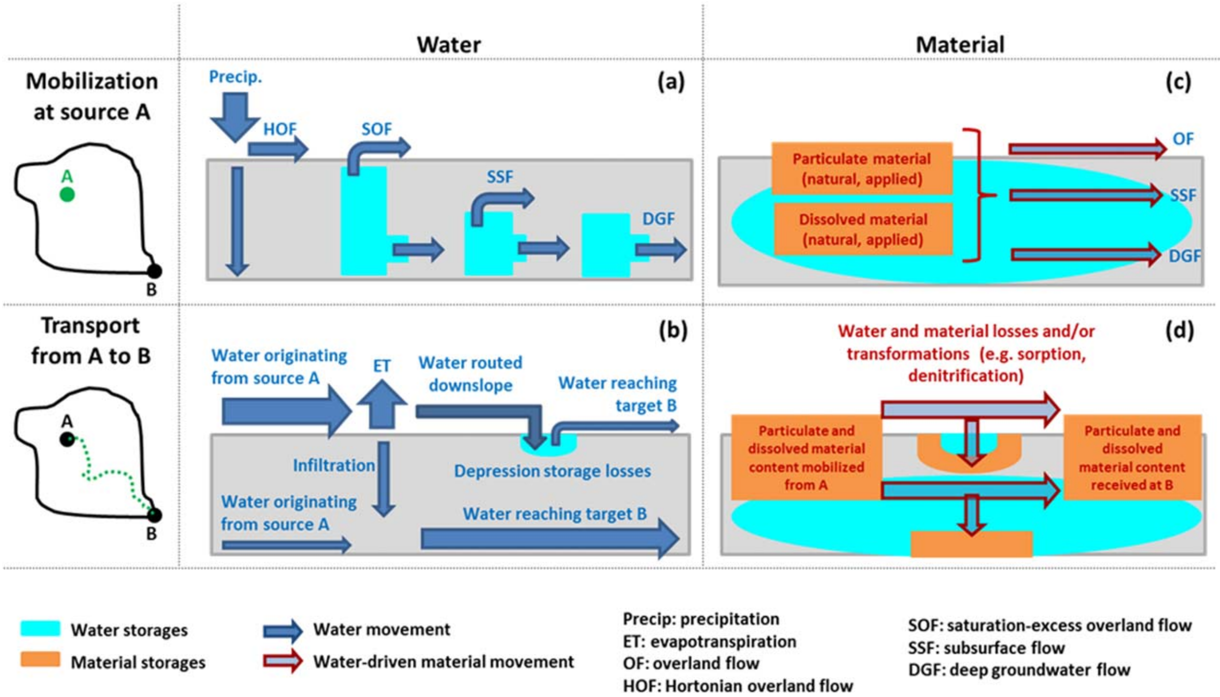


Figure 1. Overview of the different elements to consider for quantifying hydrologic connectivity and water-mediated material connectivity between a source point A and a target point B in a given watershed.

volume to breakthrough concept as applied in Hairsine et al. (2002) and Lane et al. (2006) and discussed in Bracken and Croke (2007) and Bracken et al. (2013) is an example of broad yet quantifiable definition: at the scale of a landscape unit, it expresses the volume of runoff that needs to enter the unit before any discharge is observed at the downslope boundary of that unit. Bracken and Croke (2007), however, noted that the volume to breakthrough concept describes the establishment of connectivity but not its continuity over time, or the conditions leading to disconnectivity. The use of spatial patterns of soil moisture has also been proposed to illustrate the geographic extent of water transfer (Ali & Roy, 2010; James & Roulet, 2007; Western et al., 2001) and estimate distance-based or area-based connectivity metrics. This approach is prone to challenges associated with data preprocessing (Ali & Roy, 2010) and does not quantify the actual mass of water being transferred between two locations. As for process-specific definitions (e.g., the degree to which there is subsurface water exchange among hillslopes, riparian zones, and the stream; Jencso & McGlynn, 2011), they explicitly allow for the identification of water movement but are not applicable to all flow pathways that may occur (Figure 1). Since all hydrologic connectivity definitions and metrics have their own advantages and disadvantages, some authors (e.g., Bracken et al., 2013) have implied that within a research context, it is acceptable that no single one has emerged predominant. However, the practicing hydrology community requires a standardized quantifiable definition to address water resource issues. In their use of the phrase “temporal connectivity,” Leibowitz and Vining (2003) highlighted that water connections can be impermanent, temporally discontinuous, and sporadic. Hence, knowing that connectivity may be important is not enough for water managers and policy makers; specific information related to the presence, frequency, magnitude, and duration of connectivity is needed to decide if protection or development of one watershed (or watershed unit) will influence a downstream watershed (or watershed unit).

2.2. Water-Mediated Sediment Connectivity

Definitions and metrics of water-mediated sediment connectivity are common: they typically describe actual or potential sediment transfer from one location to another, driven by erosion and deposition (Bracken et al., 2015). For instance, sediment delivery ratios (SDRs) describe the relation between erosion and sediment yield: they tend to be lower when there is increased opportunity for sediment deposition with longer travel distances associated with larger catchment area (Lane & Richards, 1997; Walling, 1999; Walling & Webb, 1996). Since SDRs are spatially and temporally lumped, however, they are not considered to be the best tools to numerically define sediment connectivity (Borselli et al., 2008). Sediment stores and sinks, such as vegetative buffers, barriers, and blankets, are often present along long sediment transport pathways and lead to sediment disconnectivity between landscape compartments (Brunsden & Thornes, 1979; Harvey, 2002; Hooke, 2003; Michaelides & Wainwright, 2002; Phillips, 1992); such sinks are difficult to capture through SDR assessments. Further, SDRs are often computed on an annual basis, thus providing an estimate of average conditions over a whole year rather responses to specific flow events. Disconnectivity is also important for sediment because of the water quality problems associated with excessive sediment loads, hence the number of studies specifically addressing conditions that promote transmission losses (Fryirs, 2013; Fryirs et al., 2007a; Thompson et al., 2011). While there are numerous factors influencing diffuse sediment connectivity, the focus is often on rainfall intensity and duration, soil roughness and the spatial organization of vegetation (Cammeraat, 2002). Topographic thresholds play a role for the initiation of erosion processes (de Vente et al., 2007) and are one reason behind the inverse correlation of sediment yield and catchment area. Metrics of sediment connectivity have been proposed: these include one index that relies solely on topographic data to assess potential connectivity via the identification of sources and sinks and the flow paths that connect them, and another that is a field index that incorporates rainfall information—thus allowing comparison of connections across a range of events (Borselli et al., 2008; Cavalli et al., 2013). Frequency and magnitude characteristics are important for sediment connectivity too (Wolman & Miller, 1960): they are a function of sediment transport processes and the temporal evolution of vegetation, land use, and management (Borselli et al., 2008). The majority of existing frameworks (e.g., Fryirs et al., 2007a; Heckmann & Schwanghart, 2013; Houben, 2008), however, describe sediment connectivity and disconnectivity among catchment cascades by inferring processes through extrapolation, interpolation, or accumulation, which Bracken et al. (2015) identified as a major limitation.

2.3. Biogeochemical Connectivity

Chemical or biogeochemical connectivity has been defined as the chemical mobility among water bodies (Likens & Bormann, 1995). Oldham et al. (2013) modified the broader connectivity definition of Pringle (2003b) to a definition of material connectivity, namely "*the ability of material to transfer between elements of the hydrologic cycle, while subject to biogeochemical or biological processing*." Although explicit "biogeochemical connectivity" definitions and metrics are uncommon, there are approaches to understanding diffuse pollution risk at the catchment scale that focus on sources and mobilisation with an implicit representation of connectivity between landscape and receiving waters. One example is the use of mixing models in hydrology, which rely on the assumption of co-connectivity of water and conservative or quasi-conservative solutes (Burns et al., 2001; Hooper, 2003; James & Roulet, 2006). The concepts of "hot spots" and "hot moments" in the mercury and nitrate literature (McClain et al., 2003; Mitchell et al., 2008) also implicitly refer to connectivity: waters carrying complementary reactants must connect at a point (the "hot spot") over a period of time (the "hot moment") to generate products of interest. However, the products may remain at the "hot spot" indefinitely, should downslope connectivity not be established (Mitchell et al., 2009). Recent work has suggested that the "hot spot-hot moment" concepts be generalized to examine the full range of biogeochemical processing rates found on the landscape (Bernhardt et al., 2017). Accordingly, biogeochemical processing rates which may not qualify as extreme can still impact material connectivity, especially over longer travel times. Further, while chemical connectivity is water mediated, important chemical carriers may also play a role in chemical mobility (e.g., organic matter for mercury; Grigal, 2002). In such cases, biogeochemical processing may be as important or more important for biogeochemical connectivity than water availability. Lastly, Hydrologically Sensitive Areas (HSAs) and Critical Source Areas (CSAs) also rely on implicit connectivity assessments. HSAs are watershed areas prone to generate runoff and therefore potentially susceptible to contaminant release (Walter et al., 2000), while CSAs are HSAs that contain pollutants available for transport (Pionke et al., 1996). For phosphorous (P) pollution specifically, CSAs are often spatially confined and reflect soil-P status, fertilizer-P, and manure-P inputs (Gburek & Sharpley, 1998; Kleinman et al., 2011; Pionke et al., 2000). For nitrogen (N) pollution, source areas are typically areas where fertilizer amounts applied in excess of crop requirements can be leached from the soil profile by percolating water (McDowell et al., 2002). Areas of nutrient-rich and/or erodible sources with a high propensity for hydrologic connectivity to the drainage network can be CSAs. However, key components such as the availability of mobilizable material at a source area, and the biogeochemistry-driven transmission losses that occur during material transport toward receiving waters, have not yet been formalized within an explicit biogeochemical connectivity assessment framework.

2.4. Literature Consensus

The large variety of connectivity definitions and associated measures available in the literature provides great evidence of a very active connectivity-minded research community. It also means that study inter-comparison might prove difficult if a common language and common tools for connectivity quantification are not used. Certain principles however apply regardless of the type of connectivity (i.e., hydrologic, sedimentological, or biogeochemical) considered. Specifically, all connectivity types can be assessed by their structural and functional traits. Structural connectivity assessments focus on the physical adjacency of landscape elements and use that adjacency as a proxy for water and/or material transfer (Bracken et al., 2013; Larsen et al., 2012; Lexartza-Artza & Wainwright, 2009; Wainwright et al., 2011). In hydrology and geomorphology, structural assessments often aim to quantify the spatial contiguity of fractures, hillslopes, or channels (Bracken et al., 2013; Larsen et al., 2012). In biogeochemistry, structural connectivity assessments are less obvious but are implied in studies of the relationship between soil variability and catchment solute outputs, where pedochemical barriers or zones of high element mobility determine outputs (Maavara et al., 2015; Sommer, 2006). Functional connectivity assessments rather aim to quantify how spatial adjacency or contiguity characteristics interact with temporally varying factors (e.g., event precipitation and antecedent moisture conditions) to connect material (Bracken et al., 2013; Turnbull et al., 2008): they typically target the estimation of water and material fluxes and their travel times (Knudby & Carrera, 2005).

While the definitions of structural versus functional connectivity are mostly agreed upon, little guidance exists on the basic data and approach needed to quantify functional connectivity (Bracken et al., 2013; Larsen et al., 2012; Okin et al., 2015). A review of the literature reveals that such guidance can be provided, as long as existing definitions of connectivity are synthesized and compared to identify commonalities and key measurable components. Notably, there is consensus that functional connectivity of water, sediment, and biogeochemical solutes between two points, A (the source) and B (the receptor), depends on (i) an excess of mobilizable elements at point A and (ii) the net rate of transfer of mass from A to B. The latter is highly dependent on the properties of the "path" that exists between A and B. To formalize that consensus, here we define connectivity between points A and B as

> *"the occurrence of water and/or material transmission between a source A and a receptor B when the magnitude of water and/or material leaving A is larger than the magnitude of water and/or material losses that occur along the flow path from A to B."*

We believe this consensus definition to be specific enough, while being process and material independent, to allow the operationalization of the connectivity concept across different landscape types and climatic regimes. As has been done by other hydrologists and geomorphologists in the past, we borrowed from the ecology literature, which has had a tradition of defining connectivity at a conceptual level in terms of "path" and "path cost." Indeed, ecological connectivity refers to the existence of at least one path between two nodes in a network (Urban & Keitt, 2001). The path(s) is (are) however associated with a cost, also known as a resistance or an impedance, which is proportional to the effort required by the organism of interest in order to travel along (some) particular path(s) (Adriaensen et al., 2003; Bunn et al., 2000; McRae et al., 2008; Pinto & Keitt, 2009; Sawyer et al., 2011; Zeller et al., 2012). That ecological definition has the great advantage of referring, explicitly, to the two elements that need to be measured or estimated, namely (i) the path and (ii) the resistance or impedance. In addition, this is an approach not dissimilar from the volume to breakthrough concept (e.g., Hairsine et al., 2002), which identifies connectivity when inputs from one landscape unit overcome transmission losses and are detected in another landscape unit. The consensus definition outlined above should therefore allow for the derivation of both conceptual and mathematical frameworks able to (i) assess the presence/absence of water and/or material inputs at the source point and (ii) quantify the flow path impedance between the source and receiving points.

3. Unified Conceptual Framework for Water and Water-Mediated Material Connectivity

Translating the aforementioned consensus definition into tangible metrics of connectivity necessitates a strategy based on four pillars or components, namely the quantification of *thresholds*, *excesses* and *losses* at specific *time scales*. First, *thresholds* are an important part of the foundation of a unifying connectivity-focused theoretical framework. For instance, sediment mobilization from a source area is strongly governed by the presence of flowing water of sufficient kinetic energy to overcome inertia of particles on land, streambeds, or banks (Léonard & Richard, 2004), thus giving rise to erosion thresholds (Dietrich et al., 1992, 1993). Along similar lines, phosphorus mobilization from agricultural soils is often conditioned by threshold values of a sorption index, or equilibrium phosphorus concentrations (e.g., Wang et al., 2016). The hydrological literature is also rich in threshold-related content. Threshold hydrological behavior has been described as "*changes in runoff response [which are. . .] disproportional to forcing inputs across the whole possible range of inputs*" (Ali et al., 2015), and it has been associated with a wide variety of runoff generation mechanisms, either implicitly or explicitly, for many decades (Ali et al., 2011, 2013, 2015; Detty & McGuire, 2010a; Dickinson & Whiteley, 1970; Lehmann et al., 2007; Mirus & Loague, 2013; Mosley, 1979; Oswald et al., 2011; Phillips, 2003; Spence, 2007; Stewart et al., 2015; Tani, 1997; Tromp-van Meerveld & McDonnell, 2006a; Uchida et al., 2005; Weiler et al., 2005; Wellen et al., 2014; Whipkey, 1965). A large majority of the literature documents surface and subsurface saturation-excess runoff mechanisms (Ali et al., 2013), which have critical threshold values of precipitation amounts or water storage capacities that need to be exceeded. The dominance of intensity thresholds (i.e., critical precipitation or infiltration rates) in some environments is however paramount (Reaney et al., 2007) and has been well known for over 80 years (Horton, 1933). Hillslope and catchment-scale threshold behaviors that have been published in the literature may in fact have been a combination of both intensity and storage thresholds (Bracken & Croke, 2007; McGrath et al., 2007), and this dynamic should be incorporated into any conceptual framework of connectivity.

Second, masses or volumes of water or material in excess of process-specific thresholds need to be quantified. Those *excesses* represent not the total amount of water or material present at a given location but rather the amount that is mobilizable by surface or subsurface flow. In biogeochemistry, excesses are typically quantified by comparing total concentrations to threshold values, in a manner largely independent from process (except for the actual threshold value). Such has not typically been the case in hydrology and geomorphology, where mobilizable water has been conceptualized differently according to different active runoff mechanisms. It has recently been argued that major similarities exist between surface and subsurface runoff generation processes, with boundary conditions being the only difference (Ameli et al., 2015; McDonnell, 2013). The parallel drawn by McDonnell (2013) between surface and subsurface flow focuses on the presence/absence of a hydrologic excess generated from either above, in the case of infiltration excess, or below, in the case of storage excess. Here we propose to use this concept of hydrologic excess as a necessary condition for the initiation of water connectivity. While this choice does not negate the complexity of processes that may be present at a given location at any point in time, it provides consistent terminology for a connectivity assessment framework, regardless of specific runoff generation mechanisms.

Third, *losses* from source area to receiving point need to be quantified. In order for water or water-mediated material connectivity to be detected at a receptor point B, any excesses available at source point A must overcome any losses encountered *en route*. For instance, hydrological losses because of evaporative or storage demands can result in cessation of streamflow (Buttle et al., 2012; Godsey & Kirchner, 2014; Spence, 2006) and therefore need to be quantified. However, material losses may or may not be present. The water-mediated transport of conservative solutes (e.g., ^{18}O) is a prime example of the co-connectivity of water and material (Burns et al., 2001; Hooper, 2003) that does not involve biogeochemistry-driven transmission losses. Conversely, when sediment is detached from uplands and transported along streams, its transport is subject to many temporary sinks along the way. Sediment can therefore be stored (or "lost") temporarily until sufficient kinetic energy is present to remobilize it (Krieger, 2003). The flow path of the water carrying nonconservative solutes (e.g., nutrients, carbon, and metals) also matters immensely, with respect to transmission losses. For example, transport of dissolved organic matter (DOM) and co-mobilized mercury (Hg) from shallow forest soils will depend on whether the flow path from source to receiving point goes through mineral soils that can effectively sequester DOM and Hg via adsorption (Kalbitz et al., 2000; Oswald et al., 2014). Reactions between the material being transported and the medium through which it is being transported, as well as the duration of transport between source and receptor points, are governed by the flow path. If the transit time of water along a flow pathway is longer than the reaction time of the material with its surrounding medium, then a loss of material between the source A and receptor B will occur. Phosphorous connectivity is particularly subject to losses that depend on relative rates of chemical and physical processes (Banaszuk & Wysocka-Czubaszek, 2005; Carlyle & Hill, 2001; Macrae et al., 2003, 2007, 2011; Reddy et al., 1999; Stone & Mudroch, 1989). Hence, from a conceptual standpoint, the slope of the material concentration profile (which represents the magnitude of material connectivity along the A to B flow pathway) depends on the ratio of material exposure time (i.e., water transit time) to material reaction time (Figure 2). Given water connectivity between A and B, it is also necessary to operationally define a threshold material concentration at B above which material connectivity is deemed to be significant. This threshold will be material specific (e.g., based on limits of detection) and may also depend on anticipated downstream ecological impacts.

Lastly, the integrity of a unified connectivity assessment framework relies on *time scales*. The selection of an observation time scale is especially critical as it defines over which duration connectivity between two points will be detected. Celerity and velocity rates (McDonnell & Beven, 2014; Quinton et al., 2003) are particularly important to consider while doing so. In a modeling investigation of long flow pathways between wetlands and a large stream, for instance, Ameli and Creed (2017) implied that subsurface transit times exceeded 10^6 days or $\sim$164,000 years. In a non-modeling context, this is arguably too long a period over which a system can be monitored and such connections identified. Consequently, detecting the occurrence of water connectivity can only be achieved as long as the water travel time between source point A and receptor point B is shorter than the time during which the system is observed (Figure 3). Water-mediated material connectivity can only be addressed once water connectivity has been detected. Material exposure time can be assumed equal to the water transit time from A to B, and water-mediated connectivity is only detected if the material is not involved in significant reactions along the A to B flow paths and able to travel to receptor B. An occurrence of material connectivity is detected when the reaction rate is slower than the water velocity (Figure 3). For conservative solutes, any lags between inputs and arrival times at the receiving point are due to differential flow velocity fields, specific flow path lengths and/or molecular diffusion (Hrachowitz et al., 2016). Nonconservative solutes, however, are subject to additional temporal dynamics. Physiochemical (e.g., adsorption) and biogeochemical (e.g., transformation) processes in soils, in the hyporheic

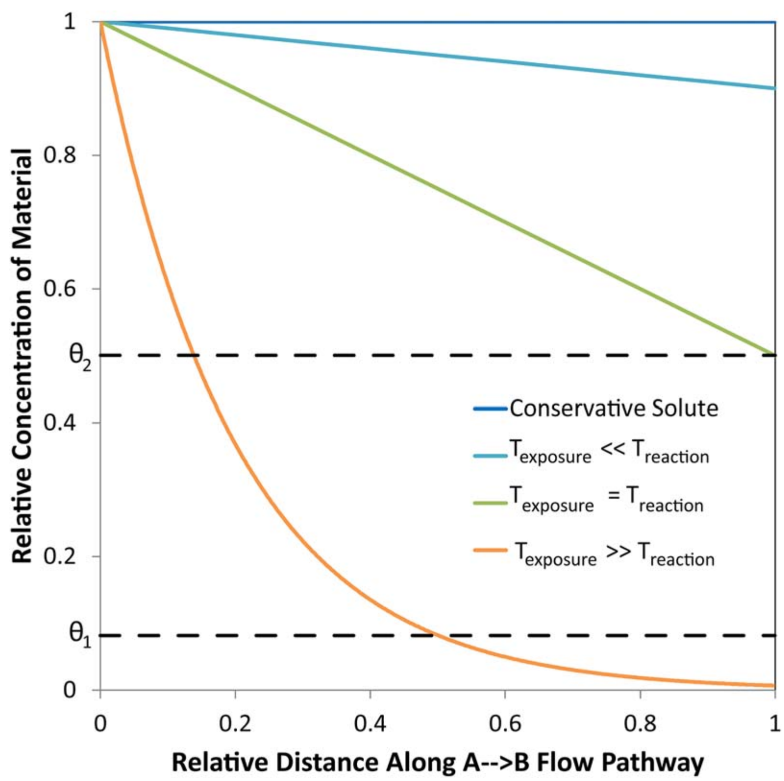


Figure 2. Example concentration profiles for conservative, near-conservative, and nonconservative materials along the A → B flow pathway. Profiles illustrate the dependence of material connectivity on the ratio of material exposure time to material reaction time. Theta values (i.e., θ_1 and θ_2) represent user-defined material-specific concentration thresholds above which material connectivity is deemed significant.

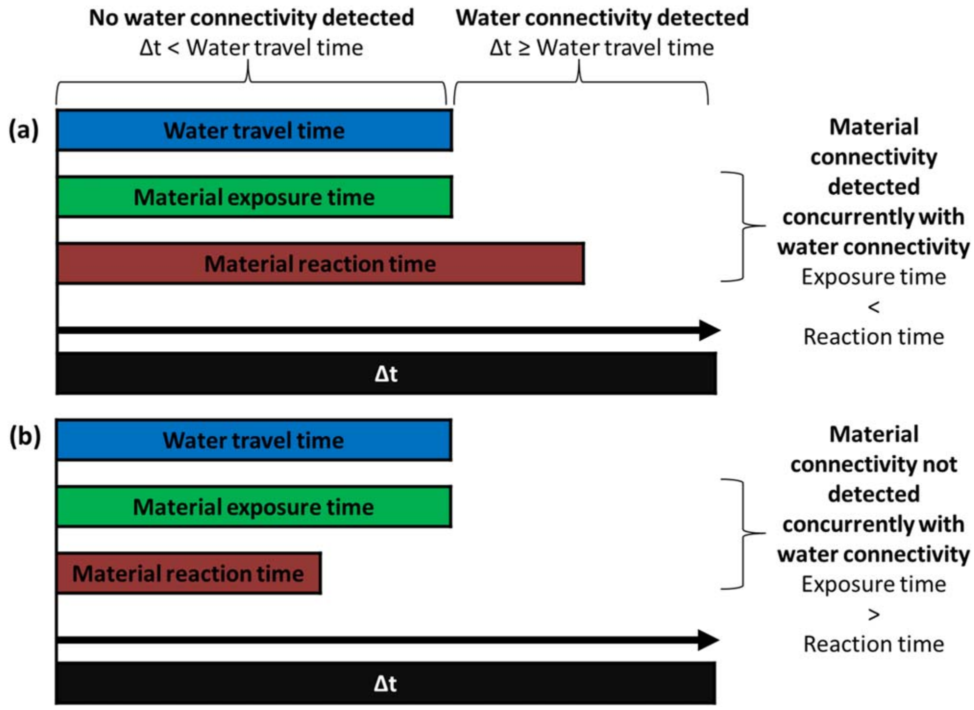


Figure 3. Balance of observation and process time scales to consider when assessing the likelihood of detecting water connectivity or water-mediated material connectivity. Δt: observation time step.

zone or in-stream can result in partial or complete losses of material between a source A and a receptor B, such as a catchment outlet.

Overall, the strategy suggested here for assessing water and water-mediated material connectivity can be summarized with the acronym "*T-TEL*," for Time scales, Thresholds, Excesses and Losses. While the literature clearly stresses the importance of all four components, here we list them in a specific order that reflects the sequence in which they should be addressed. The aforementioned unified conceptual framework is, therefore, simply a synthesis of existing literature. A mathematical structure that embeds the "T-TEL" elements is now required to standardize connectivity assessment methods.

4. Mathematical Framework for Water and Water-Mediated Material Connectivity

This section describes a mathematical framework that provides a synthetic view of the key elements to consider when assessing connectivity and allows the quantification of multiple connectivity properties. The key quantifiable properties required to define the connectivity regime of a point in space, a landscape unit or a watershed are the frequency, magnitude, duration, and spatial extent (denoted by superscripts of *freq*, *mag*, *dur* and *contrib*, respectively) of its occurrence (denoted by the superscript *occur*). These terms are commonly used to describe the regimes of other intermittent hydrometeorological phenomenon, most notably precipitation or floods (Watt, 1989) for the purposes of engineering design (e.g., intensity-duration-frequency curves). More recently, these properties have been deemed applicable to the characterization of intermittent stream regime behavior and connectivity (Buttle et al., 2012; Rains et al., 2016), though no explicit application to quantifying connectivity could be found. Since hydrologic connectivity controls material connectivity within the context of one or more of these regime properties (Laudon et al., 2011), explicitly defining regimes should ease derivation of quantifiable relationships between water and material connectivity.

The following presentation of the T-TEL mathematical framework contains a number of definitions and assumptions that are used throughout. In all equations, "distance" does not refer to a Euclidean distance between two points in space, but rather to the length of a water flow path linking the two points, also referred to as the "hydrologic distance" (e.g., stream lengths or flow path lengths obtained from digital elevation model analysis or via tracer tests). The time step over which the occurrence and magnitude of connectivity is evaluated is denoted as Δt and can be in the range of 15 min, an hour, a day, or a week, while the integrated study period (or integration time) is denoted as T and can be in the range of an event, a season, a year or longer. The integration time and time step are important variables to consider as they are critical to the determination of the occurrence of both water and water-mediated connectivity, as outlined in section 3 (Figure 3). All equations in the T-TEL framework should, ideally, be applied separately for specific flow paths (e.g., deep groundwater flow, shallow subsurface flow, and surface flow). There are two primary spatial scales to which the following equations apply. The first is a one-dimensional “point A-to-point-B” flow path on the landscape, while the second is a two-dimensional area, which can be any spatial scale in size, but most typically would range from the hillslope to the watershed scale. It is worth noting that in the one-dimensional case, the focus is solely on how much excess water or material originating from point A will make it all the way to receptor B; other potential source points that may lie on the path from A to B need to be addressed separately. This signifies that plug-flow processes, for instance, are not considered under this framework if they take place between A and B, rather than originating at A. Similarly, the different processes that may lead to material gain along a flow path are not considered in an “A-to-B” connectivity assessment because they do not originate at A.

4.1. Mathematical Framework for Water Connectivity (CW)

The occurrence of water connectivity, $CW^{occur}_{A\to B,\Delta t}$ (dimensionless), between two points, A and B, during Δt, where t is in units of time (e.g., seconds, hours, days, and weeks), is evaluated as

$$CW^{occur}_{A\to B,\Delta t}=\begin{cases}1 \ \ if \ \ CW^{mag}_{A\to B,\Delta t}>0 \ \ and \ \ \dfrac{d_{travel}}{d_{total}}\geq 1\\ 0 \ \ if \ \ CW^{mag}_{A\to B,\Delta t}\leq 0 \ \ or \ \ \dfrac{d_{travel}}{d_{total}}<1\end{cases} \tag{1}$$

$$\frac{d_{travel}}{d_{total}}=\frac{\bar{v}_{water}\times\Delta t}{d_{total}} \tag{2}$$

$CW^{mag}_{A\to B}$ is the magnitude of water connectivity between points A and B over Δt and denotes the actual depth of water (i.e., hydrologic excess) not lost during transport from point A to point B (see equations (7–9) for details). d_{travel} is the hydrologic distance travelled along the flow path between A and B during Δt, d_{total} is the total hydrologic distance between A and B, and $\bar{v}_{water}$ is the average water velocity between A and B along the targeted flow path. Water connectivity is present if $CW^{occur}_{A\to B,\Delta t}=1$. The condition that d_{travel} is equal to or exceeds d_{total} over Δt is used to ensure that when the hydrologic excess is sufficient to overcome losses along the A $\to$ B flow path, the hydraulic gradient between A and B is also sufficient for water to travel a distance that is at least equal to the hydrologic distance separating A and B. The temporal dimension of connectivity is explicitly embedded into the equation such that if Δt is not sufficiently long, equation (2) will result in a value less than 1, meaning that no water connectivity was detected over Δt. To apply equation (2), measurements are needed for d_{total} and $\bar{v}_{water}$. The former can be determined from field surveys, tracer tests or, for larger areas of interest, from digital elevation models. It is important to note the measurement of d_{total} in this case will be scale dependent, and so the method of determining d_{total} should be consistent throughout any specific application. The average water velocity can be determined in several ways depending on the flow path. In-stream velocity can be evaluated from acoustic methods, while subsurface rates can be estimated from Darcian flow principles (Dingman, 2015), and overland flow velocities can be inferred using Manning’s kinematic solution, especially in the case of sheet flow (Overton & Meadows, 1976). The approach underlying equation (1) is in contrast to many previous applications that have defined $CW^{occur}_{A\to B,\Delta t}$ as areas saturated above a given soil moisture threshold (Ali & Roy, 2010; James & Roulet, 2007; Western et al., 1998, 2001). While those previous papers were robust in their conceptual framework and methodologies, they relied on spatially detailed measurements of soil moisture which are not easy to acquire, as well as on arbitrarily defined soil moisture thresholds to classify landscape areas as active versus inactive prior to the connectivity assessment. The approach suggested above to describe the occurrence of water connectivity has the advantage of being more intuitive and explicitly time scale dependent.

The frequency of water connectivity, $CW^{freq}_{A\to B,\,T}$ (units of 1/time), over T is given by

$$CW^{freq}_{A\to B,\,T}=\frac{\sum_{\Delta t=1}^{nbts} CW^{occur}_{A\to B,\,\Delta t}}{T} \tag{3}$$

where $nbts$ is the number of time steps Δt and is related to T by

$$\Delta t\cdot nbts=T \tag{4}$$

Integration of occurrence of water connectivity over time provides an estimate of duration (in the units of time, t, selected for the application):

$$CW^{dur}_{A\to B,T}=\int_{\Delta t=1}^{T} CW^{occur}_{A\to B,\Delta t}dt \tag{5}$$

The magnitude of water connectivity between points A and B, $CW^{mag}_{A\to B}$ (units of length), is defined as the hydrologic excess measured at A minus any losses during travel toward B; both excesses and losses are expressed as water depths. There are two approaches that have been used in the hydrologic literature to determine travel losses. The first is to express these losses as a resistance function of the form:

$$Q_B=\frac{Q_A}{r_{A\to B}} \tag{6}$$

where Q_A and Q_B are flows measured at points A and B, and $r_{A\to B}$ is a resistance term that reduces and delays the flow of material between A and B (Kleidon & Schymanski, 2008). This application of Ohm's Law uses the analogy that the mass that arrives at B is equivalent to the mass that leaves A divided by the resistance along the flow path along which that transport takes place. It is also recognizable from hydrometeorological applications of canopy and stomatal resistance for estimating actual evapotranspiration rates. The disadvantage of this approach is the difficulty in estimating $r_{A\to B}$, which could be a dynamic function of slope, soil properties, vegetation, channel roughness, etc. This form of the resistance term is also dimensionless, which would be problematic for parametrization and estimation. The second, perhaps more feasible means to estimate losses is more explicit where

$$CW^{mag}_{A\to B,\,\Delta t}=H_{excess,\,A,\,\Delta t}-HA_{A\to B,\,\Delta t} \tag{7}$$

$$H_{excess,\,A,\,\Delta t}=\int_0^{\Delta t}\left(H_{total,\,A,\,\Delta t}-H'\right)dt \tag{8}$$

$$HA_{A\to B,\,\Delta t}=\int_0^{\Delta t}\left(ET+F+S_{dep}+S_{det}\right)dt \tag{9}$$

where $H_{excess,\,A}$ (units of length) is the hydrological excess (surface and/or subsurface) measured at A, $HA_{A\to B}$ (units of length) is the sum of all hydrological abstractions occurring along the flow path between A and B, $H_{total,A}$ (units of length) is the mass of cumulative inputs at point A over Δt, H' (units of length) is a threshold value of water storage at point A or the infiltration capacity integrated over Δt at point A, ET (units of length) is evapotranspiration, F (units of length) is infiltration, S_{dep} (units of length) is depression storage, and S_{det} (units of length) is detention storage. Equation (7) is a direct application of the conceptual framework presented in section 3 of this paper: the magnitude of connectivity between points A and B is estimated by (i) quantifying a hydrological excess at point A in a non process-specific manner by relying on storage-driven or intensity-driven thresholds and (ii) estimating the impedance (or resistance) to water movement between A and B in the form of hydrologic abstractions.

Integration of occurrence of water connectivity over space represents the proportion of the areal land unit in question that is contributing to water connectivity at point B, $CW^{contrib}_{Land\ \ unit,\,\Delta t}$ (dimensionless), and is given by

$$CW^{contrib}_{Land\ \ unit,\,\Delta t}=\frac{\sum_{i=1}^{n} CW^{occur}_{i\to B,\,\Delta t}}{n} \tag{10}$$

where i represents individual locations or points in the land unit and n is the total number of $i\to B$ pairs for which water connectivity is being evaluated in the land unit. Much of the recent research on water connectivity has focused on indices comparable to $CW^{contrib}_{Land\ \ unit,\,\Delta t}$ and how they control runoff response.

For instance, Phillips et al. (2011) applied graph theory to derive fractions of watersheds that were hydrologically connected to the watershed outlet. Western et al. (2001), James and Roulet (2007), and Ali and Roy (2010) developed and applied indices of connectivity based upon the spatial patterns of shallow soil moisture across small catchments in Australia and Eastern Canada, where each index was used to summarize, with a single number, the degree of connectivity between hydrologically active areas (as determined by soil moisture) and the catchment outlet. What differentiates the current framework is the explicit definition of water connectivity across space as an integration of measurements of occurrence made on a point-to-point basis. The integration of the frequency and duration of water connectivity over a land unit would be represented by probability density functions of equations (3) and (5), respectively. Similar to equation (10), to evaluate the magnitude of water connectivity of multiple points i to a single point B, $CW^{mag}_{Land\ \ unit}$ (units of length), a summation of equation (7) over the land unit in question is required:

$$CW^{mag}_{Land\ \ unit,\Delta t} = \sum_{i=1}^{n} \left(H_{excess,i,\Delta t} - HA_{i\rightarrow B,\Delta t} \right) \tag{11}$$

4.2. Mathematical Framework for Water-Mediated Material Connectivity (CM)

The framework for describing water-mediated material connectivity adapts concepts from biogeochemistry and geomorphology to partition material into what can potentially be mobilized by water, what is actually mobilized by water, and what cannot be mobilized by water. The novelty of our presentation here is that we describe availability of material in a general framework rather than doing so for a specific element or chemical species.

Water-mediated material connectivity, $CM^{occur}_{A\rightarrow B}$ (dimensionless), is present when $CM^{occur}_{A\rightarrow B}=1$ over Δt according to

$$CM^{occur}_{A\rightarrow B,\Delta t} = \begin{cases} 0 \ \ if \ \ CM^{mag}_{A\rightarrow B} < \theta \\ 1 \ \ if \ \ CM^{mag}_{A\rightarrow B} \geq \theta \end{cases} \tag{12}$$

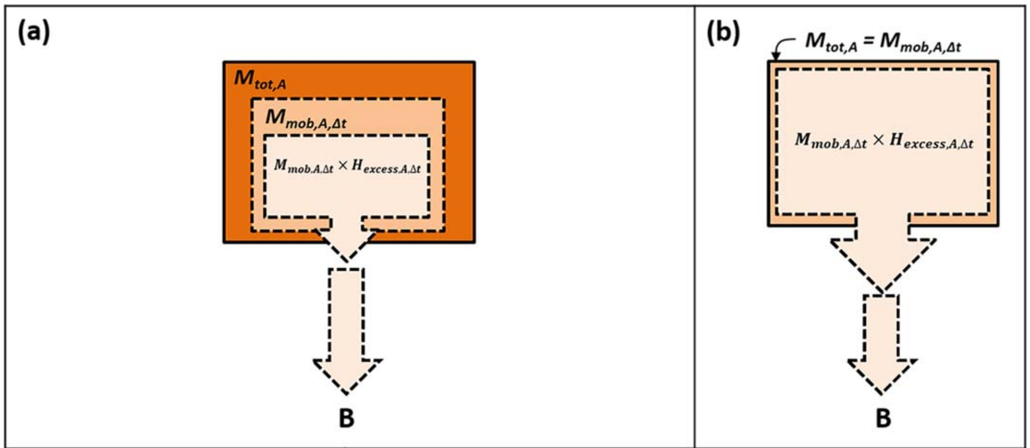
$CM^{mag}_{A\rightarrow B}$ (units of mass/area) is the magnitude of water-mediated material connectivity between points A and B over Δt and denotes the actual mass of material transported from point A to point B. Our introduction of the threshold θ is intended to differentiate between "significant" material connections between A and B and "insignificant" ones (Figure 2); neglecting this threshold may result in every point in the watershed which experiences an occurrence of water connectivity to also experience an occurrence of water-mediated material connectivity, even when only a small fraction of the source material at point A indeed reaches point B. Material connections are deemed "insignificant" if their effects are inconsequential in the context of a particular application, and these effects may vary widely. Toxicological investigations, for instance, may wish to use the analytical limit of detection of a toxic compound as θ, while agricultural conservation practice targeting will likely rely on a higher limit that accounts for a small number of areas being responsible for disproportionate amounts of nutrient transport (Kalcic et al., 2015). Hence, to assess the occurrence of water-mediated material connectivity, the selection of a threshold θ for a particular application does not rely on hydrological or biogeochemical science alone, although science may play a role in selecting said threshold. That threshold θ may also vary with the temporal and spatial scales of interest.

The magnitude of water-mediated material connectivity, $CM^{mag}_{A\rightarrow B}$, which is the mass per unit area of material transported from point A to point B, is a function of source, mobilization, and transport processes:

$$CM^{mag}_{A\rightarrow B,\Delta t} = \frac{M_{mob,A,\Delta t} \times H_{excess,A,\Delta t}}{1+Da_{x,A\rightarrow B}} - CA_{A\rightarrow B,\Delta t} \tag{13}$$

In the first term of equation (13), the numerator denotes the mass of material that is actually exported from point A (in units of mass/area) while the denominator describes the fraction of that material which arrives at point B after biogeochemical reaction losses are accounted for (dimensionless). The term $CA_{A\rightarrow B,\Delta t}$ (in units of mass/area) refers to material lost due to hydrological abstractions, such as water infiltration.

Quantifying the actual amount of material that leaves location A (numerator of equation (13)) requires the consideration of several elements, notably the mobilizable pool of material ($M_{mob,A,\Delta t}$, in units of mass/area) and the amount of water that leaves point A ($H_{excess,A,\Delta t}$, in units of length). The amount of mobilizable material $M_{mob,A,\Delta t}$ is related to the total amount of material by the fractional availability $Avail_A$, following:



$0 < Avail_{SED,A} < 1$	$0 < Avail_{BGC,A} < 1$	$Avail_A \approx 1$
Sediment	Nitrogen	Chloride
Phosphorus		δD, $\delta^{18}O$
Mercury		

Figure 4. Conceptual representation of the relationship between the total and mobilizable pools of material at a source point A for (a) nonconservative and (b) conservative materials.

$$M_{mob,A,\Delta t} = M_{tot,A} \times Avail_{BGC,A} \tag{14a}$$

$$M_{mob,A,\Delta t} = M_{tot,A} \times Avail_{SED,A} \tag{14b}$$

Material availability may be biogeochemical (e.g., dissolved NO_3 versus N bound in organic matter, Van Meter & Basu, 2015; $Avail_{BGC,A}$) or physical (P-laden soil particles, Stone & Mudroch, 1989; $Avail_{SED,A}$) and will be determined differently for different chemical species (Figure 4). Hence, even though we advocate for a general assessment framework for water-mediated material connectivity, we do recognize the need for the element-specific or (chemical) species-specific parameterization of equation (13). Indeed, biogeochemical availability is related to the well-known partition (or distribution) coefficient (K_d), which is used to estimate the potential mobility of contaminants present in aqueous solutions (e.g., soil water) in contact with a solid phase (e.g., soil). While K_d is the ratio of the chemical concentration associated with the solid to the chemical concentration in the surrounding aqueous solution, biogeochemical availability is the ratio of the chemical mass in the aqueous phase to the total chemical mass in both the aqueous and solid phases. For quasi-conservative solutes, biogeochemical availability will approach 1 but for nonconservative solutes, processes such as surface adsorption, absorption into the soil structure, and precipitation will lower biogeochemical availability below a value of 1. As for sediment availability, it is a function of water velocity in overland flow or streamflow and must exceed a threshold determined by grain size distribution (Léonard & Richard, 2004). Because of chemical and physical mobilization processes, the amount of material at point A that can be readily transported by water will always be less than or equal to the total amount of material present at point A (Figure 4).

The denominator of the first term of equation (13) corresponds to the term $r_{A \to B}$ in equation (6) in the context of water-mediated material movement. To address reactive transport of materials in a parsimonious manner, we think of each flow path as a continuously stirred tank reactor (Fogler, 1987; Van Meter & Basu, 2015). The Damköhler number, $Da_{x,A \to B}$ (dimensionless), gives an estimate of the degree of conversion of chemical species (or material) x along the flow path between A and B:

$$Da_{x,A \to B} = \frac{-r_{x,A \to B}}{v_{x,A \to B}} = k_{x,A \to B} \times \tau_{x,A \to B} \tag{15}$$

where $-r_{x,A \to B}$ (units of mass per unit time) is the rate of disappearance of material x along the flow path between A and B, $v_{x,A \to B}$ (units of mass per unit time) is the transport rate of material x along the flow path between A and B, $k_{x,A\rightarrow B}$ is the rate constant (units of 1/time) for $-r_{x,A\rightarrow B}$, and $\tau_{x,A\rightarrow B}$ (units of time) is the chemical transit time along the flow path between A and B. A low value of $Da_{x,A\rightarrow B}$ indicates low levels of loss/transformation of material x along the flow path between A and B, while a high value of $Da_{x,A\rightarrow B}$ indicates a higher level of loss/transformation. Note that Damköhler numbers can be easily modified to account for higher-order chemical behavior. The term $CA_{A\rightarrow B,\Delta t}$ is analogous to $HA_{A\rightarrow B,\Delta t}$ from equation (9): however, the term $HA_{A\rightarrow B,\Delta t}$ was not reused in equation (13) to account for the fact that some hydrological abstractions may not result in material transmission losses, e.g., evapotranspiration may result in concentration instead of loss.

Similar to equation (3) for water connectivity, the frequency of water-mediated material connectivity from A to B over the integration time T is noted as $CM^{freq}_{A\rightarrow B,T}$ (units of 1/time) and represented as

$$CM^{freq}_{A\rightarrow B,T}=\frac{\sum_{\Delta t=1}^{nbts} CM^{occur}_{A\rightarrow B,\Delta t}}{T} \tag{16}$$

where $nbts$ is the number time steps and is related to T as previously expressed in equation (4). The integration of the occurrence of water-mediated material connectivity over time provides an estimate of duration (in the units of time, t, selected for the application):

$$CM^{dur}_{A\rightarrow B,T}=\int_{\Delta t=1}^{T} CM^{occur}_{A\rightarrow B,\Delta t}dt \tag{17}$$

The summation of $CM^{occur}_{A\rightarrow B,\Delta t}$ over space represents the proportion of the land unit in question that is contributing to water-mediated material connectivity at point B, $CM^{contrib}_{Land\ \ unit,\Delta t}$ (dimensionless), and is given by

$$CM^{Contrib}_{Land\ \ unit,\Delta t}=\frac{\sum_{i=1}^{n} CM^{occur}_{i\rightarrow B,\Delta t}}{n} \tag{18}$$

where i represents individual locations or points in the land unit and n is the total number of $i\rightarrow B$ pairs for which water-mediated material connectivity is being evaluated in the land unit. The integration of the frequency and duration of water-mediated material connectivity over a land unit would be represented by probability distribution functions of equations (16) and (17), respectively. To evaluate the magnitude of water-mediated material connectivity of multiple points i in the land unit to a single point B, $CM^{mag}_{Land\ \ unit}$ (units of mass/area), a summation of equation (13) over the land unit in question is required:

$$CM^{mag}_{Land\ \ unit,\Delta t}=\sum_{i=1}^{n}\frac{M_{mob,i,\Delta t}\times CW^{mag}_{i\rightarrow B,\Delta t}}{1+Da_{x,i\rightarrow B}} \tag{19}$$

$$Da_{x,i\rightarrow B}=\frac{-r_{x,i\rightarrow B}}{v_{x,i\rightarrow B}}=k_{x,i\rightarrow B}\times t_{x,i\rightarrow B} \tag{20}$$

Moving from theory to implementation requires that a list of steps be followed as the equations are applied to a given system, as summarized in Figure 5. From here onward, we refer to the combined conceptual and mathematical frameworks described in sections 3 and 4 as the T-TEL method. When using the T-TEL method, any natural system will likely be “connected” if sufficiently long periods of time are considered; one’s ability to detect connectivity will therefore depend on the selection of time scales, i.e., the contrast between the observation time step, the integration time, the water transit time (and material exposure time) and the material reaction time. When a reasonable assumption can be made about the observation (or integration) time being long enough for water connectivity to be detected, and the reaction time long enough for water-mediated material connectivity to be detected as well, the next group of methodological steps focuses on the quantification of thresholds (Figure 5). Those thresholds are process-driven in the case of water connectivity since they are dictated by the presence of infiltration-excess or saturation-excess mechanisms. For water-mediated material connectivity, however, thresholds are not solely science driven as they may account for a variety of ecosystem management objectives. Excesses are quantified by comparing masses of water or material in excess of the identified thresholds (Figure 5). Lastly, losses are estimated by considering hydrologic abstractions in the case of water connectivity, and by considering both hydrologic abstractions and physical and biogeochemical processes that affect material mobility in the case of water-mediated material connectivity (Figure 5).

		Methodological steps associated with the quantification of…	
		Water connectivity	**Water-mediated material connectivity**
T	Timescales	• Make a hypothesis about the range of water travel times from A to B • Pick an observation period, T, that is longer than the inferred water travel time	• Make a hypothesis about the range of exposure times and the range of reaction times for the material to be mobilized from A to B If reaction time is much shorter than exposure time, connectivity is unlikely / If reaction time is much larger than exposure time, proceed to the next step
-	-	Use the observation period T and choose a timestep Δt to implement the framework	
T	Thresholds	• Determine the dominant runoff generation processes at A If infiltration-excess processes dominate, identify an intensity threshold H' / If saturation-excess processes dominate, identify a storage threshold H'	• Based on research or management objectives, determine the significance threshold θ • Assess material availability at point A based on biogeochemical ($Avail_{BGC}$) or physical ($Avail_{SED}$) availability
E	Excesses	• For each timestep Δt, consider water inputs (e.g., rainfall, snowmelt, irrigation) at point A and calculate or update H_{total} • Compute H_{excess} If $H_{excess} \leq 0$, connectivity is absent / If $H_{excess} > 0$, proceed to the next step	• For each timestep Δt, estimate the total amount of material , M_{total}, at point A • For each timestep Δt, compute the mobilizable pool of material at point A, M_{mob}
L	Losses	• Quantify HA from A to B • For each timestep Δt over the observation period T, estimate the occurrence, frequency, duration and magnitude of connectivity	• Estimate the Damköhler number from A to B • Quantify CA from A to B • For each timestep Δt over the observation period T, estimate the occurrence, frequency, duration and magnitude of connectivity

Figure 5. Methodological steps to follow when applying the T-TEL method for water and water-mediated material connectivity assessment. "A" and "B" are the locations between which connectivity is assessed.

5. Case Study: A T-TEL Method Application Example

5.1. Rationale and Research Questions

Equations (1–20), which form the core of the T-TEL method, as well as the sequence of methodological steps listed in Figure 5, were applied toward the quantification of water and water-mediated total mercury (THg) connectivity in a boreal forest environment. We chose a field-based data set from a small headwater catchment in northwestern Ontario, Canada, that was the focus of a pollutant fate and transport study from 2000 to 2010. The whole-ecosystem METAALICUS (Mercury Experiment to Assess Atmospheric Loading in

Canada and the U.S.) study used experimental deposition of mercury (Hg) isotopes to elucidate the timing and magnitude of fish Hg responses to changes in atmospheric Hg loading (Harris et al., 2007). An upland-dominated subcatchment was intensively studied to better understand the hydrobiogeochemical and landscape controls on terrestrial Hg fate and transport, and the role of uplands as sources of Hg to lakes and fish (Oswald & Branfireun, 2014; Oswald et al., 2011, 2014). Here we used the spatially and temporally rich hydrometric and water chemistry data set from this subcatchment to answer the following research questions:

a. Can the T-TEL method be applied to readily available field data to estimate the amount of subsurface water generated at a source point that travels to a receiving point?
b. Can the T-TEL method be used to estimate the proportion of the total mass of material (i.e., THg) mobilized from a source point that is transported to a receiving point?

While we acknowledge that there are many other landscapes and scales that the T-TEL method can be applied to, we feel that the case study presented below is useful as it (i) quantifies both water and water-mediated material connectivity; (ii) illustrates how landscape complexity along a flow path can be handled by the method; and (iii) demonstrates how internal checks can be used to verify connectivity estimates.

5.2. Methodology

Site description and data collection. Data used in this case study were collected in 2008 in the 7.75 ha UP1 headwater catchment of the Lake 658 experimental watershed, located in the Experimental Lakes Area (49°40′N, 93°43′W). The climate of the study region is classified as boreal cold temperate with average January and July air temperatures of −16.5 and +20.1°C, and a mean annual air temperature of +2.8°C. Mean annual precipitation is 708 mm with 75% falling as rain (based on 1970–2009 climate normals). The catchment is south-facing, has a mean slope of 12° and variable topography including exposed bedrock ridges, well-drained slopes with thin soils, and soil-filled bedrock depressions that are saturation-prone (Figure 6a). A short, ephemeral stream drains the catchment into Lake 658 (Figure 6a). The catchment is underlain by unfractured granitic bedrock and the soils are classified as silty loamy acidic brunisols. Where soil exists, mean soil depth is 54 cm and a typical profile includes a sandy mineral horizon overlain by an organic layer with a mean thickness of 10 cm. Forest cover consists of a mix of red maple (*Acer rubrum*), paper birch (*Betula papyrifera*), black spruce (*Picea mariana*), and balsam fir (*Abies balsamea*). Ground cover includes lichens (e.g., *Cladina stellaris*), mosses (e.g., *Polytrichum piliferum*) and juniper (*Juniperus virginiana*). In the wet soil-filled depressions, the organic soil horizon is thicker and the surface vegetation is dominated by *Sphagnum* spp.

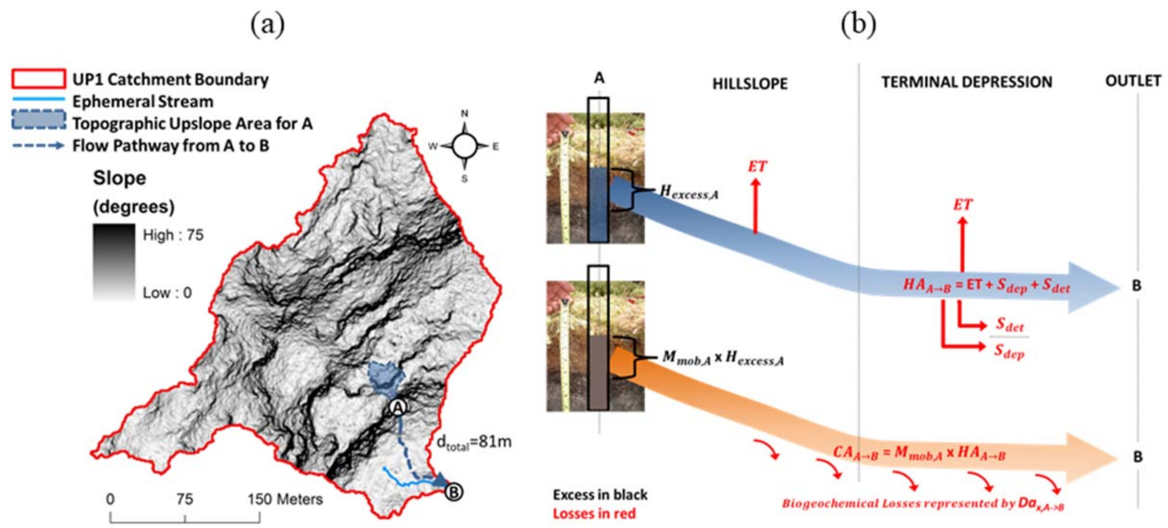


Figure 6. (a) Topography of the UP1 case study catchment showing slope, the catchment boundary, and the location of the ephemeral stream draining into Lake 658. The source point A, its topographic upslope area (*Area*$_A$), the receptor point B and the dominant A-to-B flow path are marked. (b) Schematic of the application of the T-TEL mathematical framework to the UP1 case study flow path for both water and material connectivity.

Hydrologic response units (HRUs) were delineated, classified and aggregated using a 1-m resolution digital elevation model with the methods of Hjerdt et al. (2004) and Richardson et al. (2009). Discharge was measured continuously every 15 min at the outlet of the UP1 catchment. Distributed shallow groundwater wells, piezometer nests and near-surface lysimeters (installed in the organic soil horizon on slopes) were used to characterize both the dominant hydrologic processes and the groundwater and soil water chemistry in the different HRUs. The wells ($n = 22$) were installed to refusal and surveyed relative to a datum at the catchment outlet. Capacitance water level loggers (Odyssey®, Dataflow Systems, NZ) continuously recorded 15 min average water table levels in all of the wells over the study period.

Water samples were collected manually from the UP1 catchment outlet and from all piezometers and lysimeters on a biweekly and event basis between April and October (not including July) of 2007 and 2008. All water samples were collected in the field and filtered (0.7 μm GF/F) using ultraclean trace metal protocols to prevent Hg contamination (U.S. EPA, 2001). Chemical analyses of water samples for total mercury (THg; includes all mercury species) concentration were carried out according to EPA Method 1631 (U.S. EPA, 2001) using a cold vapour atomic fluorescence system equipped with an autosampler (Tekran 2600 automatic mercury analyzer, Tekran Inc., Toronto) connected directly to an inductively coupled plasma mass spectrometer (Hewlett-Packard 4500, Agilent Technologies, USA). Quality control acceptance criteria were within acceptable limits for all analyses.

Dominant hydrobiogeochemical processes and resulting methodological considerations. For the current case study, a single A-to-B pair of points was considered (Figure 6a) using data collected in 2008. The dominant runoff generation mechanism occurring between the chosen source point A (on a hillslope) and receptor point B (i.e., the catchment outlet) is shallow subsurface flow through the highly conductive organic soil horizon. The topographic upslope area of point A (i.e., $Area_A$) and the dominant flow path from point A to point B were identified based on a LiDAR-derived digital elevation model (DEM; Figure 6a). The A-to-B flow path is 81 m long and flows through two distinct HRUs: a well-drained hillslope (26% of flow path length) and a terminal, saturation-prone depression (74% of the flow path length; Figure 6b). The complexity of the A-to-B flow path was taken into account when evaluating the average travel velocity of water ($\bar{v}_{water}$) and the hydrologic abstractions (HA) along the flow path. For example, drainable porosity (n_d) is slightly different depending on whether the flow path goes through hillslopes ($n_{d,hill} = 0.42$) or soil-filled depressions ($n_{d,dep} = 0.50$). Hence, a weighted average of the drainable porosity was calculated (i.e., $n_{d(\mathrm{A}\rightarrow\mathrm{B})} = 0.26 \times 0.42 + 0.74 \times 0.50$). The average velocity ($\bar{v}_{water}$) was then computed via Darcy's law using hydraulic gradients estimated from hydrometric data between points A and B, a uniform hydraulic conductivity across the study area of 3.35×10^{-2} m s^{-1} (Allan & Roulet, 1994), and drainable porosity as per above.

The timing and magnitude of Hg fluxes from uplands to receiving waters depend on both hydrological and biogeochemical factors (Munthe et al., 2001). With respect to the potential mobility of Hg at source point A, we need to consider both the quantity of runoff generated at A, as well as the partitioning of Hg from the solid phase (i.e., soil-bound) to aqueous phase (i.e., in shallow groundwater and soil water). With respect to the actual transport of Hg from source point A to receptor point B, we need to consider not only the runoff losses along the flow path (e.g., due to depression storage) but also biogeochemical losses (e.g., adsorption to soils). Since the concentration of THg was measured in shallow subsurface flow through the organic layer via lysimeters and piezometers, we did not need to determine an $\mathrm{Avail_{BGC}}$ term to convert $M_{total,A}$ (concentration of THg in soil at point A) to $M_{mob,A,\Delta t}$ (concentration of THg in shallow groundwater at point A at each time step). Also, since mercury exhibits a great affinity for organic matter in soils, a THg reaction time was estimated based on published adsorption kinetics experiments (Yin et al., 1997). A summary of all computational steps followed to apply the T-TEL method to our chosen case study is presented in Table 1.

5.3. Results

Over the 187 day (or 27 week) study period, 528.5 mm of rain fell and $H_{excess,A,\Delta t}$ ranged from 0 to 57 mm, with the lowest values occurring in late August and September (Figures 7a–7e). Coincident with the drop in $H_{excess,A,\Delta t}$ were relatively large hydrological abstractions due to detention and depression storage in the terminal depression along the A-to-B flow path. Combined, these resulted in a continuous loss of water connectivity from A to B between 19 August and 23 September, followed by two shorter periods of disconnection in late September and early October, and a period of reconnection in mid-October when the

Table 1
Steps Followed in the Application of the T-TEL Method to Water and Material Connectivity in the UP1 Research Catchment

	Water connectivity	Material (i.e., THg) connectivity
Spatial framework	"Source-to-outlet" assessment, where: source = site #W9 ≡ Point A; outlet = UP1 catchment outlet ≡ Point B	
Available data sets	• Water table position (relative to a datum located near point B at the catchment outlet) at the source site and along the A-to-B flow path, including in the terminal depression (*TerminalDep*) • Runoff depth at the outlet site • Daily evapotranspiration (*ET*) for the region	• Data required for water connectivity computations • THg concentrations ([*THg*], in ng L^{-1}) in shallow groundwater at the source site • [*THg*] in stream water • Drainable porosity of hillslope organic soils ($n_{d,hill} = 0.42$) and depression organic soils ($n_{d,dep} = 0.50$) • DEM-derived topographic upslope area to the source site: $Area_A = 790$ m^2
T: time scales	$T = 187$ days $\Delta t = 1$ day	$T = 187$ days = 26.7 weeks $\Delta t = 1$ week
T: thresholds	h' = height of organic-mineral soil interface relative to the same datum as above	$\theta = 0$ µg m^{-2} of THg
E: excesses	• $h_{total,A,\Delta t}$ = water table position above datum • Lateral subsurface flow is initiated when the water table at the source site rises above the organic-mineral soil interface • At each time step, the drainable pore water contributing to subsurface flow is $H_{excess,A,\Delta t} = (H_{total,A,\Delta t} - H')$ where $H_{total,A,\Delta t} = h_{total,A,\Delta t} \times n_{d,hill}$ $H' = h' \times n_{d,hill}$	• [*THg*] in shallow groundwater at the source site was used to represent $M_{mob,A,\Delta t}$ • The areal mass (µg m^{-2}) of THg mobilized from A is estimated for each time step by multiplying [*THg*] by $H_{excess,A,\Delta t}$

L: losses	• *ET* data were available
	• Since the focus was on subsurface flow, infiltration losses were omitted: $F = 0$
	• Water losses occur when the flow paths from source to outlet go through the terminal depression at the bottom of the catchment. The rules below were applied:
	  • When *TerminalDep* < 90% full, water losses along the source-to-outlet flow paths were conceptualized as depression storage losses (i.e., S_{dep})
	  • When 90% < *TerminalDep* < 100% full, losses were conceptualized as detention storage losses (i.e., S_{det}, because they are likely to be remobilized when the terminal depression spills)
	  • When *TerminalDep* > 100% full, $S_{dep} = S_{det} = 0$
	• At each time step:
	$HA_{A \to B,\Delta t} = ET + F + S_{dep} + S_{det}$
		• A constant 2 h THg reaction time was estimated based on the literature**
		• For each time step, a flow path segment-weighted, average water travel velocity from source to outlet, was estimated based on Darcy's law**
		• $Da_{x,A \to B}$ (dimensionless) was estimated as the ratio of the exposure time to the reaction time along the A-to-B flow path. The exposure time was estimated by dividing the total flow path length (81 m) by the average water velocity
		• At each time step, losses of THg due to hydrologic abstractions (i.e., $CA_{A \to B,\Delta t}$, in µg m^{-2}) along the flow paths were estimated by multiplying [*THg*] by $HA_{A \to B,\Delta t}$. Those losses include THg trapped in depressions (i.e., S_{dep}, S_{det}) as well as THg volatilization

Note. For elements flagged with "**," further details are provided in the text.

catchment wetted up again. Using a daily time step, the frequency of water connectivity was 0.74 and the duration was 138 days.

Over the 27 week study period, the area mass of $M_{mob,A,\Delta t}$ fluctuated between 0.5 and 5.5 µg m^{-2}. In total, hydrologic losses of THg were approximately double the biogeochemical losses between A and B (Figures 7f–7j). As a result, we estimated 17 weeks of THg connectivity between A and B, followed by two periods of disconnection in late August and September that are coincident with the periods of water disconnection, and a reconnection in October after several autumn storms wetted the catchment up again. Using a weekly time step, the frequency of THg connectivity was 0.78 and the duration was 21 weeks. Before and after the period of THg disconnection in late summer, the proportion of THg mobilized from point A that connected to point B was relatively constant at approximately 50% (Figure 8a). As an internal check on our THg connectivity estimates, we compared the mass of THg that connected from A to B to the total mass of THg exported from the UP1 catchment by multiplying the areal masses by their respective topographic upslope area. Up until mid-August, when

10.1002/2017WR020707

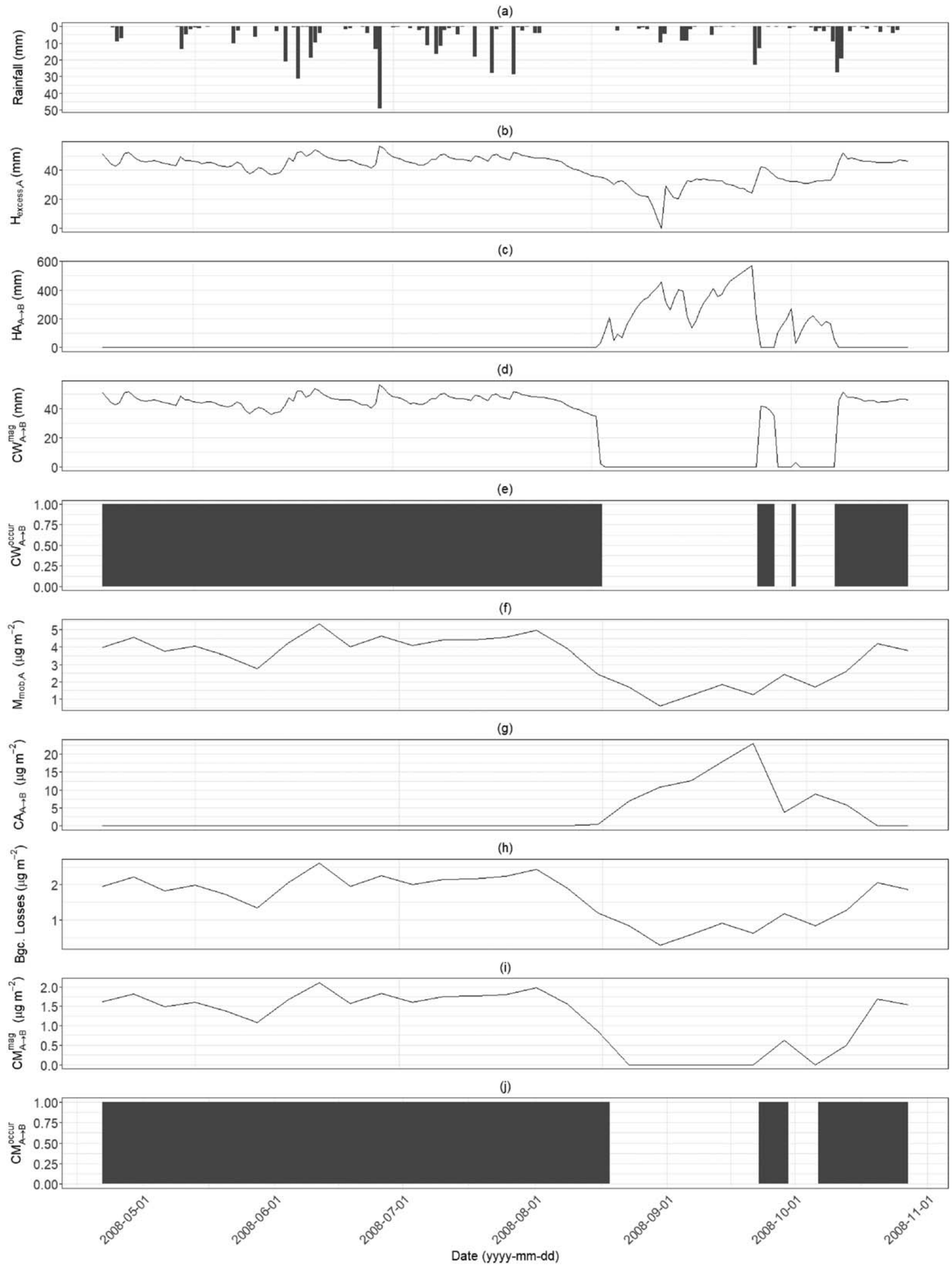


Figure 7. Results of the T-TEL case study including: (a) daily rainfall; (b) hydrological excess at point A; (c) hydrological abstractions along the A-to-B flow path; (d) magnitude of water connectivity between A and B; (e) occurrence of water connectivity between A and B (1 = occurrence; 0 = no occurrence); (f) quantity of potentially mobile THg at point A; (g) quantity of THg lost along the A-to-B flow path due to hydrological abstractions; (h) quantity of THg lost along the A-to-B flow path as a result of biogeochemical (Bgc.) processing; (i) magnitude of THg connectivity between A and B; and (j) occurrence of THg connectivity between A and B (1 = occurrence; 0 = no occurrence).

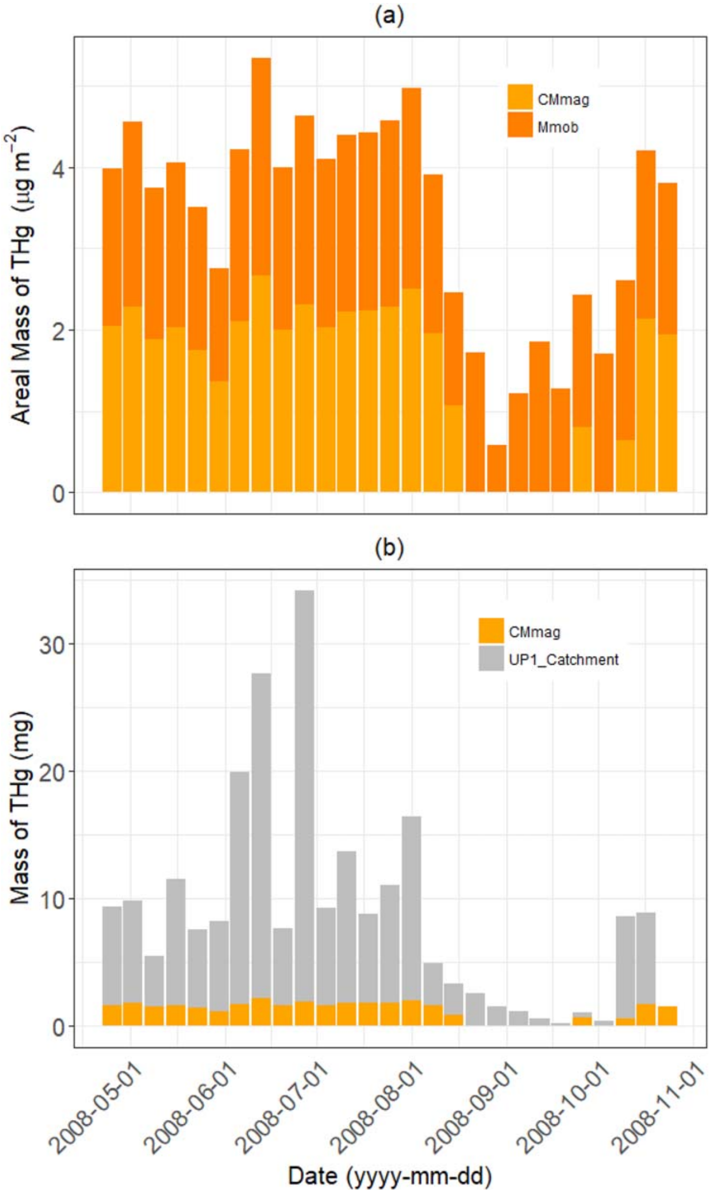


Figure 8. Comparison of (a) the areal mass of THg mobilized at source point A and the areal mass of THg that connected from A to B and (b) the mass of THg that connected from A to B and the total mass of THg exported from the whole UP1 catchment. In Figure 8b, areal masses were multiplied by topographic upslope areas (for point A and the catchment outlet) to estimate total masses.

both water and THg connection ceased, the proportion of total catchment THg export contributed by point A was on average 17% (Figure 8b). This proportion is higher than the ratio of $Area_A$ to the total UP1 catchment area, which may indicate that some locations contribute disproportionate amounts of THg to the catchment outlet. However, in the final week of the study period, the mass of $CM_{A\to B}^{mag}$ was larger than the mass of THg exported from the whole UP1 catchment: this suggests that we may be overestimating $CM_{A\to B}^{mag}$ during some time steps, especially after long dry periods associated with large abstractions.

6. Moving Forward With the T-TEL Method

6.1. Challenges

The T-TEL method relies on conceptual and mathematical frameworks that are data driven, making most of the challenges associated with the method data related. Broadly, data requirements concern the estimation of flow path distances, water storages, thresholds and abstractions, and material stocks and availabilities for transport. Parameterizing the T-TEL method equations will therefore lead to more or less uncertainty, depending on the availability of state-of-the art measurement methods or open data sources. For instance, estimating surface flow path distances in an age of ubiquitous elevation data is not a major challenge: both simple and complex topography-driven flow paths can be estimated by applying a variety of flow direction algorithms to digital elevation models. Data about subsurface topography however remain scarce, which may impede the application of the T-TEL method to situations where connectivity is driven by subsurface flow (e.g., nitrate transport) and surface topography is not a good proxy for the water table surface. Current approaches to estimating water storage include in situ measurements (e.g., wells, lysimeters, and tensiometers), process-based models, hydrograph analysis, or remote sensing (Ali et al., 2011; McNamara et al., 2011; Oswald et al., 2011; Tetzlaff et al., 2014). These methods, however, have different accompanying assumptions (McNamara et al., 2011) so intercomparison of absolute values may be inappropriate. Measurement techniques for threshold parameters such as topographic sill elevations, porosity, and infiltration capacity (i.e., H' in equation (8)) are well established. As for hydrological abstractions, they typically include losses to the atmosphere—which can be estimated with measurements of vapor pressure and winds—but also infiltration and depression losses—which are quantifiable using hydrometric techniques (Dingman, 2015).

Regarding water-mediated material connectivity, estimating the total mass of material at a point is generally a straightforward process of determining soil bulk density and homogenizing and possibly digesting a soil sample for subsequent chemical analysis. Extra consideration, however, is needed to capture the spatial variability of stocks of material, particularly in anthropogenically altered systems and possibly at spatial scales commensurate with land ownership or any given disturbance (Bennett et al., 2004; Wang et al., 2009a, 2009b). A greater challenge is to obtain spatially and temporally representative estimates of the proportion of the total mass of material that is potentially mobile. Since the mass of material in the solid phase typically exceeds the mass of material in the aqueous phase (Kalbitz et al., 2000), robust field-based measurements (e.g., colocated solid-phase and aqueous-phase material concentration measurements) or laboratory-based measurements (e.g., soil batch or column sequential extractions) designed for the chemical constituent of concern are necessary to determine partition coefficients. For some materials, breakthrough curves (e.g., for chloride, Jørgensen et al., 1998) and adsorption/desorption curves (e.g., soluble reactive phosphorus, Stone & Mudroch, 1989) might be appropriate means to estimate the available material. Regarding sediment, soil availability for mobilization

10.1002/2017WR020707

Table 2
Quick Examples of Data Requirements When the Focus is on Phosphorus (P) Connectivity Between a Source Point (A) and a Receiving Point, Driven by Either Surface or Subsurface Runoff

	HOF-driven particulate P connectivity	SOF-driven dissolved P connectivity	SSF-driven dissolved P connectivity
d_{total}	• Average flowpath distance (i.e., hydrologic distance) from source to receiving point[1,2]	• Average flowpath distance (i.e., hydrologic distance) from source to receiving point[1,2]	• Average flowpath distance (i.e., hydrologic distance) from source to receiving point[1,2]
$\bar{v}_{water}$	• Formula parameterization (Manning's kinematic equation): Flowpath gradient[1,2] Land use and land cover-based roughness coefficient[2,5] Hydraulic radius[1,2] • Tracer-based estimation Salt dilution or dye tracing[2]	• Formula parameterization (Manning's kinematic equation): Flowpath gradient[1,2] Land use and land cover-based roughness coefficient[2,5] Hydraulic radius[1,2] • Tracer-based estimation Salt dilution or dye tracing[2]	• Formula parameterization (Darcy's law equation): Hydraulic gradient[2] Soil hydraulic conductivity[2,5] Soil drainable porosity[2,5] • Tracer-based estimation $\delta^{18}O/\delta^{2}H$-based transit time modelling[2]
$H_{total,A} - H'$	• Rainfall intensity[2] **MINUS** Soil infiltration capacity[2,5] • Surface inundation data[2,3]	• Water table elevation[2,3] **MINUS** Soil profile depth[2,5,6] • Surface inundation data[2,3]	• Water table elevation[2,3] **MINUS** Depth above which perching occurs[2,5,6] • Soil moisture content[2,3] **MINUS** Field capacity[2,5]
$M_{tot,A}$	• Total soil P[2,4,5] **PLUS** phosphorus content of vegetation residues laying on the ground[2,4,5]	• Total soil P[2,4,5] **PLUS** phosphorus content of vegetation residues laying on the ground[2,4,5]	• Water-extractable soil test P (e.g., Mehlich-3, Olsen or Bray test P)[2,4,5]
$Avail_{BGC,A}$	• Not applicable	• Partition coefficient or soil phosphorus saturation ratio[2,4,5]	• Partition coefficient or soil phosphorus saturation ratio[2,4,5]
$Avail_{SED,A}$	• Soil erodibility[2,4,5]	• Not applicable	• Not applicable
$k_{x,A\rightarrow B}$	• P adsorption rate[2,4,5]	• P adsorption rate[2,4,5]	• P adsorption rate[2,4,5]
$\tau_{x,A\rightarrow B}$	• Obtained as $d_{total}/\bar{v}_{water}$	• Obtained as $d_{total}/\bar{v}_{water}$	• Obtained as $d_{total}/\bar{v}_{water}$
$M_{mob,A}$	• Obtained by applying equation (14b)	• Obtained by applying equation (14a)	• Obtained by applying equation (14a) • Alternatively, obtained directly as a dissolved phosphorus concentration in soil water (sampled from a lysimeter, a piezometer or a well)[2]

Note. Each bullet point illustrates a different quantification option for the T-TEL-related variable listed in the leftmost column. HOF, SOF, and SSF refer to Hortonian overland flow, saturation-excess overland flow, and shallow subsurface flow, respectively. Superscripts 1–6 refer to different data sources, namely: 1, digital terrain data; 2, ground-based field data; 3, large-scale remotely sensed data; 4, laboratory analyses; 5, published literature or public databases; 6, geophysical mapping investigations (e.g., ground penetrating radar and electrical resistivity).

by runoff is often measured empirically (e.g., erodibility and cover factors in the Universal Soil Loss Equation, Renard et al., 2011), though physical methods relating grain size, critical shear stress, and surface runoff velocity are used as well (Léonard & Richard, 2004). Laboratory techniques, including soil columns, incubator experiments, and isotopic tracer experiments, exist to estimate reaction rates of materials in transit or in situ.

While the data-related challenges listed above are nonnegligible, the T-TEL method is flexible enough to allow different data types and sources to be used, based on availability. Table 2 notably describes the different data options (i.e., ground-based, laboratory-based, remotely sensed) that would be available to apply the mathematical framework if the focus was on overland flow-driven or subsurface flow-driven phosphorus (P) connectivity between two points. Applying the T-TEL method to regional scales, where data availability is much more limited than in small research basins, will not be straightforward. Methodologies do exist to scale up field data about soil and hydrological properties to regional scales, including pedotransfer functions (Schapp et al., 2001), while integration of remotely sensed and field data can upscale some key process rates, such as evapotranspiration (Tang et al., 2013). Long-term commercial statistics, such as records of fertilizer sales and crop harvests (Macdonald & Bennett, 2009), may also be useful to estimate the total pool of material at a landscape scale. However, the fraction of this material available for loss will be considerably harder to estimate at a regional scale. Extrapolation across space remains a process that can introduce significant uncertainty (Langhans et al., 2010). In the end, either regional scale applications of the T-TEL method will need to contend with this uncertainty, or a critical spatial scale beyond which the method cannot reliably be applied will need to be established.

10.1002/2017WR020707

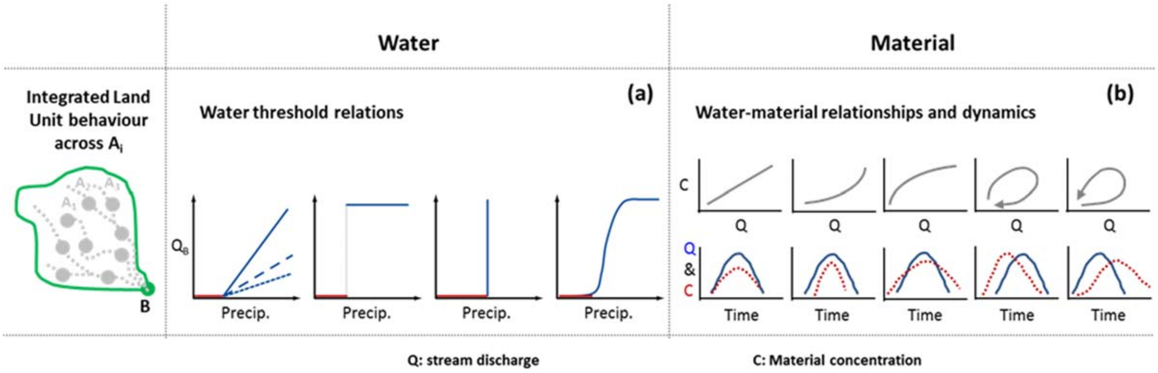


Figure 9. Integrated hillslope or watershed signals typically used to infer the presence/absence of hydrologic connectivity and water-mediated material connectivity. Precip, precipitation; Q_B, stream discharge at point B.

6.2. Strengths

The mathematical framework suggested in section 4 is a call to hydrologists and biogeochemists to reevaluate ways of assessing connectivity at the watershed scale. Specifically, it has the potential to feed the discussion regarding (i) the complementarity of bottom-up and top-down approaches to connectivity and (ii) the selection of process-independent metrics for site comparison and classification.

Recent hillslope-scale and catchment-scale studies have used top-down approaches to hypothesize connectivity based on integrated signals at outflow points. For example, Tromp-van Meerveld and McDonnell (2006a), Lehmann et al. (2007), Zehe et al. (2007), Detty and McGuire (2010a), Penna et al. (2011), Stewart et al. (2015), and others analyzed input (precipitation)-output (subsurface stormflow or stream discharge) relations and inferred connectivity occurrence once thresholds were exceeded (Figure 9a). As well, Evans and Davies (1998), McGlynn and McDonnell (2003), Creed et al. (2015), and Herndon et al. (2015), among others, estimated the proximity of material sources to the outlet from the presence or absence of hysteresis loops in concentration-discharge (C-Q) relationships (Figure 9b) and derived connectivity-related inferences from such assessments. However, one drawback of such integrated approaches is the inability to resolve identifiability issues with connectivity properties. In order for the properties $CW^{occur}_{A\to B,\Delta t}$ and $CW^{mag}_{A\to B}$ to be robust diagnostic tools, they need to exhibit different values for different runoff generation processes and their "expressions" or "spatial configurations." The current literature on runoff generation mechanisms does not provide enough evidence to determine if different patterns of active and contributing areas—driven by variable area versus partial area dynamics, for example—would result in two significantly different hydrologic threshold behaviors (i.e., two of the threshold shapes illustrated in Figure 9a) and, in turn, different values of

Table 3
Runoff Generation Mechanisms and Their Implications for the Occurrence and Spatial Extent of Water Connectivity and Water-Mediated Material Connectivity

	$CW^{occur}_{A\to B,\Delta t}$				$CM^{occur}_{A\to B,\Delta t}$			
Scenario	$CW^{occur}_{A1\to B,\Delta t}$	$CW^{occur}_{A2\to B,\Delta t}$	$CW^{occur}_{A3\to B,\Delta t}$	$CW^{contrib}_{Land\ \ unit,\Delta t}$	$CM^{occur}_{A1\to B,\Delta t}$	$CM^{occur}_{A2\to B,\Delta t}$	$CM^{occur}_{A3\to B,\Delta t}$	$CM^{contrib}_{Land\ \ unit,\Delta t}$
HOF #1	1	1	1	H	1 (S only)	1 (S only)	1 (S only)	H (S only)
HOF #2	0	1	1	M	0	1 (S only)	1 (S only)	M (S only)
SOF #1	0	0	1	L	1 (SS only)	1 (SS only)	1 (S and SS)	H (S and SS)
SOF #2	0	1	1	M	1 (SS only)	1 (S and SS)	1 (S and SS)	H (S and SS)
Subsurface flow	1	1	1	H	1 (SS only)	1 (SS only)	1 (SS only)	H (SS only)
Perched subsurface flow	1	1	1	H	1 (SS only)	1 (SS and PSS)	1 (S and SS)	H (S, SS and PSS)
Fill and spill #1	0	0	1	L	0	0	1 (S only)	L
Fill and spill #2	0	1	1	M	0	1 (S only)	1 (S only)	M (S only)

Note. The "scenario" column refers to the vignettes included in Figure 10. H, M, and L refer to high, medium, and low, respectively. Points A1, A2, A3, and B are also indicated in Figure 10. S, surface; SS, subsurface; PSS, perched subsurface. For material connectivity, the illustrated scenarios assume either full conservativeness of the targeted material or the presence of an unlimited supply of material (in which case the establishment of water-mediated material connectivity is only transport limited). For other abbreviations, see the caption of Figure 10.

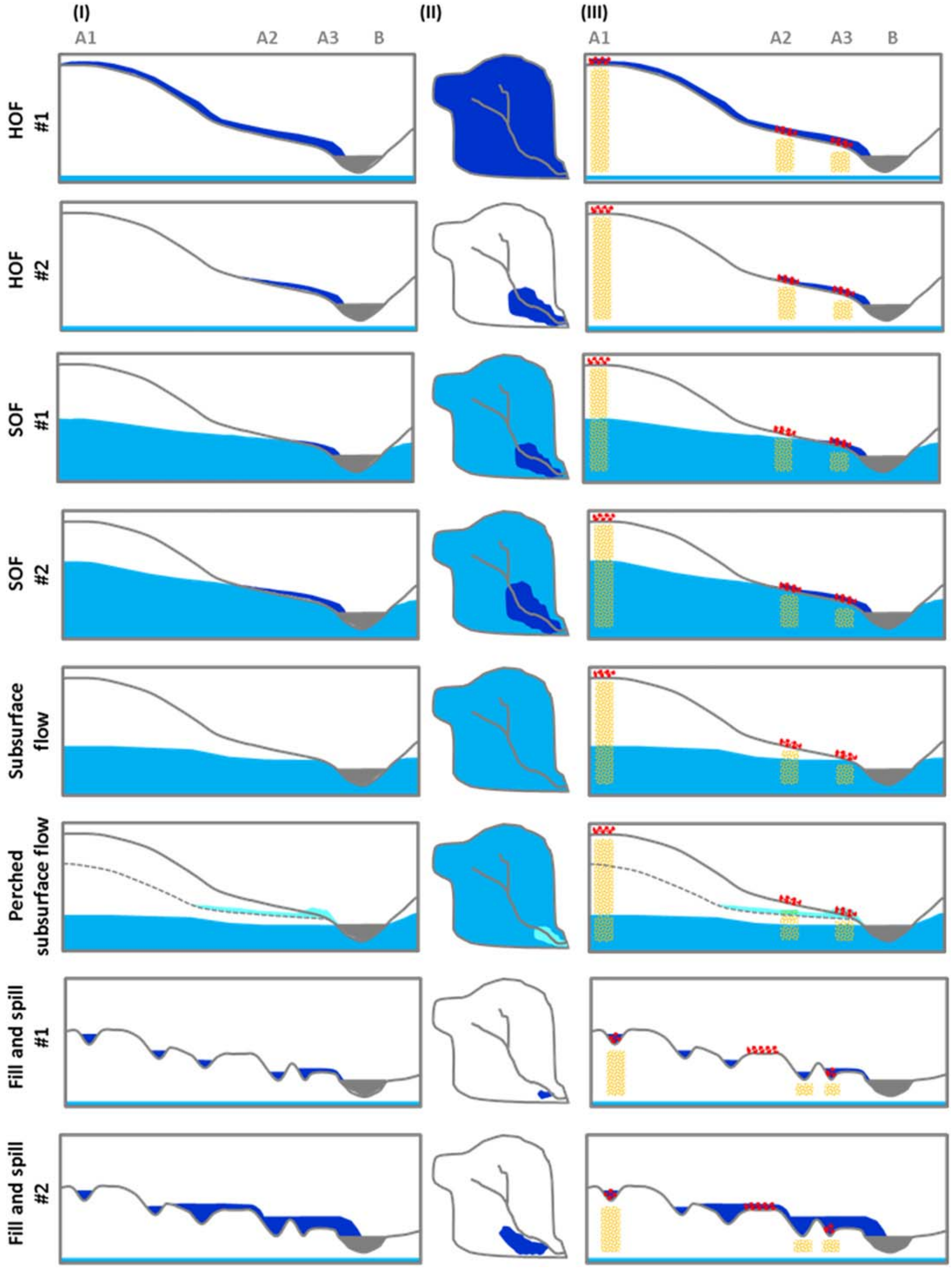


Figure 10. (I) Runoff generation mechanisms and (II) their implications for watershed-wide water connectivity and (III) the mobilization of landscape material. Surface and subsurface water in (I–III) are shown in dark and light blue, respectively. Surface and subsurface material in (III) are shown in red and orange, respectively. HOF, Hortonian overland flow; SOF, saturation-excess overland flow.

$CW^{occur}_{A\rightarrow B,\Delta t}$ and $CW^{mag}_{A\rightarrow B}$. Some manifestations of surface fill-and-spill runoff and Hortonian overland flow may produce similar patterns of connectivity (Table 3 and Figure 10) and hence result in identifiability issues which then propagate to the assessment of water-mediated material connectivity as well (Table 3 and Figure 10). Assessing the ability of equations (1–20) to help resolve such issues is an important first test of the T-TEL method.

Catchment classification can aid in finding generalities in hydrology (Barthold & Woods, 2015; McDonnell & Woods, 2004). To date, such synthesis efforts have been limited by the mostly process-specific connectivity metrics available in the literature (Bracken et al., 2013). Conversely, the T-TEL method allows different landscapes to be compared at a higher, "big picture," process-independent level, with a sole focus on whether said landscapes are "collecting," "storing," or "discharging" (in the sense of Black, 1997). The frequency and duration that a landscape unit exhibits any one of these hydrologic functions is intuitively related to connectivity frequency and duration, expressed by $CW^{freq}_{A\rightarrow B,T}$ and $CW^{dur}_{A\rightarrow B,T}$. If frequency is greater than 0.5 or duration is any larger than half of T, this indicates that for more than half the time, the landscape unit under consideration is hydrologically connected and is predominantly discharging. How these values manifest across a diversity of watersheds could be an important catchment classification tool. Furthermore, comparing these baseline values to those obtained after landscape manipulation would allow an assessment of how various disturbances affect hydrological function, and help quantify previously unknown and potentially overlapping recovery trajectories when multiple disturbances are at play. The similar use of $CM^{freq}_{A\rightarrow B,T}$ and $CM^{dur}_{A\rightarrow B,T}$ could also provide important knowledge necessary to evaluate how disruptions or stressors to water-mediated material connectivity affect biogeochemical and ecological function.

Overall, in the same way bottom-up and top-down approaches have been deemed complementary when modeling runoff processes (Hrachowitz & Clark, 2017), both approaches are useful for assessing connectivity. One disadvantage of integrated or "top-down" approaches is that they do not provide information about the dominant flow paths via which connectivity is established or broken. This can be problematic in a management context. For example, the effectiveness and efficacy of current management policies that focus on "no net loss of wetland function" within the wetland complex of the Prairie Pothole Region is typically unknown, because current approaches do not provide the appropriate data and information about how alterations of individual, or classes of, wetlands will alter how connectivity of water and material is established (Ameli & Creed, 2017; Golden et al., 2014). It is for these reasons that, when the aim is to assess connectivity to improve process understanding and/or land and water management tools, we advocate for a bottom-up approach implementing the mathematical framework—starting at the point scale (A to B) and integrating over the watershed—rather than an approach where the sole focus is on integrated or emergent signals measured at an outflow point. We do, however, acknowledge that such an approach may be effort-intensive and time consuming in understudied or data-poor regions.

6.3. Opportunities

The proposed T-TEL method can be seen as a "model of connectivity" and as such, it opens the door for a range of single-site and cross-site studies never carried out before. One such study could take the form of a hypothesis testing exercise regarding the relative role of different climatic and landscape factors on connectivity (e.g., Bracken & Croke, 2007; Bracken et al., 2013). Do topographic, soil, climate and other factors have a similar influence on different properties of connectivity (i.e., occurrence, magnitude, frequency, duration, and spatial extent)? Does the answer to that question vary across time at a given site, as well as across sites? Equations (1–20) do provide a means to address such questions in a standardized manner among various research groups. From a technical standpoint, it would also be interesting to carry out sensitivity analyses to assess whether some parameters included in equations (1–20) have a disproportionate influence on connectivity results, especially when it comes to magnitude estimates. For example, it is clear from equation (13) that choosing an appropriate value or range of values for the Damköhler number will have a significant impact on the magnitude of material connectivity. In the THg case study outlined in section 5, the proportion of material mobilized at point A that connected to point B increased from 8% to 60% as the value of the Damköhler was decreased from 7.5 to 0.01. Additional sensitivity analyses are needed. Because there are no "connectivity meters" deployable in the field for direct measurements of water and water-mediated material connectivity, virtual experiments (Weiler & McDonnell, 2004, 2006) might be needed, whereby physical models of hillslopes or watersheds with known connectivity dynamics would be created. The ability of the T-TEL method equations to reasonably predict A-to-B connectivity given different data inputs would then be assessed. To the fact that the single A-to-B equations in section 4 can be scaled up to multiple $i \rightarrow B$ pairs of points, the T-TEL method could serve as the basis for fully distributed geospatial models that target the prediction of connectivity in a spatially explicit manner. Further, the T-TEL method could be used to summarize the results of multiple models of hydrological connectivity. For example, Scavia et al. (2017) recently synthesized the results of a number of modeled source areas of phosphorus to the Maumee river.

While their analysis focused on summarizing areas of yield to the stream, the T-TEL approach could be used to assess how each of the models conceptualizes all aspects of water-mediated material connectivity, and hence go beyond the comparison of modeled source areas to a comparison of all aspects of water-mediated material connectivity. There are also opportunities for the broader research community to explore important process dynamics and interactions that are currently omitted from the T-TEL framework as presented in this paper. For instance, our conceptual model does not explicitly address the coupled nature of biogeochemical transport, for instance the carbon and nitrogen cycles that are quite interdependent. Our aim was not to exhaustively describe biogeochemical processes but rather to express them in sufficient detail to differentiate cases when material connectivity is water (i.e., transport) or material (i.e., supply) limited (Basu et al., 2011; Godsey et al., 2009). Other biogeochemists might, however, wish to examine whether chemical fluxes known to be tightly coupled (e.g., carbon and nitrogen) should be examined simultaneously or not. Lastly, while the data requirements of the T-TEL method are high, they can be satisfied in many intensively studied sites around the world. The example in section 5 was conducted on a data set collected during the course of a single PhD thesis, and there are currently data sets of similar or greater process detail from research catchments (e.g., Long Term Ecological Research network, Critical Zone Observatories, and CEAP watersheds in the United States; Experimental Lakes Area in Canada). Some research catchment data sets are open-source (e.g., H.J. Andrews Experimental Forest, Panola, and Tarrawarra catchment), while some countries have made extensive data sets available at the national level (e.g., GRACE, NHD, SSURGO data in the United States). The T-TEL method as outlined in this paper could also be used as a guide to inform future data collection efforts when the goal is to quantify water and material connectivity.

7. Conclusion

The overall goals of this paper were to (i) review a range of existing hydrologic, sediment, and biogeochemical connectivity definitions and metrics for common and transferable language; (ii) propose a consensus and operationalizable definition of water and water-mediated material connectivity; (iii) lay out conceptual and mathematical frameworks to quantify these connectivities; and (iv) use a small case study as well as a broader research agenda to illustrate the potential application of these frameworks in various environments. In addition to relying on well-established concepts of Time scales, Thresholds, Excesses, and Losses (T-TEL), the proposed frameworks are designed for application across spatial scales, from the quantification of connectivity between two points on a hillslope to the quantification of connectivity between a multitude of points across a watershed and a receiving point. Furthermore, the outlined mathematical framework allows the quantification of the occurrence, frequency, duration, and magnitude of connectivity, a multifaceted strategy which can help elucidate predominant hydrological, geomorphological, and biogeochemical processes and functions.

While talking about connectivity in a standardized, quantitative manner is imperative to facilitate intersite comparison in a research context, it is especially critical in the context of whole-ecosystem management and policy making for which quantifiable targets are needed. The proposed mathematical framework could serve as a starting point—and a research catalyst—for the water resource community to study and report on connectivity or disconnectivity in a consistent manner. The next step is to test it. We encourage hydrologists, geomorphologists and biogeochemists to challenge and refine the conceptual and mathematical frameworks that underlie the T-TEL connectivity assessment method through a number of experimental and modeling studies, including (i) parameterization studies in single catchments (similar to the case study presented in this review paper); (ii) comparative studies across multiple catchment types; and (iii) studies across scales. We look forward to seeing how the T-TEL method performs in the research and management of connectivity in both pristine and human-impacted landscapes.

Acknowledgments
We thank the Associate Editor, David Rupp, as well as Jacky Croke, John Selker, and two other anonymous reviewers for their very insightful comments and suggestions regarding an earlier version of this review paper. The data used for the case study included in this paper were previously published in Oswald et al. (2011, 2014) and Oswald and Branfireun (2014).

References

Adriaensen, F., Chardon, J. P., De Blust, G., Swinnen, E., Villalba, S., Gulinck, H., et al. (2003). The application of 'least-cost' modelling as a functional landscape model. *Landscape and Urban Planning*, *64*(4), 233–247. https://doi.org/10.1016/S0169-2046(02)00242-6

Ali, G., Oswald, C. J., Spence, C., Cammeraat, E. L. H., McGuire, K. J., Meixner, T., et al. (2013). Towards a unified threshold-based hydrological theory: Necessary components and recurring challenges. *Hydrological Processes*, *27*(2), 313–318. https://doi.org/10.1002/hyp.9560

Ali, G., Tetzlaff, D., McDonnell, J. J., Soulsby, C., Carey, S., Laudon, H., et al. (2015). Comparison of threshold hydrologic response across northern catchments. *Hydrological Processes*, *29*(16), 3575–3591. https://doi.org/10.1002/hyp.10527

Ali, G. A., L'Heureux, C., Roy, A. G., Turmel, M.-C., & Courchesne, F. (2011). Linking spatial patterns of perched groundwater storage and stormflow generation processes in a headwater forested catchment. *Hydrological Processes*, *25*(25), 3843–3857. https://doi.org/10.1002/hyp.8238

Ali, G. A., & Roy, A. G. (2009). Revisiting hydrologic sampling strategies for an accurate assessment of hydrologic connectivity in humid temperate systems. *Geography Compass*, *3*(1), 350–374. https://doi.org/10.1111/j.1749-8198.2008.00180.x

Ali, G. A., & Roy, A. G. (2010). Shopping for hydrologically representative connectivity metrics in a humid temperate forested catchment. *Water Resources Research*, *46*, W12544. https://doi.org/10.1029/2010WR009442

Allan, C. J., & Roulet, N. T. (1994). Runoff generation in zero-order precambrian shield catchments: The stormflow response of a heterogeneous landscape. *Hydrological Processes*, *8*, 369–388. https://doi.org/10.1002/hyp.3360080409

Ambroise, B. (2004). Variable, 'active' versus 'contributing' areas or periods: A necessary distinction. *Hydrological Processes*, *18*(6), 1149–1155.

Ameli, A. A., Craig, J., & McDonnell, J. (2015). Are all runoff processes the same? Numerical experiments comparing a Darcy-Richards solver to an overland flow based approach for subsurface storm runoff simulation. *Water Resources Research*, *51*, 10008–10028. https://doi.org/10.1002/2015WR017199

Ameli, A. A., & Creed, I. F. (2017). Quantifying hydrologic connectivity of wetlands to surface water systems. *Hydrology and Earth System Sciences*, *21*(3), 1791–1808. https://doi.org/10.5194/hess-21-1791-2017

Amoros, C., & Bornette, G. (2002). Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology*, *47*(4), 761–776.

Antoine, M., Javaux, M., & Bielders, C. (2009). What indicators can capture runoff-relevant connectivity properties of the micro-topography at the plot scale? *Advances in Water Resources*, *32*(8), 1297–1310.

Antoine, M., Javaux, M., & Bielders, C. L. (2011). Integrating subgrid connectivity properties of the micro-topography in distributed runoff models, at the interrill scale. *Journal of Hydrology*, *403*(3–4), 213–223. https://doi.org/10.1016/j.jhydrol.2011.03.027

Banaszuk, P., & Wysocka-Czubaszek, A. (2005). Phosphorus dynamics and fluxes in a lowland river: The narew anastomosing river system, ne poland. *Ecological Engineering*, *25*(4), 429–441. https://doi.org/10.1016/j.ecoleng.2005.06.013

Barthold, F. K., & Woods, R. A. (2015). Stormflow generation: A meta-analysis of field evidence from small, forested catchments. *Water Resources Research*, *51*, 3730–3753. https://doi.org/10.1002/2014WR016221

Basu, N. B., Thompson, S. E., & Rao, P. S. C. (2011). Hydrologic and biogeochemical functioning of intensively managed catchments: A synthesis of top-down analyses. *Water Resources Research*, *47*, W00J15. https://doi.org/10.1029/2011WR010800

Bennett, E. M., Carpenter, S. R., & Clayton, M. K. (2004). Soil phosphorus variability: Scale-dependence in an urbanizing agricultural landscape. *Landscape Ecology*, *20*(4), 389–400. https://doi.org/10.1007/s10980-004-3158-7

Bernhardt, E. S., Blaszczak, J. R., Ficken, C. D., Fork, M. L., Kaiser, K. E., & Seybold, E. C. (2017). Control points in ecosystems: Moving beyond the hot spot hot moment concept. *Ecosystems*, *20*(4), 665–682. https://doi.org/10.1007/s10021-016-0103-y

Black, P. E. (1997). Watershed functions. *Journal of the American Water Resources Association*, *33*(1), 1–11. https://doi.org/10.1111/j.1752-1688.1997.tb04077.x

Borselli, L., Cassi, P., & Torri, D. (2008). Prolegomena to sediment and flow connectivity in the landscape: A gis and field numerical assessment. *Catena*, *75*(3), 268–277. https://doi.org/10.1016/j.catena.2008.07.006

Bracken, L. J., & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, *21*(13), 1749–1763. https://doi.org/10.1002/hyp.6313

Bracken, L. J., Turnbull, L., Wainwright, J., & Bogaart, P. (2015). Sediment connectivity: A framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms*, *40*(2), 177–188. https://doi.org/10.1002/esp.3635

Bracken, L. J., Wainwright, J., Ali, G., Roy, A. G., Smith, M. W., Tetzlaff, D., et al. (2013). Concepts of hydrological connectivity: Research approaches, pathways and future agendas. *Earth-Science Reviews*, *119*, 17–34.

Brunsden, D., & Thornes, J. B. (1979). Landscape sensitivity and change. *Transactions of the Institute of British Geographers*, *4*(4), 463–484.

Bunn, A. G., Urban, D. L., & Keitt, T. H. (2000). Landscape connectivity: A conservation application of graph theory. *Journal of Environmental Management*, *59*(4), 265–278. https://doi.org/10.1006/jema.2000.0373

Burns, D. A., McDonnell, J. J., Hooper, R. P., Peters, N. E., Freer, J. E., Kendall, C., & Beven, K., (2001). Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the panola mountain research watershed (Georgia, USA). *Hydrological Processes*, *15*(10), 1903–1924.

Buttle, J. M., Boon, S., Peters, D. L., Spence, C., van Meerveld, H. J., & Whitfield, P. H. (2012). An overview of temporary stream hydrology in canada. *Canadian Water Resources Journal*, *37*(4), 279–310. https://doi.org/10.4296/cwrj2011-903

Calabrese, J. M., & Fagan, W. F. (2004). A comparison-shopper's guide to connectivity metrics. *Frontiers in Ecology and the Environment*, *2*(10), 529–536.

Cammeraat, L. H. (2002). A review of two strongly contrasting geomorphological systems within the context of scale. *Earth Surface Processes and Landforms*, *27*(11), 1201–1222.

Carlyle, G. C., & Hill, A. R. (2001). Groundwater phosphate dynamics in a river riparian zone: Effects of hydrologic flowpaths, lithology and redox chemistry. *Journal of Hydrology*, *247*(3–4), 151–168. https://doi.org/10.1016/S0022-1694(01)00375-4

Cavalli, M., Trevisani, S., Comiti, F., & Marchi, L. (2013). Geomorphometric assessment of spatial sediment connectivity in small alpine catchments. *Geomorphology*, *188*, 31–41. https://doi.org/10.1016/j.geomorph.2012.05.007

Cohen, M. J., Creed, I. F., Alexander, L., Basu, N. B., Calhoun, A. J. K., Craft, C., et al. (2016). Do geographically isolated wetlands influence landscape functions? *Proceedings of the National Academy of Sciences of the United States of America*, *113*(8), 1978–1986. https://doi.org/10.1073/pnas.1512650113

Creed, I. F., McKnight, D. M., Pellerin, B. A., Green, M. B., Bergamaschi, B. A., Aiken, G. R., et al. (2015). The river as a chemostat: Fresh perspectives on dissolved organic matter flowing down the river continuum. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(8), 1272–1285. https://doi.org/10.1139/cjfas-2014-0400

Croke, J., Mockler, S., Fogarty, P., & Takken, I. (2005). Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. *Geomorphology*, *68*(3–4), 257–268.

Detty, J. M., & McGuire, K. J. (2010a). Threshold changes in storm runoff generation at a till-mantled headwater catchment. *Water Resources Research*, *46*, W07525. https://doi.org/10.1029/2009WR008102

Detty, J. M., & McGuire, K. J. (2010b). Topographic controls on shallow groundwater dynamics: Implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. *Hydrological Processes*, *24*(16), 2222–2236.

de Vente, J., Poesen, J., Arabkhedri, M., & Verstraeten, G. (2007). The sediment delivery problem revisited. *Progress in Physical Geography*, *31*(2), 155–178.

Dickinson, W. T., & Whiteley, H. (1970). *Watershed areas contributing to runoff*. Paper presented at Results of research on representative and experimental basins (Wellington symposium 1970) (Vol. 96, pp. 12–26), IAHS Red Books, Wellington, New Zealand.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., & McKean, J. (1993). Analysis of erosion thresholds, channel networks, and landscape morphology using a digital terrain model. *Journal of Geology*, *101*(2), 259–278.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., McKean, J., & Bauer, R. (1992). Erosion thresholds and land surface-morphology. *Geology*, *20*(8), 675–679. https://doi.org/10.1130/0091-7613(1992)020<0675:ETALSM>2.3.CO;2

Dingman, S. L. (2015). *Physical hydrology* (3rd ed.). Long Grove, IL: Waveland Press.

Evans, C., & Davies, T. D. (1998). Causes of concentration/discharge hysteresis and its potential as a tool for analysis of episode hydrochemistry. *Water Resources Research*, *34*(1), 129–137.

Fogler, H. S. (1987). *Elements of chemical reaction engineering* (Vol. 42). Englewood Cliff, NJ: Prentice-Hall.

Freeman, M. C., Pringle, C. M., & Jackson, C. R. (2007). Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association*, *43*(1), 5–14. https://doi.org/10.1111/j.1752-1688.2007.00002.x

Fryirs, K. (2013). (dis)connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*, *38*(1), 30–46. https://doi.org/10.1002/esp.3242

Fryirs, K. A., Brierley, G. J., Preston, N. J., & Kasai, M. (2007a). Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena*, *70*(1), 49–67.

Fryirs, K. A., Brierley, G. J., Preston, N. J., & Spencer, J. (2007b). Catchment-scale (dis)connectivity in sediment flux in the upper hunter catchment, new south wales, australia. *Geomorphology*, *84*(3–4), 297–316. https://doi.org/10.1016/j.geomorph.2006.01.044

Gburek, W. J., & Sharpley, A. N. (1998). Hydrologic controls on phosphorus loss from upland agricultural watersheds. *Journal of Environmental Quality*, *27*(2), 267–277.

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. https://doi.org/10.1002/hyp.10310

Godsey, S. E., Kirchner, J. W., & Clow, D. W. (2009). Concentration-discharge relationships reflect chemostatic characteristics of us catchments. *Hydrological Processes*, *23*(13), 1844–1864. https://doi.org/10.1002/hyp.7315

Golden, H. E., Lane, C. R., Amatya, D. M., Bandilla, K. W., Kiperwas, A. R., Knightes, C. D., et al. (2014). Hydrologic connectivity between geographically isolated wetlands and surface water systems: A review of select modeling methods. *Environmental Modelling & Software*, *53*, 190–206.

Gomi, T., Sidle, R. C., Miyata, S., Kosugi, K., & Onda, Y. (2008). Dynamic runoff connectivity of overland flow on steep forested hillslopes: Scale effects and runoff transfer. *Water Resources Research*, *44*, W08411. https://doi.org/10.1029/2007WR005894

Grigal, D. F. (2002). Inputs and outputs of mercury from terrestrial watersheds: A review. *Environmental Reviews*, *10*(1), 1–39. https://doi.org/10.1139/a01-013

Hairsine, P. B., Croke, J. C., Mathews, H., Fogarty, P., & Mockler, S. P. (2002). Modelling plumes of overland flow from logging tracks. *Hydrological Processes*, *16*(12), 2311–2327. https://doi.org/10.1002/hyp.1002

Harris, R. C., Rudd, J. W. M., Amyot, M., Babiarz, C. L., Beaty, K. G., Blanchfield, P. J., et al. (2007). Whole-ecosystem study shows rapid fish-mercury response to changes in mercury deposition. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 16586–16591. https://doi.org/10.1073/pnas.0704186104

Harvey, A. M. (2002). Effective timescales of coupling within fluvial systems. *Geomorphology*, *44*(3–4), 175–201.

Heckmann, T., & Schwanghart, W. (2013). Geomorphic coupling and sediment connectivity in an alpine catchment—Exploring sediment cascades using graph theory. *Geomorphology*, *182*, 89–103. https://doi.org/10.1016/j.geomorph.2012.10.033

Herndon, E. M., Dere, A. L., Sullivan, P. L., Norris, D., Reynolds, B., & Brantley, S. L. (2015). Landscape heterogeneity drives contrasting concentration-discharge relationships in shale headwater catchments. *Hydrology and Earth System Sciences*, *19*(8), 3333–3347. https://doi.org/10.5194/hess-19-3333-2015

Hjerdt, K. N., McDonnell, J. J., Seibert, J., & Rodhe, A. (2004). A new topographic index to quantify downslope controls on local drainage. *Water Resources Research*, *40*, W05602. https://doi.org/10.1029/2004WR003130

Hooke, J. (2003). Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. *Geomorphology*, *56*(1–2), 79–94.

Hooper, R. P. (2003). Diagnostic tools for mixing models of stream water chemistry. *Water Resources Research*, *39*(3), 1055. https://doi.org/10.1029/2002WR001528

Horton, R. E. (1933). The role of infiltration in the hydrologic cycle. *Eos, Transactions, American Geophysical Union*, *14*, 446–460.

Houben, P. (2008). Scale linkage and contingency effects of field-scale and hillslope-scale controls of long-term soil erosion: Anthropogeomorphic sediment flux in agricultural loess watersheds of southern germany. *Geomorphology*, *101*(1–2), 172–191. https://doi.org/10.1016/j.geomorph.2008.06.007

Hrachowitz, M., Benettin, P., van Breukelen, B. M., Fovet, O., Howden, N. J. K., Ruiz, L., et al. (2016). Transit times-the link between hydrology and water quality at the catchment scale. *Wiley Interdisciplinary Reviews: Water*, *3*(5), 629–657. https://doi.org/10.1002/wat2.1155

Hrachowitz, M., & Clark, M. P. (2017). Hess opinions: The complementary merits of competing modelling philosophies in hydrology. *Hydrology and Earth System Sciences*, *21*(8), 3953–3973. https://doi.org/10.5194/hess-21-3953-2017

James, A. L., & Roulet, N. T. (2006). Investigating the applicability of end-member mixing analysis (emma) across scale: A study of eight small, nested catchments in a temperate forested watershed. *Water Resources Research*, *42*, W08434. https://doi.org/10.1029/2005WR004419

James, A. L., & Roulet, N. T. (2007). Investigating hydrologic connectivity and its association with threshold change in runoff response in a temperate forested watershed. *Hydrological Processes*, *21*(25), 3391–3408.

Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, *47*, W11527. https://doi.org/10.1029/2011WR010666

Jencso, K. G., McGlynn, B. L., Gooseff, M. N., Wondzell, S. M., Bencala, K. E., & Marshall, L. A. (2009). Hydrologic connectivity between landscapes and streams: Transferring reach-and plot-scale understanding to the catchment scale. *Water Resources Research*, *45*, W04428. https://doi.org/10.1029/2008WR007225

Jørgensen, P. R., McKay, L. D., & Spliid, N. H. (1998). Evaluation of chloride and pesticide transport in a fractured clayey till using large undisturbed columns and numerical modeling. *Water Resources Research*, *34*(4), 539–553. https://doi.org/10.1029/97WR02942

Kalbitz, K., Solinger, S., Park, J. H., Michalzik, B., & Matzner, E. (2000). Controls on the dynamics of dissolved organic matter in soils: A review. *Soil Science*, *165*(4), 277–304. https://doi.org/10.1097/00010694-200004000-00001

Kalcic, M. M., Frankenberger, J., & Chaubey, I. (2015). Spatial optimization of six conservation practices using swat in tile-drained agricultural watersheds. *Journal of the American Water Resources Association*, *51*(4), 956–972. https://doi.org/10.1111/1752-1688.12338

Kleidon, A., & Schymanski, S. (2008). Thermodynamics and optimality of the water budget on land: A review. *Geophysical Research Letters*, *35*, L20404. https://doi.org/10.1029/2008GL035393

Kleinman, P., Sharpley, A., Buda, A., McDowell, R., & Allen, A. (2011). Soil controls of phosphorus in runoff: Management barriers and opportunities. *Canadian Journal of Soil Science*, *91*(3), 329–338. https://doi.org/10.4141/cjss09106

Knudby, C., & Carrera, J. (2005). On the relationship between indicators of geostatistical, flow and transport connectivity. *Advances in Water Resources*, *28*(4), 405–421.

Krieger, K. A. (2003). Effectiveness of a coastal wetland in reducing pollution of a laurentian great lake: Hydrology, sediment, and nutrients. *Wetlands*, *23*(4), 778–791. https://doi.org/10.1672/0277-5212(2003)023[0778:EOACWI]2.0.CO;2

Lane, P. N. J., Hairsine, P. B., Croke, J. C., & Takken, I. (2006). Quantifying diffuse pathways for overland flow between the roads and streams of the Mountain Ash Forests of Central Victoria Australia. *Hydrological Processes*, *20*(9), 1875–1884.

Lane, S. N., Brookes, C. J., Hardy, R. J., Holden, J., James, T. D., Kirkby, M. J., et al. (2003). *Land management, flooding and environmental risk: New approaches to a very old question*. Paper presented at Proceedings of Chartered Institution of Water Environmental Management (CIWEM) Conference, Harrogate, UK.

Lane, S. N., & Richards, K. S. (1997). Linking river channel form and process: Time, space and causality revisited. *Earth Surface Processes and Landforms*, *22*(3), 249–260.

Langhans, C., Govers, G., Diels, J., Clymans, W., & Van den Putte, A. (2010). Dependence of effective hydraulic conductivity on rainfall; intensity: Loamy agricultural soils. *Hydrological Processes*, *24*, 2257–2268.

Larsen, L. G., Choi, J., Nungesser, M. K., & Harvey, J. W. (2012). Directional connectivity in hydrology and ecology. *Ecological Applications*, *22*(8), 2204–2220.

Laudon, H., Berggren, M., Ågren, A., Buffam, I., Bishop, K., Grabs, T., et al. (2011). Patterns and dynamics of dissolved organic carbon (doc) in boreal streams: The role of processes, connectivity, and scaling. *Ecosystems*, *14*(6), 880–893. https://doi.org/10.1007/s10021-011-9452-8

Lehmann, P., Hinz, C., McGrath, G., Tromp-Van, M., & McDonnell, J. J. (2007). Rainfall threshold for hillslope outflow: An emergent property of flow pathway connectivity. *Hydrology and Earth System Sciences*, *11*(2), 1047–1063.

Leibowitz, S. G., & Vining, K. C. (2003). Temporal connectivity in a prairie pothole complex. *Wetlands*, *23*(1), 13–25.

Leibowitz, S. G., Wigington, P. J., Rains, M. C., & Downing, D. M. (2008). Non-navigable streams and adjacent wetlands: Addressing science needs following the Supreme Court's Rapanos decision. *Frontiers in Ecology and the Environment*, *6*(7), 366–373. https://doi.org/10.1890/070068

Léonard, J., & Richard, G. (2004). Estimation of runoff critical shear stress for soil erosion from soil shear strength. *Catena*, *57*(3), 233–249. https://doi.org/10.1016/j.catena.2003.11.007

Lexartza-Artza, I., & Wainwright, J. (2009). Hydrological connectivity: Linking concepts with practical implications. *Catena*, *79*(2), 146–152.

Lexartza-Artza, I., & Wainwright, J. (2011). Making connections: Changing sediment sources and sinks in an upland catchment. *Earth Surface Processes and Landforms*, *36*(8), 1090–1104. https://doi.org/10.1002/esp.2134

Likens, G. E., & Bormann, F. H. (1995). *Biogeochemistry of a forested ecosystem*. New York, NY: Springer.

Maavara, T., Parsons, C. T., Ridenour, C., Stojanovic, S., Dürr, H. H., Powley, H. R., et al. (2015). Global phosphorus retention by river damming. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(51), 201511797. https://doi.org/10.1073/pnas.1511797112

Macdonald, G. K., & Bennett, E. M. (2009). Phosphorus accumulation in Saint Lawrence River watershed soils: A century-long. *Ecosystems*, *12*, 621–635. https://doi.org/10.1007/s10021-009-9246-4

Macrae, M. L., English, M. C., Schiff, S. L., & Stone, M. (2007). Capturing temporal variability for estimates of annual hydrochemical export from a first-order agricultural catchment in Southern Ontario, Canada. *Hydrological Processes*, *21*(13), 1651–1663. https://doi.org/10.1002/hyp.6361

Macrae, M. L., English, M. C., Schiff, S. L., & Stone, M. A. (2003). Phosphate retention in an agricultural stream using experimental additions of phosphate. *Hydrological Processes*, *17*(18), 3649–3663. https://doi.org/10.1002/hyp.1356

Macrae, M. L., Zhang, Z., Stone, M., Price, J. S., Bourbonniere, R. A., & Leach, M. (2011). Subsurface mobilization of phosphorus in an agricultural riparian zone in response to flooding from an upstream reservoir. *Canadian Water Resources Journal*, *36*(4), 293–311. https://doi.org/10.4296/cwrj3604810

McClain, M. E., Boyer, E. W., Dent, C. L., Gergel, S. E., Grimm, N. B., Groffman, P. M., et al. (2003). Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems*, *6*(4), 301–312.

McDonnell, J. J. (2013). Are all runoff processes the same? *Hydrological Processes*, *27*(26), 4103–4111. https://doi.org/10.1002/hyp.10076

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

McDonnell, J. J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., et al. (2007). Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resources Research*, *43*, W07301. https://doi.org/10.1029/2006WR005467

McDonnell, J. J., & Woods, R. A. (2004). On the need for catchment classification. *Journal of Hydrology*, *299*, 2–3.

McDowell, R. W., Sharpley, A. N., & Kleinman, P. J A. (2002). Integrating phosphorus and nitrogen decision management at watershed scales. *Journal of the American Water Resources Association*, *38*(2), 479–491. https://doi.org/10.1111/j.1752-1688.2002.tb04331.x

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

McGrath, G. S., Hinz, C., & Sivapalan, M. (2007). Temporal dynamics of hydrological threshold events. *Hydrology and Earth System Sciences*, *11*(2), 923–938.

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

McNamara, J. P., Tetzlaff, D., Bishop, K., Soulsby, C., Seyfried, M., Peters, N. E., et al. (2011). Storage as a metric of catchment comparison. *Hydrological Processes*, *25*(21), 3364–3371. https://doi.org/10.1002/hyp.8113

McRae, B. H., Dickson, B. G., Keitt, T. H., & Shah, V. B. (2008). Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology*, *89*(10), 2712–2724. https://doi.org/10.1890/07-1861.1

Michaelides, K., & Wainwright, J. (2002). Modelling the effects of hillslope-channel coupling on catchment hydrological response. *Earth Surface Processes and Landforms*, *27*(13), 1441–1457.

Mirus, B. B., & Loague, K. (2013). How runoff begins (and ends): Characterizing hydrologic response at the catchment scale. *Water Resources Research*, *49*, 2987–3006. https://doi.org/10.1002/wrcr.20218

Mitchell, C. P. J., Branfireun, B. A., & Kolka, R. K. (2008). Spatial characteristics of net methylmercury production hot spots in peatlands. *Environmental Science & Technology*, *42*(4), 1010–1016. https://doi.org/10.1021/es0704986

Mitchell, C. P. J., Branfireun, B. A., & Kolka, R. K. (2009). Methylmercury dynamics at the upland-peatland interface: Topographic and hydrogeochemical controls. *Water Resources Research*, *45*, W02406. https://doi.org/10.1029/2008WR006832

Mosley, M. P. (1979). Streamflow generation in a forested watershed. *Water Resources Research*, *15*(4), 795–806.

Munthe, J., Lyven, B., Parkman, H., Lee, Y.-H., Iverfeldt, Å., Haraldsson, C., et al. (2001). Mobility and methylation of mercury in forest soils—Development of an in-situ stable isotope tracer technique and initial results. *Water, Air, & Soil Pollution: Focus*, *1*, 385–393.

Ocampo, C. J., Sivapalan, M., & Oldham, C. (2006). Hydrological connectivity of upland-riparian zones in agricultural catchments: Implications for runoff generation and nitrate transport. *Journal of Hydrology*, *331*(3–4), 643–658. https://doi.org/10.1016/j.jhydrol.2006.06.010

Okin, G. S., Moreno-de las Heras, M., Saco, P. M., Throop, H. L., Vivoni, E. R., Parsons, A. J., et al. (2015). Connectivity in dryland landscapes: Shifting concepts of spatial interactions. *Frontiers in Ecology and the Environment*, *13*(1), 20–27. https://doi.org/10.1890/140163

Oldham, C. E., Farrow, D. E., & Peiffer, S. (2013). A generalized damköhler number for classifying material processing in hydrological systems. *Hydrology and Earth System Sciences*, *17*(3), 1133–1148. https://doi.org/10.5194/hess-17-1133-2013

Oswald, C. J., & Branfireun, B. A. (2014). Antecedent moisture conditions control mercury and dissolved organic carbon concentration dynamics in a boreal headwater catchment. *Water Resources Research*, *50*, 6610–6627. https://doi.org/10.1002/2013WR014736

Oswald, C. J., Heyes, A., & Branfireun, B. A. (2014). Fate and transport of ambient mercury and applied mercury isotope in terrestrial upland soils: Insights from the metaalicus watershed. *Environmental Science & Technology*, *48*(2), 1023–1031. https://doi.org/10.1021/es404260f

Oswald, C. J., Richardson, M. C., & Branfireun, B. A. (2011). Water storage dynamics and runoff response of a boreal shield headwater catchment. *Hydrological Processes*, *25*(19), 3042–3060. https://doi.org/10.1002/hyp.8036

Overton, D. E., & Meadows, M. E. (1976). *Storm water modelling*. New York, NY: Academic Press.

Penna, D., Tromp-van Meerveld, H. J., Gobbi, A., Borga, M., & Dalla Fontana, G. (2011). The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences*, *15*(3), 689–702. https://doi.org/10.5194/hess-15-689-2011

Phillips, J. D. (1992). The end of equilibrium? *Geomorphology*, *5*(3), 195–201.

Phillips, J. D. (2003). Sources of nonlinearity and complexity in geomorphic systems. *Progress in Physical Geography*, *27*(1), 1–23.

Phillips, R. W., Spence, C., & Pomeroy, J. W. (2011). Connectivity and runoff dynamics in heterogeneous basins. *Hydrological Processes*, *25*(19), 3061–3075. https://doi.org/10.1002/hyp.8123

Pinto, N., & Keitt, T. H. (2009). Beyond the least-cost path: Evaluating corridor redundancy using a graph-theoretic approach. *Landscape Ecology*, *24*(2), 253–266. https://doi.org/10.1007/s10980-008-9303-y

Pionke, H. B., Gburek, W. J., & Sharpley, A. N. (2000). Critical source area controls on water quality in an agricultural watershed located in the chesapeake basin. *Ecological Engineering*, *14*(4), 325–335. https://doi.org/10.1016/S0925-8574(99)00059-2

Pionke, H. B., Gburek, W. J., Sharpley, A. N., & Schnabel, R. R. (1996). *Flow and nutrient export patterns for an agricultural hill-land watershed*. Paper presented at Clean Water, Clean Environment, 21st Century: Team Agriculture, Working to Protect Water Resources: Conference Proceedings, Kansas City, MO, March 5–8, 1995.

Pringle, C. (2003a). The need for a more predictive understanding of hydrologic connectivity. *Aquatic Conservation-Marine and Freshwater Ecosystems*, *13*(6), 467–471.

Pringle, C. (2003b). What is hydrologic connectivity and why is it ecologically important? *Hydrological Processes*, *17*(13), 2685–2689.

Pringle, C. M. (2001). Hydrologic connectivity and the management of biological reserves: A global perspective. *Ecological Applications*, *11*(4), 981–998.

Quinton, W. L., Hayashi, M., & Pietroniro, A. (2003). Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydrological Processes*, *17*(18), 3665–3684. https://doi.org/10.1002/hyp.1369

Rains, M. C., Leibowitz, S. G., Cohen, M. J., Creed, I. F., Golden, H. E., Jawitz, J. W., et al. (2016). Geographically isolated wetlands are part of the hydrological landscape. *Hydrological Processes*, *30*(1), 153–160. https://doi.org/10.1002/hyp.10610

Reaney, S. M., Bracken, L. J., & Kirkby, M. J. (2007). Use of the Connectivity of Runoff Model (CRUM) to investigate the influence of storm characteristics on runoff generation and connectivity in semi-arid areas. *Hydrological Processes*, *21*, 894–906.

Reddy, K. R., Kadlec, R. H., Flaig, E., & Gale, P. M. (1999). Phosphorus retention in streams and wetlands: A review. *Critical Reviews in Environmental Science and Technology*, *29*(1), 83–146. https://doi.org/10.1080/10643389991259182

Renard, K. G., Yoder, D. C., Lightle, D. T., & Dabney, S. M. (2011). Universal soil loss equation and revised universal soil loss equation. In *Handbook of erosion modelling* (pp. 135–167). Chichester, UK: John Wiley.

Renard, P., & Allard, D. (2013). Connectivity metrics for subsurface flow and transport. *Advances in Water Resources*, *51*, 168–196.

Richardson, M. C., Fortin, M., & Branfireun, B. A. (2009). Hydrogeomorphic edge detection and delineation of landscape functional units from lidar digital elevation models. *Water Resources Research*, *45*, 1–18. https://doi.org/10.1029/2008WR007518

Sawyer, S. C., Epps, C. W., & Brashares, J. S. (2011). Placing linkages among fragmented habitats: Do least-cost models reflect how animals use landscapes? *Journal of Applied Ecology*, *48*(3), 668–678. https://doi.org/10.1111/j.1365-2664.2011.01970.x

Scavia, D., Kalcic, M., Muenich, R. L., Read, J., Aloysius, N., Bertani, I., et al. (2017). Multiple models guide strategies for agricultural nutrient reductions. *Frontiers in Ecology and the Environment*, *15*(3), 126–132. https://doi.org/10.1002/fee.1472

Schapp, M. G., Leij, F. J., & van Genuchten, M. T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology*, *251*, 163–176.

Smith, T., Marshall, L., McGlynn, B., & Jencso, K. (2013). Using field data to inform and evaluate a new model of catchment hydrologic connectivity. *Water Resources Research*, *49*, 6834–6846. https://doi.org/10.1002/wrcr.20546

Sommer, M. (2006). Influence of soil pattern on matter transport in and from terrestrial biogeosystems—A new concept for landscape pedology. *Geoderma*, *133*(1–2), 107–123. https://doi.org/10.1016/j.geoderma.2006.03.040

Spence, C. (2006). Hydrological processes and streamflow in a lake dominated watercourse. *Hydrological Processes*, *20*(17), 3665–3681. https://doi.org/10.1002/hyp.6381

Spence, C. (2007). On the relation between dynamic storage and runoff: A discussion on thresholds, efficiency, and function. *Water Resources Research*, *43*, W12416. https://doi.org/10.1029/2006WR005645

Stewart, R. D., Abou Najm, M. R., Rupp, D. E., Lane, J. W., Uribe, H. C., Arumi, J. L., et al. (2015). Hillslope run-off thresholds with shrink-swell clay soils. *Hydrological Processes*, *29*(4), 557–571. https://doi.org/10.1002/hyp.10165

Stieglitz, M., Shaman, J., McNamara, J., Engel, V., Shanley, J., & Kling, G. W. (2003). An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport. *Global Biogeochemical Cycles*, *17*(4), 1105. https://doi.org/10.1029/2003GB002041

Stone, M., & Mudroch, A. (1989). The effect of particle size, chemistry and mineralogy of river sediments on phosphate adsorption. *Environmental Technology Letters*, *10*(5), 501–510. https://doi.org/10.1080/09593338909384766

Tang, R., Li, Z.-L., & Sun, X. (2013). Temporal upscaling of instantaneous evapotranspiration: An intercomparison of four methods using eddy covariance measurements and modis data. *Remote Sensing of Environment*, *138*, 102–118.

Tani, M. (1997). Runoff generation processes estimated from hydrological observations on a steep forested hillslope with a thin soil layer. *Journal of Hydrology*, *200*(1–4), 84–109.

Tetzlaff, D., Birkel, C., Dick, J., Geris, J., & Soulsby, C. (2014). Storage dynamics in hydropedological units control hillslope connectivity, runoff generation, and the evolution of catchment transit time distributions. *Water Resources Research*, *50*, 969–985. https://doi.org/10.1002/2013WR014147

Tetzlaff, D., Soulsby, C., Bacon, P. J., Youngson, A. F., Gibbins, C., & Malcolm, I. A. (2007). Connectivity between landscapes and river-scapes—A unifying theme in integrating hydrology and ecology in catchment science? *Hydrological Processes*, *21*(10), 1385–1389.

Thompson, S. E., Basu, N. B., Lascurain, J., Jr., Aubeneau, A., & Rao, P. S. C. (2011). Relative dominance of hydrologic versus biogeochemical factors on solute export across impact gradients. *Water Resources Research*, *47*, W00J05. https://doi.org/10.1029/2010WR009605

Tromp-van Meerveld, H. J., & McDonnell, J. J. (2006a). Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope. *Water Resources Research*, *42*, W02410. https://doi.org/10.1029/2004WR003778

Tromp-van Meerveld, H. J., & McDonnell, J. J. (2006b). Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research*, *42*, W02411. https://doi.org/10.1029/2004WR003800

Turnbull, L., Wainwright, J., & Brazier, R. E. (2008). A conceptual framework for understanding semi-arid land degradation: Ecohydrological interactions across multiple-space and time scales. *Ecohydrology*, *1*(1), 23–34. https://doi.org/10.1002/eco.4

Uchida, T., Tromp-van Meerveld, I., & McDonnell, J. J. (2005). The role of lateral pipe flow in hillslope runoff response: An intercomparison of non-linear hillslope response. *Journal of Hydrology*, *311*, 117–133.

Urban, D., & Keitt, T. (2001). Landscape connectivity: A graph-theoretic perspective. *Ecology*, *82*(5), 1205–1218.

U.S. Army Corps of Engineers, Department of the Army, Department of Defense, & Environmental Protection Agency. (2015). *Definition of "waters of the united states"* (final rule 80 CFR).

U.S. EPA. (2001). *Method 1631, revision c: Mercury in water by oxidation, purge and trap, and cold vapor atomic fluorescence spectrometry*. Paper presented at the Environmental Protection.

Van Meter, K. J., & Basu, N. B. (2015). Catchment legacies and time lags: A parsimonious watershed model to predict the effects of legacy storage on nitrogen export. *PLoS ONE*, *10*(5), 22. https://doi.org/10.1371/journal.pone.0125971

Vidon, P. G. F., & Hill, A. R. (2004). Landscape controls on the hydrology of stream riparian zones. *Journal of Hydrology*, *292*(1–4), 210–228.

Wainwright, J., Turnbull, L., Ibrahim, T. G., Lexartza-Artza, I., Thornton, S. F., & Brazier, R. E. (2011). Linking environmental regimes, space and time: Interpretations of structural and functional connectivity. *Geomorphology*, *126*(3–4), 387–404. https://doi.org/10.1016/j.geomorph.2010.07.027

Walling, D. E. (1999). Linking land use, erosion and sediment yields in river basins. *Hydrobiologia*, *410*, 223–240. https://doi.org/10.1023/a:1003825813091

Walling, D. E., & Webb, B. W. (1996). Erosion and sediment yield: A global overview. In D. E. Walling & B. W. Webb (Eds.), *Erosion and sediment yield: Global and regional perspectives* (pp. 3–19). Exeter, UK: Department of Geography, University of Exeter.

Walter, M. T., Walter, M. F., Brooks, E. S., Steenhuis, T. S., Boll, J., & Weiler, K. (2000). Hydrologically sensitive areas: Variable source area hydrology implications for water quality risk assessment. *Journal of Soil and Water Conservation*, *55*(3), 277–284.

Wang, Y., Zhang, X., & Huang, C. (2009b). Spatial variability of soil total nitrogen and soil total phosphorus under different land uses in a small watershed on the Loess Plateau, China. *Geoderma*, *150*(1–2), 141–149. https://doi.org/10.1016/j.geoderma.2009.01.021

Wang, Y., Zhang, X.-C., Zhang, J.-L., & Li, S.-J. (2009a). Spatial variability of soil organic carbon in a watershed on the loess plateau. *Pedosphere*, *19*(4), 486–495. https://doi.org/10.1016/S1002-0160(09)60141-7

Wang, Y. T., Zhang, T. Q., O'Halloran, I. P., Tan, C. S., & Hu, Q. (2016). A phosphorus sorption index and its use to estimate leaching of dissolved phosphorus from agricultural soils in ontario. *Geoderma*, *274*, 79–87. https://doi.org/10.1016/j.geoderma.2016.04.002

Watt, E. W. (1989). *Hydrology of floods in Canada—A guide to planning and design*. Ottawa, ON, Canada: National Research Council Canada.

Weiler, M., & McDonnell, J. (2004). Virtual experiments: A new approach for improving process conceptualization in hillslope hydrology. *Journal of Hydrology*, *285*(1–4), 3–18.

Weiler, M., McDonnell, J., Tromp-Van, M., & Uchida, T. (2005). Subsurface stormflow. In M. G. Anderson (Ed.), *Encyclopedia of hydrological sciences* (pp. 1719–1732). Chichester, UK: John Wiley.

Weiler, M., & McDonnell, J. R. J. (2006). Testing nutrient flushing hypotheses at the hillslope scale: A virtual experiment approach. *Journal of Hydrology*, *319*(1–4), 339–356. https://doi.org/10.1016/j.jhydrol.2005.06.040

Wellen, C., Arhonditsis, G. B., Long, T., & Boyd, D. (2014). Accommodating environmental thresholds and extreme events in hydrological models: A bayesian approach. *Journal of Great Lakes Research*, *40*(S3), 102–116. https://doi.org/10.1016/j.jglr.2014.04.002

Western, A. W., Blöschl, G., & Grayson, R. B. (1998). How well do indicator variograms capture the spatial connectivity of soil moisture? *Hydrological Processes*, *12*(12), 1851–1868.

Western, A. W., Blöschl, G., & Grayson, R. B. (2001). Toward capturing hydrologically significant connectivity in spatial patterns. *Water Resources Research*, *37*(1), 83–97.

Whipkey, R. Z. (1965). Subsurface stormflow from forested slopes. *Bulletin of the International Association of Scientific Hydrology*, *10*, 74–85.

Wolman, M. G., & Miller, J. P. (1960). Magnitude and frequency of forces in geomorphic processes. *The Journal of Geology*, *68*(1), 54–74.

Yin, Y., Allen, H. E., Huang, C. P., & Sanders, P. F. (1997). Kinetics of mercury(II) adsorption and desorption on soil. *Environmental Science & Technology*, *31*, 496–503.

Zehe, E., Elsenbeer, H., Lindenmaier, F., Schulz, K., & Blöschl, G. (2007). Patterns of predictability in hydrological threshold systems. *Water Resources Research*, *43*, W07434. https://doi.org/10.1029/2006WR005589

Zeller, K. A., McGarigal, K., & Whiteley, A. R. (2012). Estimating landscape resistance to movement: A review. *Landscape Ecology*, *27*(6), 777–797. https://doi.org/10.1007/s10980-012-9737-0