Document 6: Hydrologic connectivity definitions

For the 19 February 2025 IRST Meeting

Hydrologic Connectivity Definitions

Search terms: hydrologic connectivity, 'hydrologic connectivity and roads, hydrologic connectivity and sediment, hydrologic connectivity stream pollution, hydrologic connectivity and riparian, hydrologic connectivity and chemicals, surface hydrologic connectivity, subsurface connectivity

Brief summary

- The most commonly cited definition of hydrologic connectivity is that of Freeman, et al (2007) ***Hydrologic connectivity is the water-mediated transport of matter, energy and organisms within or between elements of the hydrologic cycle.***
- Most definitions include transport of sediment and dissolved constituents as components of hydrologic connectivity.
- Papers distinguish between surface flow and subsurface flow, recognizing that subsurface flow is an important component of hydrologic connectivity between uplands and streams, water bodies, etc.
- Croke, et al (2005) considers two types of hydrologic connectivity: Direct, via channels/gullies, and Indirect, via surface flow.
- Blume and Van Meerveld (2015) and Jencso,2009 consider subsurface flow to be an important category of hydrologic connectivity.
- Luce & Wemple, (2001) Documented interception of subsurface flow in roadcuts and its contribution to erosion and sedimentation related to roads.
- We also provide an example of how the Minnesota Department of Natural Resources defines connectivity and its dimensions.

Papers reviewed and their findings related to hydrologic connectivity definition(s)

1. Freeman, M. C., Pringle, C. M., & Jackson, C. R. (2007). Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales 1. JAWRA Journal of the American Water Resources Association, 43(1), 5-14

- Hydrologic connectivity is the water-mediated transport of matter, energy and organisms within or between elements of the hydrologic cycle.
- Hydrologic connectivity also directs and facilitates the flow of exotic species, human-derived nutrients, and toxic wastes in the landscape.

2. Pringle CM (2003) What is hydrologic connectivity and why is it ecologically important? Hydrol Process 17(13):2685–2689

- Hydrologic connectivity (sensu Pringle, 2001) is used here in an ecological context to refer to water-mediated transfer of matter, energy and/or organisms within or between elements of the hydrologic cycle.
- Hydrologic connectivity is essential to the ecological integrity of the landscape

3. Zhang, Y., Huang, C., Zhang, W., Chen, J., & Wang, L. (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales. Environmental Science and Pollution Research, 28, 52724-52743.

- Hydrological connectivity is used to refer to water-mediated transfer of matter, energy, and organisms within or between elements of hydrological cycles (Pringle 2001).
- Two elements of hydrological connectivity have been identified: structural connectivity and functional connectivity (Bracken and Croke 2007; Turnbull et al. 2008).
- Structural connectivity refers to the spatial patterns of elements in the landscapes, such as the spatial distribution of landscape units and physical characteristics of the catchments (Lexartza-Artza and Wainwright 2009).
- Functional connectivity refers to how these spatial patterns affect ecohydrology (Turnbull et al. 2008).

4. 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.

- Hydrological connectivity is a term often used to describe the internal linkages between runoff and sediment generation in upper parts of catchments and the receiving waters. In this paper,
- we identify two types of connectivity: direct connectivity via new channels or gullies, and diffuse connectivity as surface runoff reaches the stream network via overland flow pathways

5. 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.

- Hydrologic connectivity is a continuum of hydrological states characterized by an increased contribution from lateral subsurface flow that sporadically activates topographic linkages between riparian and upland areas and thus gives rise to highly correlated spatial patterns of hydrologic state variables (e.g. Soil and Moisture) at hillslope and catchment scales.

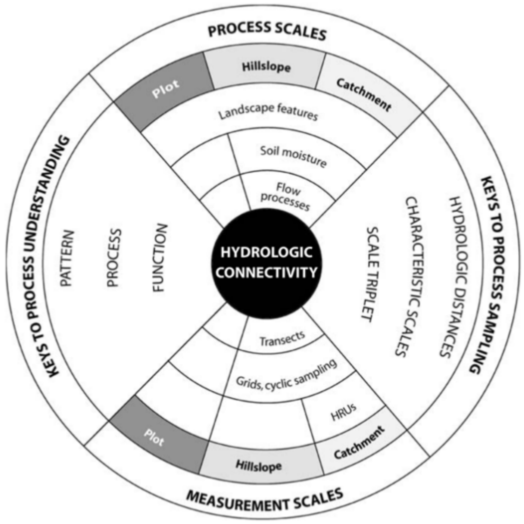

Fig. 7. Synthesis of variables and concepts involved in hydrologic connectivity definition and sampling.

Table 1. Synthesis of hydrologic connectivity definitions.

Water cycle	[. . .] An ecological context to refer to water-mediated transfer of matter, energy and/or organisms within or between elements of the hydrologic cycle (Pringle 2003)	Watershed scale
Landscape features	All the former and subsequent positions, and times, associated with the movement of water or sediment passing through a point in the landscape (Bracken and Croke 2007)	Watershed scale
	Flows of matter and energy (water, nutrients, sediments, heat, etc.) between different landscape components (Tetzlaff et al. 2007)	Watershed scale
	The extent to which water and matter that move across the catchments can be stored within or exported out of the catchment (Lane et al. 2004)	Watershed scale
	Physical linkage of sediment through the channel system, which is the transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system (Hooke 2003)	Hillslope scale
	The physical coupling between discrete units of the landscape, notably, upland and riparian zones, and its implication for runoff generation and chemical transport (Stieglitz et al. 2003)	Hillslope scale
	The internal linkages between runoff and sediment generation in upper parts of catchments and the receiving waters [. . .] two types of connectivity: direct connectivity via new channels or gullies, and diffuse connectivity as surface runoff reaches the stream network via overland flow pathways (Croke et al. 2005)	Hillslope scale
Spatial patterns	Hydrologically relevant spatial patterns of properties (e.g. high permeability) or state variables (e.g. soil moisture) that facilitate flow and transport in a hydrologic system (e.g. an aquifer or watershed) (Western et al. 2001)	Watershed and Hillslope scale
	Spatially connected features which concentrate flow and reduce travel times (Knudby and Carrera 2005)	Watershed and Hillslope scale
Flow processes	The condition by which disparate regions on a hillslope are linked via lateral subsurface water flow (Hornberger et al. 1994; Creed and Band 1998)	Hillslope scale
	Connection, via the subsurface flow system, between the riparian (near-stream) zone and the upland zone (also known as hillslope) occurs when the water table at the upland-riparian zone interface is above the confining layer (Vidon and Hill 2004; Ocampo et al. 2006)	Hillslope scale

6. Kastridis, A. (2020). Impact of forest roads on hydrological processes. Forests, 11(11), 1201.

- The transportation of road runoff and sediment depends on the hydrologic connectivity, where connectivity is defined as the linkage between runoff locations and the receiving waters [13]. Understanding the road-stream hydrologic connectivity is essential to reduce the amount of surface and intercepted subsurface flow that concludes in streams and influences the quality of downstream aquatic habitats.

7. Luce, C. H. (2002). Hydrological processes and pathways affected by forest roads: what do we still need to learn?. Hydrological Processes, 16(14), 2901-2904.

- Effects of roads on sediment generation are closely tied to runoff generation and redistribution processes. The nearly impervious nature of road surfaces (or treads) makes them unique within forested environments and causes runoff generation even in mild rainfall events, leading to chronic fine sediment contributions of minor magnitude to water bodies.

8. Najafi, S., Dragovich, D., Heckmann, T., & Sadeghi, S. H. (2021). Sediment connectivity concepts and approaches. Catena, 196, 104880.

- In recent years the concept of connectivity has emerged in sediment management to describe transfer of sediment from different sections of landscapes at various spatial and temporal scales. The sediment connectivity concept has two distinct components: structural and functional. Structural and functional sediment connectivities have a hard and soft nature, respectively, in which the former relates to physical characteristics and the latter to soil erosion and sediment transport processes.

9. Lesschen, J. P., Schoorl, J. M., & Cammeraat, L. H. (2009). Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. Geomorphology, 109(3-4), 174-183

- Hydrological connectivity can be defined as the physical linkage of water and sediment through the fluvial system (Hooke, 2003). This definition is scale independent, which makes the concept of hydrological connectivity useful to take account of scale dependency in soil erosion research.
- Since hydrological connectivity describes the linkage of runoff and sediment, it finally determines whether runoff and sediment will become connected at broader scales. Identification of the areas that function as a sink is therefore crucial to model runoff and erosion at the catchment scale.

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

- 'Hydrologic connectivity is the water-mediated transport of matter, energy and organisms within or between elements of the hydrologic cycle' (Freeman et al., 2007, p1).
- The development of hydrological connections via overland and subsurface flows is a function of water volume (supplied by rainfall and runoff, depleted by infiltration, evaporation,

transpiration and transmission losses) and rate of transfer (a function of pathway, hillslope length and flow resistance).

- Existing research is categorized into five different approaches to investigating hydrological connectivity:
- i) evaluating soil -moisture patterns (soil26 moisture connectivity);
- ii) understanding runoff patterns and processes on hillslopes (flow-process connectivity);
- iii) investigating topographic controls (terrain-connectivity) including the impact of road networks on hydrological connectivity and catchment runoff;
- iv) developing models to explore and predict hydrological connectivity; and v) developing indices of hydrological connectivity.
- Analysis of published research suggests a relationship between research group, approach, geographic setting and the interpretation of hydrological connectivity.

11. McGuire, K. J., & McDonnell, J. J. (2010). Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities. Water Resources Research, 46(10).

- Hydrological connectivity between uplands (also known as the hillslopes) and the stream or riparian network has been defined in many ways, but perhaps it is most commonly used to describe when water tables develop between the hillslope and riparian zone [*Vidon and Hill*, 2004; *Ocampo et al.*, 2006] and result in a measurable runoff response [*Bracken and Croke*, 2007]
- Here we use the term to describe the initiation of a shallow groundwater table across hillslope, riparian, and stream zones. The development of water table connectivity across the hillslope-riparian-stream (HRS) continuum is considered a requisite for throughflow and solute transport to streams.

12. Blume, T., & Van Meerveld, H. J. (2015). From hillslope to stream: methods to investigate subsurface connectivity. Wiley Interdisciplinary Reviews: Water, 2(3), 177-198.

- 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.

13. Luce, C. H., & Wemple, B. C. (2001). Introduction to special issue on hydrologic and geomorphic effects of forest roads. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 26(2), 111-113.

- Forest roads alter watershed hydrology from creation of infiltration excess overland flow from compacted road surfaces and interception of subsurface flow paths at road cuts (e.g., Kastridis, 2020, Luce, 2002, Wemple et al., 1996).

14. Surfleet, C. G., & Marks, S. J. (2021). Hydrologic and suspended sediment effects of forest roads using field and DHSVM modelling studies. Forest Ecology and Management, 499, 119632.

- The acceleration of chronic surface erosion from forest roads and subsequent sediment delivery is forced primarily by the hydrologic effects of the roads (e.g. Luce and Black, 1999; Surfleet et al, 2011).

- These hydrologic effects include reduced infiltration capacity, interception of sub-surface flow (Luce, 2002), and increased connectivity of overland flow to watercourses (Kastridis, 2020; Luce and Black, 1999; Wemple, 1996).

15. 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(4).

- Hydrologic connectivity is the water-mediated transport of matter, energy and organisms within or between elements of the hydrologic cycle' (Freeman et al., 2007, p1).
- The development of hydrological connections via overland and subsurface flows is a function of water volume (supplied by rainfall and runoff, depleted by infiltration, evaporation, transpiration and transmission losses) and rate of transfer (a function of pathway, hillslope length and flow resistance).
- In forested mountain landscapes, hillslopes comprise the major landscape element. Hillslope soils are often shallow and located on moderate to steep slopes. Hillslopes typically have relatively low antecedent wetness due to their steep slopes and well drained soils. During periods of high wetness hillslope soils can be highly transmissive and contribute significant quantities of water to near stream areas and the stream network [*Peters et al.*, 1995; *McGlynn and McDonnell*, 2003b]. This hydrologic connectivity is requisite for the flushing of solutes and nutrients downslope through the riparian zone to the stream [*Creed et al.*, 1996; *Buttle et al.*, 2001; *Stieglitz et al.*, 2003].

Hydrologic Connectivity Dimensions: Minnesota Department of Natural Resources

The following text is copied verbatim from: https://www.dnr.state.mn.us/whaf/5-component/connectivity.html#:~:text=Hydrologic%20Connectivity,processes%20that%20vary%20over%20time.

Connectivity is defined as the maintenance of lateral, longitudinal, and vertical pathways for biological, hydrological, and physical processes (Annear, 2004). It refers to the flow, exchange, and pathways that move organisms, energy, and matter throughout the watershed. The most obvious example of connectivity may be the free flow of water downstream in a river and the passage of fish upstream. The construction of a high dam across a stream is a vivid and obvious illustration of fragmentation or the loss of connectivity.

This exchange of energy, nutrients and material does not stop at the water's edge, it can be observed at many scales throughout the surrounding landscape. Complex, interdependent processes are continuously present throughout the watershed landscape and are required to maintain the ecological health of the system as a whole.
Hydrologic Connectivity

Connectivity refers to the flow, exchange and pathways that move organisms, energy and matter throughout the watershed system. These interactions create complex, interdependent processes that vary over time.

Four Dimensions

For example, the stream continuum concept describes stream connectivity in four dimensions (Annear, 2004).

- longitudinal – linear connectivity
- lateral – floodplain connectivity
- vertical – hyporheic (below the stream bed)
- temporal (time) – many scales; seasonal, multiyear, generational

Longitudinal

Within the stream system, ***longitudinal connectivity*** refers to the pathways along the entire length of a stream. As the physical gradient changes from source to mouth, chemical systems and biological communities shift and change in response. The River Continuum Concept (RCC) can be applied to this linear cycling of nutrients, continuum of habitats, influx of organic materials, and dissipation of energy.

For example:

- A headwater woodland stream has steep gradient with riffles, rapids and falls.
- Sunlight is limited by overhanging trees, so photosynthesis is limited.
- Energy comes instead from leaves and woody material falling into the stream
- Aquatic insects break down and digest the terrestrial organic matter.
- Water is cooled by springs and often supports trout.

In the mid-reaches,

- The gradient decreases and there are fewer rapids and falls.
- The stream is wider, sunlight reaches the water allowing growth of aquatic plants.
- Insects feed on algae and living plants.
- Proportion of groundwater to runoff is lower so stream temperatures are warmer.
- The larger stream supports a greater diversity of invertebrates and fish.

The river grows and the gradient lessens with few riffles and rapids.

- Terrestrial organic matter is insignificant in comparison to the volume of water
- Energy is supplied by dissolved organic material from upstream reaches.
- Drifting phytoplankton and zooplankton contribute to the food base as does organic matter from the floodplain during flood pulses.
- Increasing turbidity reduces sunlight to the streambed causing a reduction in rooted aquatic plants.
- Backwaters may exist where turbidity has settled and aquatic plants are abundant.
- Fish species are omnivores and plankton feeders such as carp, buffalo, suckers, and paddlefish.
- Sight feeders are limited due to the turbidity (Minnesota DNR, Healthy Rivers).

Lateral

Lateral connectivity refers to the periodic inundation of the floodplain and the resulting exchange of water, sediment, organic matter, nutrients, and organisms. Lateral connectivity becomes especially important in large rivers with broad floodplains.

Periodic floods refill oxbow lakes and recharge wetlands. Inundated areas may be used as spawning areas by species such as northern pike. Floodwaters carry nutrients and organic matter from the land to the stream's aquatic plants, plankton, stream invertebrates, and fish. Seasonal flooding produces a variety of streamside vegetation and habitat for a diversity of birds and mammals (Minnesota DNR, Healthy Rivers).

Access to floodplain is also important for small streams that can experience dramatic episodic flooding. Heavy, localized rains can cause small streams to rise several feet in a few hours. This flashiness is largely a result of more overland flow and less infiltration following the conversion of native land cover to row crops and human communities. Large amounts of sediment are mobilized by these events, impacting all trophic levels and altering biological communities in the stream and the adjacent floodplain.

Vertical

Vertical connectivity is represented by the connection between the atmosphere and groundwater. The ability of water to cycle through soil, river, and air as liquid, vapor, or ice is important in storing and replenishing water. This exchange is usually visualized as unidirectional–precipitation falling onto land and then flowing over land or percolating through the ground to the stream.

An equally important transfer of water occurs from the streambed itself to surrounding aquifers. Groundwater can contribute to flows in the river at certain times in the year and at certain locations on the same stream. Streams may either gain or lose water to the surrounding aquifer depending on their relative elevations. Lowering the water table through groundwater withdrawals may change this dynamic exchange in unanticipated ways (Stream Corridor, FISRWG).

The slow movement of water through sediments to the river produces several ecological benefits.

- The water is filtered of many impurities.
- It usually picks up dissolved minerals.
- The water is cooled.
- The water is metered out slowly over time.

This is particularly important in smaller, cooler streams for the maintenance of critical habitat for fish, wildlife and invertebrate species.

Temporal

A stream exhibits ***temporal connectivity*** of continuous physical, chemical, and biological interactions over time, according to a rather predictable pattern. These patterns and continuity are important to the functioning of the ecosystem. Over time, sediment shifts, meanders form, bends erode, oxbows break off from the main channel, channels shift and braid. A stream rises and falls according to seasonal patterns, depending on rain and snowmelt. Throughout most of Minnesota, free-flowing rivers experience high water in spring, falling flows in summer, moderate flows in fall, and base flows in winter. The watershed has adjusted to these normal fluctuations, and many organisms have evolved to depend on them (Minnesota DNR, Healthy Rivers).

Landscape Connectivity

Landscape connectivity is 'the degree to which the landscape facilitates or impedes movement among resource patches' (Taylor et al, 1993). Biological components - both plant and animal – must have access to all the habitats necessary for all stages of their life cycle. This includes both physical and temporal access to habitats. For example, the need for seasonal timing is acute for many wildlife species to accommodate breeding, reproduction, and migration. For plant species it is equally important for dispersal, growth and competition.

Landscape connectivity has two components:

- Structural connectivity – the spatial structure of a landscape that can be described from map elements
- Functional connectivity – the response of individuals to landscape features (Brooks).

Habitat does not need to be structurally connected in order to be functionally connected. Some organisms have the ability to bridge the gaps between habitat patches and can link resources by crossing over uninhabitable or partially inhabitable locations (Taylor, 2006). For example, a neotropical migrant bird will perceive a landscape as connected across a greater range than would a salamander restricted to moist forest floors (With). “These movements… of individuals, materials, nutrients, energy or disturbances… are affected by how (habitat) patches are arrayed in the mosaic…. Although landscape connectivity is often thought of in terms of corridors - roughly linear strips of habitat connecting otherwise isolated habitat patches – connectivity is in fact a complex product of:

- patch quality (e.g. resistance to movement or patch-residence time)
- boundary properties ...
- the movement characteristics of the features of interest” (Weins).

Fragmentation

As people use the land, the natural landscape is divided into ever-smaller pieces by elements like railways, utility lines, roads, houses, and parking lots. The remaining natural areas, or fragments, are reduced in size and degraded in quality, resulting in a decline in plant and animal populations, and the disappearance of some sensitive animal species and plant communities.