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Abstract

Hydrologic connectivity is the linkage of separate regions of a catchment via water flow. Knowledge of hillslope-stream connectivity (both at the surface and in the subsurface) is essential for understanding and predicting runoff responses and streamwater quality. Connectivity can be very dynamic: hillslopes may connect to the stream only during certain events or seasons. While surface connectivity is often discussed, particularly in the context of sediment transport, subsurface connectivity is more difficult to describe and assess. This difficulty has led to a wide variety in methodologies that are used in various contexts. This overview focuses on how hillslope-stream connectivity has been studied and describes the advantages, disadvantages and challenges of the different methods. Field approaches have focused on intensive monitoring of processes on the hillslope or the fingerprint of connectivity in the stream. Combining experimental studies with modelling allows for testing of hypotheses with respect to thresholds and controls on connectivity and extrapolation from the hillslope scale to the catchment scale. However, as most modelling approaches are based on datasets from a few intensively studied hillslopes, this carries the inherent risk of oversimplification because it assumes that the observed hillslope responses are representative for the catchment or even the region. Focussed efforts on catchment scale assessment of hillslope-stream connectivity, as well as site inter-comparisons and the search for similarity measures may allow us to capture the wider picture of the mechanisms and factors that control hillslope-stream connectivity, and its effects on flow and transport at the catchment scale

Introduction

Hydrologic connectivity is the linkage of separate regions of a catchment via water flow (see sidebar 1) and may be achieved through surface flow (overland flow) or subsurface flow. Subsurface hillslope-stream connectivity occurs when hillslopes become hydrologically connected to the stream by (saturated) subsurface flow. This connectivity can be widespread (diffuse)¹⁻³, concentrated along channels in the bedrock topography^{1,4} or concentrated in preferential flow pathways⁵⁻⁸ (Figure 1). Some hillslopes are connected to the stream for several months per year⁹, while others may be connected for only several hours or days¹⁰⁻¹¹ or only under extreme conditions, although deeper groundwater flow pathways from the hillslope may contribute to streamflow throughout the year. Only a fraction of the hillslope may be connected to the stream during rainfall or snowmelt events, while other parts (e.g. ridge sites) may remain disconnected. The connected area (where flow occurs that is connected to the stream) is generally smaller than the active area (all the locations where flow occurs)¹².

In many areas in temperate climates, subsurface stormflow is the main runoff generation mechanism on hillslopes¹³. Subsurface stormflow generally results from the development of saturation above a less permeable layer (e.g., the soil-bedrock interface, a fragipan or a capillary barrier) and subsequent lateral transport of water through this saturated layer. Subsurface flow can also occur when groundwater levels rise into more permeable layers and water flows laterally through the more permeable layers to the stream (e.g. transmissivity feedback). This onset of lateral subsurface flow from the hillslope to the stream results in hydrological connectivity of the hillslope to the stream. However, quick rises in near-stream groundwater levels and flow reversals in the riparian zone due to riverbank infiltration may lead to a temporary disconnection of the hillslopes from the stream and an accumulation of hillslope water in the riparian zone during events¹⁴⁻¹⁶.

The establishment and the extent of subsurface connectivity are controlled by physical structures on the one hand (e.g. soil type, layering, and preferential flowpath networks), and catchment state (antecedent wetness conditions) and driving forces (rainfall and snowmelt) on the other hand. Soil and bedrock permeability, surface and subsurface topography, depth to bedrock and vegetation also influence hillslope-stream connectivity¹⁷⁻²⁴. Tile drains in agricultural areas and other anthropogenic features can further enhance connectivity. The relative size of the hillslope and riparian zone may also influence connectivity of hillslopes to the streams, with large rivers with wide floodplains generally being less connected to the local hillslopes than smaller headwater streams²⁵⁻²⁷.

The onset of functional hillslope-stream connectivity²⁸ (see sidebar 1) leads to the addition of hillslope water to the stream and can thus result in large increases in streamflow and a threshold runoff response²⁹⁻³³. Because hillslope soil- and groundwater can have a different biogeochemical signature than riparian soil- and groundwater, hillslope-stream connectivity may also lead to marked changes in stream chemistry and water quality^{9, 34-40} and stream temperature⁴¹. Knowledge of subsurface hillslope-stream connectivity is thus essential for understanding and predicting runoff responses (including floods) and streamwater quality. We therefore need to understand how and when hillslopes become hydrologically connected to the stream and what controls this connectivity. However, due to its occurrence in the subsurface, determining hillslope-stream connectivity is a challenging task as it cannot be observed directly. Different methods have been used in different contexts to determine subsurface hillslope-stream connectivity, e.g., trenches⁴²⁻⁴⁵, spatially

distributed groundwater^{10, 23, 46-47} or soil moisture measurements⁴⁸⁻⁵⁰, plot scale runoff and tracer experiments, time lapse images of the subsurface⁵¹⁻⁵², as well as streamflow and stream chemistry measurements^{39, 53-54}. Most studies have used a multi-method approach (e.g. measured flow in trenches in combination with groundwater level measurements and streamflow measurements) as this strengthens the interpretation of the individual measurements^{24, 55-57}. This overview focuses on how subsurface hillslope-stream connectivity has been studied and describes the advantages, disadvantages and challenges of the different methods (Table 1). We distinguish between methods that are hillslope centred and those that are stream centred (Figure 2) and include an overview of the methodologies used to extrapolate the results from individual research hillslopes to the catchment scale.

HILLSLOPE CENTERED EXPERIMENTAL APPROACHES

Hillslope-stream connectivity can be investigated by studying how, when and where water moves through a hillslope. This can be done by measuring the amount of subsurface flow in trenches or directly or indirectly measuring shallow groundwater levels or moisture content across a hillslope. The distributed groundwater and soil moisture approach assumes that saturation is an indication of subsurface flow and hillslopes are connected to the stream if saturated areas connect to the stream. Applying tracers to the hillslope and measuring the resulting concentrations in trenches, road cuts or the stream also sheds light on the connectedness of flow pathways and gives additional information about transport velocities. Dyes can be used to trace the actual flow pathways.

Trenched hillslope studies

Hillslope trenches (Figure 3a) are excavated perpendicular to the slope^{18, 42, 58}, installed in gullies, the streambank and other natural seepage faces^{32, 59} or at road cuts^{44, 60}. They extend over several (5-60) meters and if possible down to the bedrock or another low permeability layer. Trenches allow for direct measurement of the amount of subsurface flow and thus provide information on when hillslopes contribute significantly to streamflow. They also allow for measurements of flow from individual soil pipes and other preferential flow pathways^{1, 3, 18, 61-63} (Figure 3a) and thus for the quantification of both diffuse and concentrated subsurface flow. If troughs are installed at different depths, determination of the dominant depth of subsurface flow is also possible⁶⁴⁻⁶⁶. Similarly, measurements from individual trench sections provide information about the spatial variability of subsurface flow^{1, 43} (Figure 3a-b). Trenches can also be used for sampling subsurface flow and thus to study hillslope nutrient fluxes⁶⁷⁻⁶⁸. Hillslope trench studies have shown *i*) that the subsurface flow volume depends on rainfall or snowmelt amount and antecedent wetness conditions^{3, 59, 69-72}; *ii*) that the amount of subsurface flow varies spatially and is dependent on topography^{1, 20, 45}, but also that the locations of the dominant flow sections change with storm size or the amount of flow^{3, 24, 42-44, 73}; *iii*) that subsurface flow peaked before or at the same time as streamflow^{65-67, 73-74}, after streamflow⁷⁵, or that the timing is dependent on antecedent wetness conditions^{10, 76}; *iv*) the importance of macropore flow^{3, 58, 60-62, 77}; and *v*) the importance of flow through the underlying bedrock^{63, 78} or fragipan^{72, 79-80}.

However, installation and maintenance of trenches is time consuming. Trenches have to be deep enough to capture the subsurface flow and wide enough to capture the spatially varying flow pathways. Many of the trenches used in previous studies may have been too small to adequately

capture the spatial variability in subsurface flow. Furthermore, the artificial boundary causes trenches to capture more water during wet conditions and less water during dry conditions than would have occurred without the presence of the trench⁸¹. Finally, measurements at trenches are only representative of the study site and extrapolation of these observations to the catchment scale is difficult and prone to errors. The few times that multiple trenched hillslopes were studied, the results have shown that there is a large variability in subsurface flow responses between sites⁸²⁻⁸⁵. Therefore, more studies with comparable trenches are needed to study the variability in subsurface flow responses, as well as comparisons between existing datasets from trench sites to look for commonalities and differences in the observed subsurface flow responses (e.g. ⁸⁶).

Distributed groundwater level measurements

Measurements of shallow groundwater responses to determine hillslope-stream connectivity assume that a hydrologic connection is established when there is a connected watertable between the stream and the hillslope². Simultaneous measurements of groundwater responses and the presence of subsurface saturation across hillslopes provide crucial information about the timing of the onset of (transient) saturation (and assumingly subsurface flow), as well as the expansion of saturated areas and thus diffuse connectivity during events (Figure 4). Measurements of water quality in the wells, e.g. Electrical Conductivity (EC) or temperature, can provide additional information about hillslope connectivity⁸⁷ or preferential flow⁸⁸. Previous studies using a large number of wells or piezometers (Figure 3c) have shown that groundwater responses to rainfall can vary significantly across a hillslope or catchment^{17, 44, 89-92} and gave insight into how saturated areas connect across a hillslope and how this is influenced by the surface topography, the topography of the lower conductivity layer or spatial variability in soil depth^{11, 46, 90, 93}. They have also shown that saturated areas expand from the stream up the hillslope^{46, 94} or from shallow soil areas downward^{11, 95-96}. Furthermore, it was found that spatial variability in annual water table connectivity of different hillslope transects was related to the upslope accumulated area²³ or that the percent of time that wells contained water was related to slope position (e.g. Topographic Wetness Index (TWI) or upslope distance)^{10, 46, 91}.

The representativeness of groundwater level measurements depends on whether or not they can capture the spatially variable flow pathways²⁴. Because the occurrence of saturated areas can be very heterogeneous and patchy (two wells located only a few meters from each other can show very different responses^{11, 24}), interpolation between measurements at individual wells is difficult and measurements in many wells or piezometers across the hillslope are required (i.e., single transects extending from the stream to the hillslope might not be sufficient). Groundwater level measurements cannot provide information about channelled hydrologic connectivity through macropore networks, although hydraulically limited water tables (i.e. water tables that do not rise above a certain level)^{17, 47} may indicate preferential flow (or fast flow through a high conductivity layer). Wells also need to be installed deep enough, as otherwise the occurrence of saturation may be missed. While new techniques allow for installation of wells in bedrock⁹⁷, installation of wells and piezometers in rocky soils remains challenging because “hitting rock” does not necessarily mean bedrock.

Tracer experiments

Applied tracer tests are frequently used in groundwater studies or to study transport through the vadose zone. Tracer experiments have also been carried out at the large plot to hillslope scale to study subsurface flow processes, to quantify transport parameters or to determine hillslope properties (e.g. hydraulic conductivity). Most hillslope tracer experiments have used salts (such as NaCl or LiBr), fluorescent dyes (e.g. uranine, rhodamine) or labelled water (e.g. water with a high tritium concentration or a specific isotopic signature). Other tracers, such as microbial tracers⁹⁸ and DNA tracers⁹⁹⁻¹⁰⁰, are being developed and tested and provide new opportunities for multi-tracer experiments. In general, the tracer is applied to the surface of the soil or just below the litter layer as a line source (e.g.⁶²), a point source (e.g. small plots, soil pits^{4,101} or in piezometers⁶⁰) or sprayed over the entire surface of the hillslope as artificial rainfall¹⁰²⁻¹⁰³, and the breakthrough is measured in a trench, road cut, tile drains or the stream. The recovery of an artificial tracer applied to the hillslope in the stream (or at a trench at the bottom of the hillslope) is a clear indication of hillslope-stream connectivity. Tracer experiments are especially useful to determine the travel time (velocity) of water relative to the timing of runoff generation (celerity)^{102,104} (for a description of the difference between velocity and celerity, see McDonnell and Beven (2014)¹⁰⁵). When tracer test data are combined with modelling, they can provide particularly useful information on subsurface flow pathways and transit times. The use of tracer data in models is also useful for narrowing parameter ranges and reducing equifinality¹⁰⁶⁻¹⁰⁷.

Most hillslope scale tracer studies have shown a very fast breakthrough of the tracer due to flow in preferential flow pathways^{4,32,60,101,108-113}. However, other studies found relatively slow tracer breakthrough⁵⁷. Tracer experiments have also revealed that once hillslope-stream connectivity is established, hillslope sections at significant distances upslope can contribute to streamflow³². Measurements of tracer breakthrough in different trench sections have highlighted the spatial variability in flow pathways along the confining layer¹¹⁴. When flow from individual macropores is collected, then the tracer breakthrough in macropore flow can be compared to the tracer breakthrough in matrix flow. During tests under very wet conditions, tracer concentrations in macropore flow were lower than in matrix flow, which suggests dilution by upslope drainage⁶². These fast responses and sometimes high tracer concentrations do not contradict the observation that subsurface flow consists predominantly of pre-event water¹¹⁴. Tracer experiments have also been very useful to determine the importance of flow through the bedrock^{78,102}, although at other sites flow occurred mainly in the top soil layers^{110,115}.

While tracer experiments provide critical information about hillslope pathways and subsurface flow velocities, they require a big logistical effort and analysis of a large number of samples is expensive. This situation might change with more and higher resolution data becoming available⁹³ and the possibility of in-situ measurements (e.g. using ion selective probes)¹⁰⁵. Tracers tend to be applied on relatively small hillslope sections and thus only provide information about this location. This can be overcome by applying tracers over larger areas¹⁰²⁻¹⁰³ or at multiple locations in the catchment¹¹⁶⁻¹¹⁷. The outcome of tracer experiments also depends on the sequence of events after tracer application, which can be partly overcome by applying different tracers at different times^{112,117}.

Large scale sprinkling experiments, with or without artificial tracers, are very useful for studying hydrological flow pathways because in these controlled experiments water can be applied to the soil surface at a uniform rate for a specified time. Large scale sprinkling experiments have been particularly useful for determining the relative importance of flow through shallow soil and deeper

bedrock^{78, 102, 118-119}. Significant leakage through bedrock will delay the onset of connectivity between the hillslope and the stream during events but provides connectivity at a longer time scale.

In addition to applied tracers, natural tracers (e.g. calcium, silica, chloride, sulphate, radon or stable water isotopes) can also be used to determine hillslope contributions to streamflow (see section on stream centred approaches).

Dye staining and excavation

Hillslope scale dye staining experiments provide valuable information about how individual flow pathways are connected to each other and thus how hillslopes may connect to the stream. Dye staining experiments generally involve the application of a dye or paint to the soil surface, just below the organic horizon or in a trench, and subsequent excavation. During excavation, description and photographing of the soil and dye stains allows the direct visualization and analysis of the flow pathways. Dye staining experiments are common for plot scale measurements¹²⁰⁻¹²². Only a few studies have extended plot scale dye staining experiments to the hillslope scale because the method is time consuming and destructive. These hillslope scale dye staining experiments have shown that water flows through connected preferential flow pathways with relatively little interaction with the surrounding matrix²¹. The connected flow pathways consisted of root channels or other cavities, exchange between macropores and mesopores, buried organic material and loose material, small depressions and channels in the bedrock or fractures in the bedrock^{21, 7, 120, 123}. The channels in the bedrock depressions where lateral flow occurs can be very narrow (< 1m)^{4, 123} (Figure 3d). Other studies showed that flow mainly occurred at the organic–mineral soil interface¹²³⁻¹²⁴.

Dye staining experiments do not provide information about how flow pathways change with antecedent wetness conditions or rainfall conditions because the large scale dye staining experiments are usually done under steady state conditions and the destructive nature means that they cannot be repeated at the same location under different conditions. Antecedent wetness conditions and rainfall amount likely control whether or not the nodes that connect the individual macropores are activated¹²³, whereas topography influences the number of hydraulically connected preferential flow pathways²¹. Small scale dye staining experiments have been repeated under different conditions and have shown the effect of antecedent moisture conditions on the interaction between flow in macropores and the matrix¹²⁵ and the influence of hydrophobicity^{87, 126} and shrinkage cracks¹²⁶ on preferential flow, although the effect of antecedent moisture conditions was considered minor for other soils¹²⁷.

Geophysical measurements

Visualizing subsurface flow pathways and subsurface connectivity non-destructively (i.e. having “X-ray vision”) would be a dream come true for many hillslope hydrologists. Near surface geophysics has been considered promising to fulfill this dream: surface measurements allow for imaging of the subsurface, providing information on bedrock topography, soil layering and soil moisture content. However, geophysical methods are indirect measurements and the challenge lies in the translation of the geophysical data into hydrologically relevant information (e.g.¹²⁸⁻¹³⁰).

There have been only a few geophysical studies at the hillslope scale (e.g.^{51, 131-136}). This lack of hillslope-scale studies has been acknowledged in the geophysical community¹³⁷ and becomes

apparent in the fact that lateral subsurface flow is not even mentioned in an extensive review on advancing process-based watershed hydrological research using near-surface geophysics¹³⁸. The few hillslope scale geophysical studies can be grouped into two general approaches: *i*) a joint interpretation of the geophysical characterization of the subsurface with hydrometric data sets, such as soil moisture, groundwater levels or pore pressures^{132-133, 139} and *ii*) imaging of water or solute fluxes based on time-lapse measurements^{51-52, 136, 140-141}. The disadvantage of the first approach is that it relies on auxiliary point scale measurements and that differences in the footprint of the measurements (i.e. the support of the measurements¹⁴²) makes comparison of the measurements difficult. The difficulty of the second approach lies in the geometric mismatch between repeat measurements¹⁴³ and measurement uncertainties obscuring small changes between measurements.

Mapping preferential flow pathways, such as soil pipes with a relatively small diameter is an additional challenge. Possible methodologies to do this include high resolution Electrical Resistivity Tomography (ERT)¹⁴⁴ and Ground Penetrating Radar (GPR; Figure 3e), particularly when combined with a salt tracer¹⁴⁵. However, the ERT method suffers from the fact that many soil pipes occur directly above a high electric resistivity layer (e.g. the bedrock or a restrictive clay soil layer) obscuring the high resistivity anomalies that indicate soil pipes¹⁴⁴. The GPR salt tracer method requires previous mapping of the pipe features to identify locations for the subsurface injection and sampling of the salt tracer. GPR was therefore not used to map pipe networks per se, but to identify connectivity between previously mapped pipe features¹⁴⁵. However, new field measurements and post processing algorithms suggest that with repeat GPR measurements it is possible to reconstruct preferential flow networks at the centimeter scale without a salt tracer¹⁴⁰.

STREAM CENTERED APPROACHES

Hillslope-stream connectivity can also be investigated by focussing on the fingerprints of hillslope water in the stream. Signals of hillslope water can be found in the spatial and temporal variability in the amount of streamflow, stream chemistry and stream temperature. Sampling within the stream can be carried out *i*) at the catchment outlet to obtain an integral signal of streamwater sources, *ii*) in a nested design of sub-catchments for more spatially distributed information or *iii*) along stream reaches for more detailed information on the contribution of individual hillslopes. Flow from individual soil pipes intersecting the streambank can be sampled as well (Figure 5).

Hydrograph separation and source area identification

Streamflow is usually composed of water from several geographic sources, such as groundwater, soil water and surface runoff. Based on stream water chemistry and hydrograph separation or End-Member Mixing Analysis (EMMA)¹⁴⁶⁻¹⁴⁷, it is possible to disentangle these sources and to obtain insight into the relative contributions of the different sources (e.g.^{54, 148-152}). EMMA based hillslope runoff contributions at the Panola Mountain Research Watershed, for example, were similar to subsurface stormflow responses measured at a trench, except for a time lag of a few hours³⁹. However, for a different event with multiple peaks, the EMMA based results suggested hillslope subsurface flow contributions to streamflow occurred already during the first peak, which was not observed at the trench³⁹. This difference may reflect spatial variation in hillslope-stream connectivity in the catchment, with some hillslopes connecting earlier than others.

Comprehensive (and critical) reviews on hydrograph separation were written by Buttle (1994)¹⁵³ and Klaus and McDonnell (2013)¹⁵⁴, the latter especially pointing out the value of 3-component hydrograph separation, and thus accounting for soil water contributions to streamflow. Both reviews also point to the need for additional hydrometric measurements for the interpretation of the analyses. A recent study using many tracers, showed that the major elements that have been used in past hydrograph separation studies are not always the most useful tracers and that minor trace elements provide very valuable information¹⁵⁵. It also highlighted the need for large tracer datasets to avoid false conclusions about hydrological flow pathways¹⁵⁵. EMMA can only identify inflows from specific regions or areas if their chemical signatures are distinctly different. As a result, it is rarely possible to identify contributions from specific hillslopes, although it can be possible to identify water coming from hillslope soil- or groundwater or the riparian zone. This provides information on the temporal dynamics of these contributions and thus, for example, the temporal dynamics of unsaturated zone connectivity to the stream. One of the critical assumptions of the hydrograph separation approach is that end member chemistry remains constant in space and time or that differences can be accounted for^{154, 156} but relatively few studies have thoroughly quantified the spatial and temporal variation in the chemical signature of the end members.

A number of studies have pointed to the scale dependence of hydrograph separation based analyses^{54, 157}. This influences the interpretations if measurements at a catchment outlet are used to determine the contributions from all hillslopes in the catchment. Nested sampling approaches strongly increase the information content of hydrograph separation studies because it makes it possible to study the spatial variability of source contributions to streamflow¹⁵⁸⁻¹⁶². For example, the combination of detailed hydrometric data in a nested setup, Dissolved Organic Carbon (DOC) data, and both "hydrological" (i.e. based on flow measurements at the trenched hillslope) and EMMA-based hydrograph separation allowed identification of the connection/disconnection of different landscape units at the Maimai catchment^{33, 40}. Snapshot sampling along stream reaches (under quasi steady state conditions) can also be used to obtain insight in the spatial patterns of source water contributions¹⁶³⁻¹⁶⁶.

Even though non-conservative tracers, such as DOC or nutrients, are affected by rapid transformations in the riparian zone or wetland areas, they may still provide useful information on source areas. For example, carbon isotopes in DOC were successfully used for source area identification and to study the temporal dynamics of water sources¹⁶⁷. While DOC is non-conservative, it has the advantage that it usually has distinct signatures for different depths in the soil profile and can therefore be particularly helpful to differentiate between water inflows from the riparian zone and hillslope¹⁶⁸. Combining field observations of DOC and residual analysis for chemical mixing models provided useful information on areas that were not well represented in the model or conditions when mixing did not occur¹⁶⁹ and thus provided information on areas that were not connected to the stream network. Other elements, such as base cations and silica, may vary with depth as well and these depth distributions can similarly be used to differentiate source areas¹⁷⁰. Elements that accumulate in the riparian zone or wetland peat, such as uranium and thorium¹⁷¹, can also still provide useful information on source areas and the relative role of hillslopes in streamflow generation.

Radon measurements

Radon concentrations in stream water are a strong indication of groundwater inflows as groundwater is naturally enriched in radon, while it degasses quickly in surface water¹⁷²⁻¹⁷⁴. Locally high radon concentrations in the stream therefore provide information on groundwater inflows. However, they do not allow for the differentiation of deep and shallow groundwater, or hillslope and riparian groundwater when all residence times exceed 20-25 days (which is when maximum radon concentrations are reached by equilibration with the surrounding geologic material). An additional challenge is the quantification of degassing rates within the stream, as these can be spatially variable due to variability in turbulence and stream surface area.

Stream temperature

If temperature gradients between groundwater or soil water and stream water are large, stream and stream sediment temperature patterns can be good indicators of subsurface contributions to streamflow¹⁷⁵⁻¹⁷⁹ and can even allow for quantification of these inflows by fitting the heat transport equation under simplifying assumptions^{177, 180}. In recent years, thermal infrared imagery has been used for qualitative mapping of inflows¹⁸¹⁻¹⁸³. Furthermore, fibre optic temperature sensing (DTS) has become more and more popular, as it allows for high spatial resolution temperature measurements. The fibre optic cable can be installed at the stream sediment interface and can cover several hundred meters in length¹⁸⁴⁻¹⁸⁹. The advantage of this methodology is the high spatial coverage and the ability to produce data with a high spatial and temporal resolution, which is a great improvement compared to snapshot surveys. This high resolution allows for the analysis of the temporal dynamics in temperature patterns and signal strengths during individual rainfall or snowmelt events. However, unless the temperature of hillslope subsurface flow is significantly different from riparian groundwater, the only way to assess the onset of hillslope stream connectivity, as opposed to riparian contributions, would be by interpretation of signal strength dynamics, preferably combined with additional hydrometric or hydrochemical measurements.

Incremental streamflow gauging

Measurements of streamflow along stream reaches can produce spatial information on hillslope and groundwater inflows to the stream. In incremental streamflow gauging, the difference in streamflow at two (or multiple) locations along a stream reach is used to determine the local inflow to the stream between the measurement locations. Incremental streamflow gauging is, therefore, a way to determine where, when, and how much water enters the stream and can thus be used to determine if the hillslopes and riparian zone bracketing the investigated stream reach are connected to the stream^{186, 190-197}. However, relatively few studies have investigated lateral inflows into the stream in detail. Beven (2006)¹⁹⁸ therefore states that “we need more studies of the incremental discharges into stream channels, so that we are encouraged to explore the reasons for the heterogeneity of inputs found”. Differential streamflow gauging has shown that topography controlled the amount of water that hillslopes contributed to the stream and the differences in the onset of hillslope contributions (and thus hillslope-stream connectivity)⁹³ and that bedding planes of the underlying bedrock also affected subsurface flow inputs to the stream¹⁹⁹.

Determining inflows from groundwater and hillslope subsurface flow from incremental streamflow gauging is challenging because the calculated inflows are influenced by the measurement errors at the two gauging sites and because it is difficult to take many streamflow measurements along a stream in a short period of time. As the inflow for a given reach is determined from the difference in

streamflow measured at the upstream and downstream location, conditions should not change significantly between the two measurements. Thus incremental streamflow gauging to determine inflows from hillslope subsurface flow to the stream during events is only possible with continuous measurements at both sites. Furthermore, it is not possible to differentiate between hillslope or groundwater contributions to streamflow without additional measurements on stream chemistry. Finally, incremental streamflow gauging usually only provides information about the net increase or decrease in streamflow between the two measurement locations, which is the sum of inflows and outflows in different parts of the stream reach (i.e. if subsurface flow increases streamflow in one section of the studied stream reach but channel bed infiltration causes similar losses, the difference in streamflow measured at the two gauging sites is zero, which could be interpreted as no contribution from the hillslopes to streamflow). However, if dilution gauging is used, determination of tracer mass losses provides information about streamflow losses and can be thus used to determine the patterns of gross gains and losses along the stream reach^{194, 200-201}.

MODELS AND UPSCALING

Hillslope models and virtual experiments

Even for well studied hillslopes and catchments, it is difficult to determine the main controls on subsurface flow and hillslope-stream connectivity because of our limited ability to observe flow pathways within the soil, the spatial variability in soil properties, temporal variability in antecedent moisture conditions, and because datasets are usually short and do not include extreme events. While essential for understanding hydrological processes, field studies are also necessarily limited to a few study sites and usually do not allow for systematic testing of the factors that control hillslope runoff responses and hillslope-stream connectivity²⁰². Inter-site comparisons^{42, 86} have been shown to provide useful information on commonalities and differences in the factors that control subsurface flow and hillslope-stream connectivity, but remain rare, in part because of the different experimental approaches used to study subsurface flow generation or hillslope-stream connectivity at each site and because of a lack of publicly available data from experimental hillslopes.

Numerical simulations have the advantage of allowing analyses of hydrological responses without requiring a large number of observations. Models can be used to interpret and visualize field data, and study situations that have not been encountered in the field. Virtual experiments are “numerical experiments driven by a collective field intelligence”²⁰³ and are a tool to understand observed phenomena and test hypotheses²⁰⁴. Virtual experiments do not attempt to fully describe or model a particular system or field site but rather allow for the study of the effects of hillslope characteristics, initial conditions and input variables, and particularly the interactions between these factors, on hillslope hydrological responses. Virtual experiments thus allow for generalization of findings from individual study sites.

Hillslope scale hydrologic modelling and virtual experiments have been used to study the effects of soil properties²⁰⁵⁻²⁰⁶, macropore flow²⁰⁷⁻²⁰⁸, the depth distribution of transmissivity and drainable porosity²⁰³, permeability of the bedrock^{202, 205-206, 208-209}, spatial variability in soil depth and bedrock topography^{205, 207-208}, mean soil depth²⁰², surface topography²¹⁰⁻²¹¹, slope angle²⁰², antecedent moisture conditions²¹²⁻²¹³, event size^{202, 209}, rainfall intensity^{210, 214} and spatial variability in (throughfall) inputs²¹⁵⁻²¹⁶ on subsurface flow responses from hillslopes. Hillslope models have also

been used to study how short macropores connect to form preferential flow networks²¹⁷⁻²¹⁸ or pipe networks²¹⁹, the factors and pathways that control nutrient export from hillslopes²⁰⁴, and the effect of spatially variable hillslope properties and flow pathways on slope stability²²⁰. These model studies have also shown which data is most useful for model testing and provide useful information for the design of field experiments. In addition to the simulation models described above, percolation theory has been used to simulate the establishment of connected subsurface flow pathways and observed threshold responses²²¹⁻²²², as well as how connected subsurface flow pathways change when the soil depth distribution or slope of the soil-bedrock interface changes²²³.

Upscaling from individual hillslopes to the catchment scale

While measuring hillslope-stream connectivity is a challenging task, the same is true for moving beyond single hillslopes and estimating connectivity at larger scales. Three major approaches for upscaling exist: *i*) field surveys and mapping, *ii*) the use of topographic metrics and landscape analyses and *iii*) the use of simulation models (Table 2). While the first two approaches usually produce static maps of potential connectivity (structural connectivity, see sidebar 1), the third has the advantage of including the dynamic and thus functional aspect of connectivity.

Mapping connectivity

Mapping and assessment of the dominant hydrological processes, including connectivity, can be achieved by combining a field based decision scheme for the identification of dominant runoff processes (including lateral subsurface flow) with maps of topography, soil type, geology and land use²²⁴⁻²²⁶. Both, the morphological runoff zone framework²²⁷⁻²²⁸ and the delineation of hydrological response units⁵⁵ are based on field mapping and provide some information on connectivity (focusing on surface connectivity in the first case). Pipe networks can, in some cases, be mapped using a combination of field surveys and aerial photos (based on the identification of collapsed roofs)²²⁹⁻²³¹.

Landscape analyses

The wide availability of Digital Elevation Models (DEMs) provides the basis for many landscape analyses based on surface topography. Most of the upscaling efforts using landscape analyses to date, are based on individual hillslopes or (small) experimental catchments (generally < 50 km²). This carries the inherent risk that these sites may not be representative for the overall catchment or the larger scale. Furthermore it is not unlikely that the identified relations are specific to the region or even the particular watershed and cannot easily be transferred to other locations¹⁵⁹. Several topographic indices that have been used to determine the potential for hillslope-stream connectivity are discussed here. The review paper by Ali and Roy (2010)²³² contains additional terrain based connectivity metrics (see also sidebar 2, with a stronger focus on functional connectivity).

The Topographic Wetness Index (TWI)²³³ is a classic topographic metric that contains information on potential connectivity; it can give an indication of the depth to water table²³⁴ and has been used to estimate subsurface discharge²³⁵. While some studies found a clear correlation between TWI and depth to groundwater^{91, 236}, others found a weak correlation between the TWI or upslope accumulated area and the duration of shallow groundwater table occurrence^{10, 46, 237}. As this index is usually based on surface topography, it does not capture concentrated flow at the soil-bedrock interface, which is more related to the bedrock topography^{1, 3, 45}. Connectivity as a result of

concentrated flow in preferential flow networks is also not captured by this index, although the occurrence of preferential flow pathways may be related to topography²¹ and connectivity of preferential flow pathways is dependent on the watertable level²¹⁷.

The relative network index²³⁸ is based on the TWI and shows which cells are more likely to connect with the stream network and which cells act as controls on upslope connectivity by including an effective contributing area. This is done by tracing flow pathways upslope and continuously assigning the lowest encountered topographic index to all cells upslope, until a cell with an even lower index is encountered²³⁹.

Another metric that can be calculated based on a DEM and the average saturated depth is the hillslope Peclet number: the ratio of advective forces vs. diffusion forces, or gravity vs. pressure forces, calculated based on geomorphic properties, such as slope, soil depth, and convergence. The hillslope Peclet number was shown to be closely related to the characteristic response function of hillslope outflow and is thus a possible similarity measure to describe subsurface flow responses from hillslopes²⁴⁰⁻²⁴².

The relation between upslope accumulated area and the annual duration of hillslope-stream connectivity^{2, 243-244} was used to quantify the frequency distribution of connectivity through time and to relate the connectivity duration curve - flow duration curve relationship to topography, land cover and geology. Evapotranspiration (tree height), topographic redistribution (the ratio of flowpath distance and gradient to the creek) and geology explained most of the observed variability in streamflow yield per unit connectivity²⁴³.

The ratio of riparian area over hillslope area (or upslope accumulated area) for a given stream reach or stream cell can be a good indicator of the buffering capacity of the riparian zone, and thus how closely streams are connected to their local hillslope²⁷. Mapping of riparian zones can be based on field observations²⁷, remote sensing, the analysis of the DEM and morphometric rules, such as calculating the elevation above the stream along a given flowpath and specifying a threshold²⁴⁵, or by a linear regression between upslope accumulating area and riparian zone width²⁷. A further improvement of this methodology allowed for a differentiation of stream sides instead of lumping both riparian zones and hillslope areas together²³⁶.

Catchment scale models

While hillslope scale modelling studies provide useful information about the factors that control hillslope subsurface flow generation, catchment scale models can be used to extrapolate process understanding to the larger scale and to investigate scaling effects. However, implementing connectivity and its threshold dominated response into catchment scale models is not a simple task.

One example is the extension of TOPMODEL to permit discharge from areas near saturation and an implicit representation of depth to bedrock to investigate the dynamics of catchment-wide hillslope-stream connectivity³⁵. These simulations showed that ridge to valley connectivity only occurred during rare events, coinciding with high antecedent wetness conditions. The Vertical Equilibrium Model (VEM²⁴⁶), on the other hand, uses a high level of spatial aggregation and estimates lateral flow based on storage dynamics, assuming that lateral flow occurs only in the saturated zone²⁴⁷. It was used to investigate lateral flow and connectivity in the context of the transmissivity feedback

mechanism. Focussing on the source areas of diffuse pollution from agricultural areas, the TOPMANAGE model was also used to simulate hillslope-stream connectivity²⁴⁸. This model distinguishes between surface and subsurface lateral flow and includes the effect of drains.

The Catchment Connectivity Model (CCM)²⁴⁹ was developed based on a detailed analysis of hillslope-stream connectivity^{2, 244}. The CCM is a conceptual model based on landscape analysis, soil moisture storage accounting and hydrologic connectivity estimation. Despite its simplicity, it was able to successfully simulate internal catchment dynamics, such as patterns of connectivity and the connectivity duration curve.

Modelling approaches aiming at larger scales, can be based on a GIS analysis that incorporates dominant runoff generation processes, including subsurface flow processes, such as macropore flow and interflow²⁵⁰. In this framework, macropore flow simulations were based on land use specific macropore distributions, corrected for soil stone fraction²⁵⁰.

Hydrologic connectivity: terminology

Connectivity is the quality, state, or capability of being connective or connected. Hydrologic connectivity is the linkage of separate regions of a catchment via water flow. Several studies have identified the connectivity framework as a promising way forward for experimental studies and hydrological modeling^{28, 49, 251-254}. However, all of them also acknowledge the ambiguity of the term as it is currently used and the resulting lack of focus (see Bracken et al. (2013)²⁸ and Michaelides and Chappell (2009)²⁵³ for a summary). Structural connectivity results from patterns in the landscape and the spatial distribution of landscape units^{28, 255}. It is static at short time scales but can be dynamic at longer time scales, for example as a result of erosion. Functional or process based connectivity, on the other hand, is the result of how the spatial patterns of structural connectivity translate into fluxes of water, sediment and solutes²⁸. Functional connectivity is heterogeneous (i.e. high spatial variability) and varies temporally (i.e. different parts of the catchment may connect during events and become disconnected in between events). Functional connectivity is more difficult to measure and grasp than structural connectivity: we know less about the dynamics of connectivity than its static or structural part²⁵¹. The majority of studies on functional connectivity to date have looked at surface connectivity, particularly with respect to overland flow and sediment transport^{227, 256-262}. Fewer studies have focused explicitly on subsurface hillslope-stream connectivity but hillslope hydrological studies often contain important information on how and when hillslopes connect to the stream.

Descriptors of connectivity

In order to describe connectivity, researchers have come up with a number of different “assessment tools”, including systematic and objective pattern analysis. Because geostatistical measures are not successful in differentiating between connected and disconnected patterns²⁶³⁻²⁶⁴, Western et al. (2011)²⁶⁴ suggested connectivity functions based on percolation theory and the integral connectivity scale (representing the average distance over which pixels are connected). These measures can also be based on soft data if the patterns are not exhaustively known. For the saturated zone, differentiation between flow and transport connectivity resulted in two indicators to capture these processes: *i*) the ratio between effective hydraulic conductivity and the geometric mean of the hydraulic conductivity (high values indicate preferential flow paths) and *ii*) the ratio between the average arrival time and the arrival time of the first 5% of particles (high values indicate channeling)²⁶⁵⁻²⁶⁶. Other descriptors come from percolation theory²²¹, queuing theory²⁶⁷ or graph theory²⁶⁸. Graph theory was used to study and describe basin-scale hydrological connectivity as the ratio of actively flowing to potentially flowing stream reaches and to identify so-called “gatekeeper elements”, which strongly control connectivity at larger scales²⁶⁸. In a study focussing on surface microtopography, the connectivity function’s integral scale, the percolation threshold and the Euler number were considered most promising to assess structural connectivity, while the ratio of the connected surface to the actual surface storage was suggested as an index of functional connectivity²⁶³. The review by Ali and Roy (2010)²³² provides a good overview of a range of other connectivity metrics.

Conclusion

Knowledge of hillslope-stream connectivity is essential for understanding and predicting runoff responses and streamwater quality. The connectivity framework has been proposed as a promising way forward for understanding and parameterizing catchment responses to rainfall and snowmelt^{24, 28, 227, 232, 253-254}, but most connectivity studies, so far, have concentrated on surface connectivity (i.e., overland flow). Few studies have focused explicitly on subsurface hillslope-stream connectivity, although, many hillslope hydrological investigations have touched on the subject. Subsurface hillslope-stream connectivity is difficult to observe and quantify; the wide range of methods and approaches to study hillslope-stream connectivity all have their respective advantages, disadvantages and challenges. Multi-method approaches strengthen the interpretation of individual measurements and have, therefore, proven to be most useful^{24, 55-57}. However, there is a large variability in the observed hillslope responses and the factors that control hillslope-stream connectivity. Despite recent calls for inter-site comparisons and the development of classification tools²⁵⁴, there have been few comparative hillslope studies to date. Most studies have focused on the intrinsic responses at individual research sites, rather than extracting more general rules and controls on hillslope-stream connectivity²⁵³⁻²⁵⁴. Comparative studies would be facilitated by making data from research hillslopes publicly available. Due to the large variability of hillslope responses, scaling the results from individual hillslopes to the catchment scale or extrapolating responses to other hillslopes is difficult. Combining hillslope centric and stream centric approaches might be a way forward, if stream based indicators of connectivity can be mapped or measured along the stream network at a relatively high spatial and temporal resolution and then linked to hillslope processes and thresholds at several locations within the catchment. This might require novel experimental approaches but has the potential to provide information on the spatial and temporal variability in subsurface connectivity at the catchment scale. Upscaling could then be based on the linkage of hillslope scale processes and thresholds and catchment scale patterns of connectivity, possibly combined with landscape metrics. The transferability of these complex linkages will have to be tested by applying the concepts elsewhere, if necessary modified for the local geological or climatic context. Adapting models and metrics that describe surface connectivity (e.g. developed by geomorphologists or ecologists) for subsurface hillslope-stream connectivity will also be beneficial, as surface and subsurface processes are closely related²⁶⁹.

Possible novel developments with respect to experimental methods could include the advancement of in situ sensors for water chemistry, delivering high temporal resolution datasets and which— if sensors are cheap enough – also allow for spatial coverage. Another possibility could be the development of new tracers, such as local microbial communities, specific to a certain depth or habitat (such as upper soil horizons or weathering zone) or artificial tracers, such as DNA, which have the advantage of being infinite in number and can thus be applied to as many hillslopes as required⁹⁹⁻¹⁰⁰. Interdisciplinary work will facilitate the development of new field methodologies. Ideally, comparable measurements would be taken in different environments (c.f.²³⁷) to systematically investigate hillslope-stream connectivity²⁸. These measurements should consider the high spatial variability at the plot and hillslope scale²⁴ and include observations across different hillslope and catchment sizes^{24, 28}.

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Figure Captions

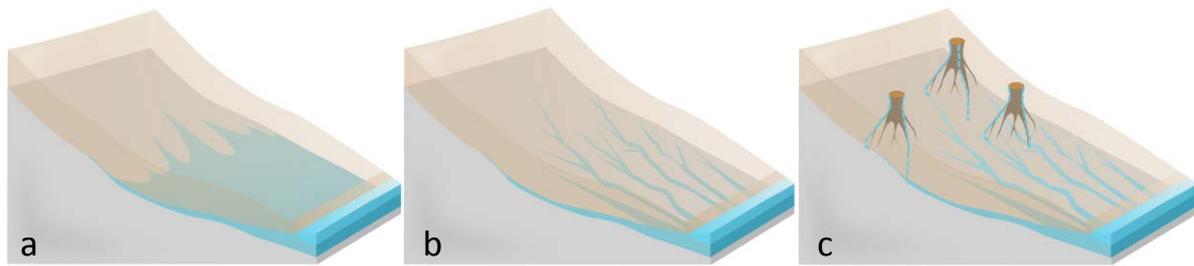


Figure 1. Diffuse hillslope-stream connectivity (a), focused hillslope-stream connectivity due to concentrated flow at the soil-bedrock interface (b), and concentrated flow in macropores (c).

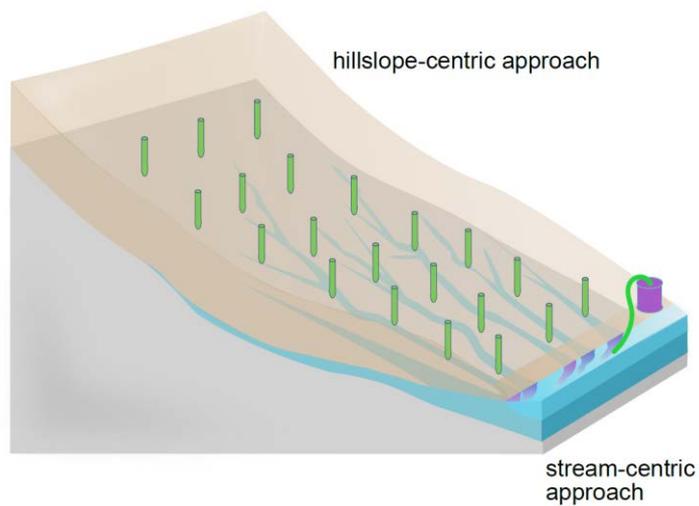


Figure 2. Hillslope-centered (e.g. piezometers, soil moisture or ERT probes in green) and stream-centered (sampler to collect stream water samples in purple) approaches to study hillslope-stream connectivity.



Figure 3. Hillslope-centered measurements: a: subsurface flow measurements at the Panola trench showing the 2 m sections collecting diffuse subsurface flow and macropore flow collectors collecting concentrated subsurface flow, b: tipping buckets collecting subsurface flow from the trench, c: groundwater wells for detailed measurements of saturation at the soil bedrock-interface at the Panola hillslope, showing the trench on the lower part of the hillslope, d: dye staining in Maimai to study channelized subsurface flow at the soil-bedrock interface, e: GPR measurements during a tracer experiment in Luxembourg (photos: a-c: Ilja van Meerveld, d: Chris Graham, e: Niklas Allroggen).

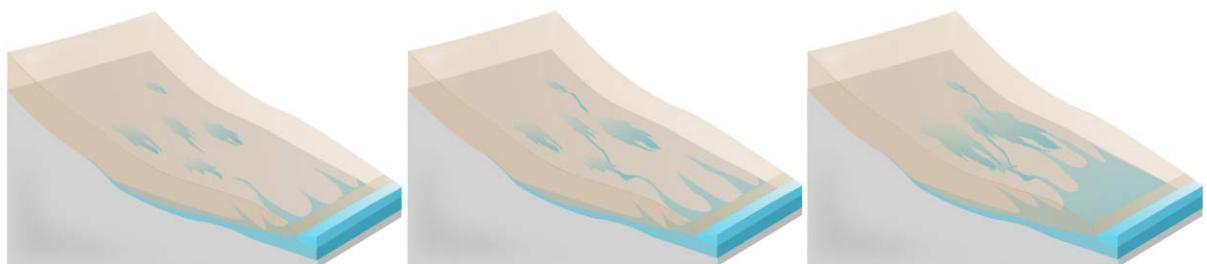


Figure 4. Establishment of subsurface connectivity across a hillslope during events.



Figure 5. Focused hillslope-stream connectivity, water flowing out of preferential flow pathway in Luxembourg (Photo: Theresa Blume)

Tables

Table 1. Overview of the advantages and disadvantages of the field methods used to study subsurface hillslope-stream connectivity: ++= very good, += good, -+ = neither good nor bad, -= poor, -- = very poor

| Method | Ability to measure diffuse connectivity | Ability to measure concentrated flow and connectivity | Spatial coverage (measurement extent) | Spatial resolution (support of measurement) | Repeatability / ability to study different events | Ability to measure continuously | Time and cost efficiency |
|--------------------------------------|---|---|---------------------------------------|---|---|---------------------------------|--------------------------|
| <i>Hillslope centered approaches</i> | | | | | | | |
| Trench measurements | ++ | + | + | + | ++ | + | -+ |
| Groundwater level measurements | ++ | - | ++ | - | ++ | ++ | + |
| Tracer experiments | ++ | + | + | + | -+ | -+ | -+ |
| Dye staining and excavation | - | ++ | -+ | + | -- | -- | -+ |
| Geophysical measurements | - | - | + | + | + | -+ | -+ |
| <i>Stream centered approaches</i> | | | | | | | |
| Incremental stream gauging | -+* | -+* | ++ | -+ | + | - | + |
| Stream chemistry (EMMA) | +* | -+* | ++ | - | + | - | + |
| Radon | -* | +* | + | -+ | + | - | -+ |
| Temperature | -+ | + | + | + | + | -+ | + |

* Difficult to differentiate between concentrated and diffuse flow pathways

Table 2. Overview of the advantages and disadvantages of the methods used to extrapolate measurements from individual hillslopes to other hillslopes or the catchment scale. ++= very good, += good, -+= neither good nor bad, -= poor, -- = very poor

| Method | Representation of diffuse connectivity | Representation of concentrated flow and connectivity | Representation of potential connectivity (static) | Representation of temporally changing connectivity (dynamic) | Transfer of process knowledge to other hillslopes | Upscaling to the catchment scale |
|--|---|---|--|---|--|---|
| Hillslope models (virtual experiments) | ++ | + | + | ++ | + | - |
| Mapping connectivity | + | -+ | ++ | - | -+ | + |
| Landscape analysis | ++ | -+ | ++ | + | + | + |
| Catchment models | ++ | -+ | ++ | + | -+ | ++ |

Further Reading/Resources

Related Articles

| DOI | Article title |
|-------------------|--|
| 10.1002/wat2.1045 | Conservation of aquatic landscapes: ponds, lakes, and rivers as integrated systems |
| | |
| | |