REVIEWS/RAZGLEDI

HYDROLOGICAL CONNECTIVITY: AN INTRODUCTION TO THE CONCEPT
HIDROLOŠKA POVEZLJIVOST – TEMELJNI KONCEPTUALNI OKVIR

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ABSTRACT
Hydrological connectivity: an introduction to the concept
The concept of connectivity, especially hydrological connectivity, is used in Earth and environmental sciences as a term and as a conceptual framework for addressing spatial and temporal variability in runoff and sediment transport. Hydrological connectivity can be defined as the transfer of water and sediment through a fluvial system or a dynamic linkage between surface and subsurface waters flowing through a landscape. Five forms of hydrological connectivity may be distinguished: stream-hillslope connectivity, river-floodplain connectivity, stream-lake connectivity, longitudinal or upstream-downstream connectivity, and stream-groundwater connectivity. All of them are interconnected. Hydrological connections are not only unidirectional but cover multiple dimensions and operate across different temporal scales. As a framework, connectivity is useful for understanding spatial variations in runoff.

KEY WORD
hydrology, hydrogeography, geomorphology, runoff, sediment transport

IZVLEČEK
Hidrološka povezljivost – temeljni konceptualni okvir
Pojem povezljivosti, zlasti hidrološke povezljivosti, se v vedah o Zemlji in okolju uporablja kot strokovni izraz in kot konceptualni okvir za obravnavo prostorske ter časovne spremenljivosti v pretoku vode in prenosu

gradiva. Hidrološko povezljivost lahko opredelimo kot prenašanje vode in sedimentov skozi rečni sistem ali kot dinamično povezavo med nadzemnimi in podzemnimi vodami, ki tečejo skozi pokrajino. Razlikujemo lahko pet oblik hidrološke povezljivosti: povezljivost med vodotokom in pobočjem, povezljivost med vodotokom in njegovim poplavnim območjem, povezljivost med vodotokom in jezerom, vzdolžno povezljivost med vodotokovim povirnim in izlivnim delom ter povezljivost med vodotokom in podzemno vodo. Vse so med sabo povezane. Vodne povezave niso samo enosmerne, ampak imajo več razsežnosti glede na prostor in čas. Kot okvir je povezljivost koristna za razumevanje prostorskih razlik pri odtoku.

KLJUČNE BESEDE
hidrologija, hidrogeografija, geomorfologija, odtok, prenašanje gradiva

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1 Basic terms

Connectivity as a term and as a concept is increasingly being used in Earth and environmental sciences as a conceptual framework for addressing spatial and temporal variability in runoff and sediment transport (e.g., Lexartza-Artza and Wainwright 2009; Michaelides and Chappell 2009; Reaney 2010; Bracken et al. 2013; 2015; Parsons et al. 2015; Masselink 2017; Wohl, Magilligan, and Rathburn 2017; Wohl 2017; 2020). Connected to these, there has been a shift from thinking about the transfer of matter between different compartments in the landscape to a continuum-based approach seeking to understand pathways, routes, and scales of movement (Bracken et al. 2015; Masselink 2017).

Landscape properties accelerate or impede the movement of water. At each point, water can move forward down a slope, enter depression storage, infiltrate into the ground, evaporate into the air, or be taken by living beings. Water may move above the surface, along the surface (down a slope), or through the subsurface (within the soil or a groundwater aquifer).

Thus, connectivity can be defined as »the efficiency of transfer of materials between system components« (Wohl et al. 2019, 5) or »the degree to which matter (water, solutes, sediment, organic matter) and organisms can move among spatially defined units in a natural system« (Wohl 2017, 345–346). Bracken and Croke (2007, 1751) write that »at its most general, connectivity describes all the former and subsequent positions, and times, associated with the movement of water or sediment passing through a point in the landscape,« and Keesstra et al. (2018, 1557, 1560) write that it can be used »as a means to describe and quantify the influences on the fluxes of water and sediment on different scales: aggregate, pedon, location on the slope, slope, watershed, and basin,« and that »the connectivity concept provides a skeleton that allows an understanding of the transfer of water and sediment through landscapes.« Connectivity is limited to some degree through time and across space, so that understanding one extreme of the continuum, disconnectivity, is equally important. Components or processes that are disconnected are those that either are too remote from each other in space or time, so that a change in one component or process does not lead to change in another, or those in which a threshold must be overcome to allow connectivity (Wohl et al. 2019).

The connectivity-based approach is used in various fields – for example, geology, geomorphology, soil science, hydrology, ecology, and atmospheric sciences (Keesstra et al. 2018) – but also in fields such as social network science or neuroscience (Masselink 2017). In the ecological context, connectivity is defined as »all the functional and effective linkages necessary for the functioning, stability and resilience of ecosystems over the long term« and in the geographical context as »all the links that connect one place to another« (Cossart, Lissak, and Viel 2017, 4).

The concept that fluxes of matter and energy occur over diverse spatial and temporal scales is inherently connected with physical geography; for example, through the hydrological cycle or the rock cycle; or as Brierley et al. (2006, 173) put it »analyses of landscape relationships and modelling of biophysical fluxes lie at the heart of the geographic tradition«. Past physical geographical research on sediment fluxes, runoff, river networks, groundwater and so on involved the identification and quantification of connectivity, although the term as such was not used (Wohl 2017). Today as well there is confusion about how the term is used and defined.

Within hydrology and geomorphology, three main »types« of connectivity can be identified (Bracken and Croke 2007):

- 1) »landscape connectivity,« which relates to the physical coupling of landforms (e.g., hillslope to channel) within a drainage basin,
- 2) »hydrological connectivity,« which refers to the transfer of water from one part of the landscape to another, and
- 3) »sedimentological connectivity,« which relates to the transfer of sediments through the drainage basin.

2 Historical perspective

The term *connectivity* entered Earth sciences from ecology and a primarily biological context (e.g., gene flow between subpopulations of a metapopulation). It emerged in Earth sciences from two perspectives. One involves the management of river basins for flood control, irrigation, and water supply, and the other involves observations linking Earth's surface processes to landform dynamics, such as source to sink connections. These origins can be traced back thousands of years. Perhaps the most fundamental question in those times was the source of the continued flow of rivers in the absence of precipitation. The hydrological cycle that explained this was developed in the late sixteenth century (Wohl et al. 2019). Renaissance scholars examined landscape-scale processes of erosion, transport, and deposition, and their role in creating channel networks in the landscape and major river valleys. During the nineteenth century, this perceived connectivity between rivers and the landscapes that they drain prompted the recognition that geomorphic effects could propagate through the landscape, linking, for example, deforestation on slopes and floods in channels. In the 1970s, the concept of process–response coupling was developed, arguing that the process of landscape change is driven by the capacity of the landscape to transmit an impulse between system components, and that the capacity is controlled by the landscape connection between components and the strength of the coupling. The sensitivity of landscape change is then determined by the rate of response. Highly connected and strongly coupled systems respond quickly and are commonly more morphologically complex, whereas less-connected and weakly coupled systems respond slowly and are less complex (Wohl et al. 2019). Several authors suggest distinguishing the term *coupling* for the study of elementary links, and using the term *connectivity* for the study of the assemblage of these links (Cossart, Lissak, and Vie 2017).

The term was introduced to the hydrological context in the late 1980s, when hydrological connectivity was described by Amoros and Roux (1988) »as the exchange of matter, energy, and biota between different elements of the riverine landscape via the aqueous medium« (Wohl 2017, 345).

3 Hydrological context

»Hydrologic connections can link hillslopes to channel networks, streams to lakes, subsurface to surface, land to atmosphere, terrestrial to aquatic, and upstream to downstream. These connections can develop across vertical, lateral, and longitudinal dimensions and span spatial and temporal scales. Each of these dimensions and scales are interconnected, creating a mosaic of nested hydrologic connections and associated processes. In turn, these interacting and nested processes influence the transport, cycling, and transformation of organic material and inorganic nutrients through watersheds and along fluvial networks« (Covino 2017, 133). Because the term *hydrological connectivity* covers a broad spectrum, there is (still) no consensus about its definition (see Ali and Roy 2009, and Wohl et al. 2019 for a synthesis of definitions). According to Pringle (2003, 2685) hydrological connectivity is the »water-mediated transport of matter, energy and/or organisms within or between elements of the hydrologic cycle« and according to Hooke (2003) it can be defined as the physical linkage of water and sediment through the fluvial system. Bracken et al. (2013, 18) describe hydrological connectivity as a connection, via the subsurface flow system, between the riparian zone and the upland zone, which occurs when the water table at the upland–riparian zone interface is above the confining layer, and Masselink (2017, 12) as »the physical coupling (linkages) of different elements within a landscape regarding (sub) surface flows.« Whatever the definition, as a frame it is useful for understanding spatial variations in runoff (Bracken et al. 2013). Covino (2017, 133) writes that »hydrologic connectivity can be established via surface or subsurface pathways and occurs along four dimensions.« Three dimensions are spatial (lateral, vertical, and longitudinal), and time is the fourth dimension. Hydrological connections are not only unidirectional, but also cover multiple dimensions and operate across different temporal scales, from seconds to millennia, and across spatial scales from millimeters to thousands of kilometers.

Hydrological connectivity is conceptualized in two ways, as »structural« (static) and »functional« (dynamic or process-based) connectivity. Structural connectivity involves spatial patterns in the landscape, such as the spatial distribution of landscape units that influence water transfer patterns and flow paths, and functional connectivity involves how these spatial patterns interact with catchment processes to produce runoff, connected flow, and hence water transfer in catchments (Turnbull, Wainwright, and Brazier 2008; Bracken et al. 2013). In other words, »structural connectivity is the form and architecture of the landscape, while all the processes acting upon that structure are captured within functional connectivity« (Masselink 2017, 3). Research so far has been successful at describing the elements defining structural connectivity; however, the elements defining functional connectivity are more difficult to measure and quantify. Nonetheless, in understanding hydrological connectivity one must not forget the importance of the interaction between topographic controls and catchment processes (Bracken et al. 2013). Wohl et al. (2019, 8) write that »static frameworks provide a snapshot of how the landscape is structured and functioning at any particular point in time. Dynamic frameworks recognize three key factors. First, the structure of the landscape can change and therefore the type, position, and pattern of landforms in a landscape can change, producing alterations in connectivity. Second, the strength of functional connectivity is likely to change in association with changes to structural configuration. Third, structural configuration and functional connectivity may change depending on the magnitude of the disturbances that drive fluxes of water and sediment through landscapes.«

Covino (2017, 134) distinguishes five forms of hydrological connectivity:

- 1) »stream-hillslope connectivity,« as a fundamental linkage between terrestrial and aquatic environments, which can be established via surface overland flow or subsurface connections and is spatially and temporally variable,

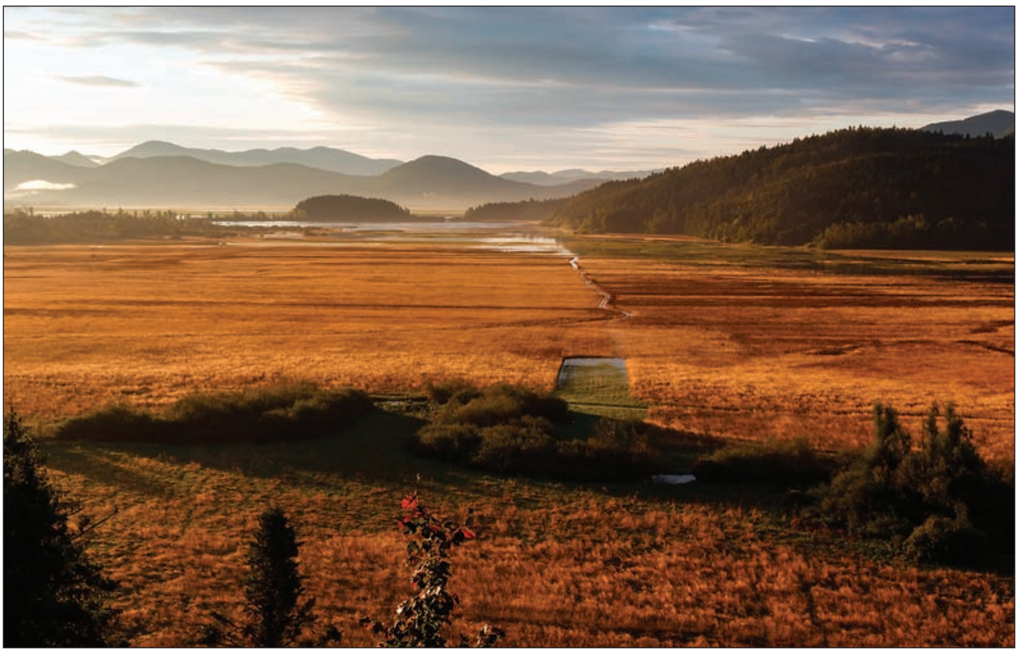

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Figure 1: The intermittent Lake Cerknica is a very interesting example of hydrological stream-groundwater connectivity, as it changes markedly during different seasons and intertwines with other connectivity.

- 2) »stream-groundwater connectivity,« as stream-groundwater exchange or bidirectional connection between streams and subsurface water (Figure 1),
- 3) »river-floodplain connectivity,« as bidirectional movement of water, sediment, organic material, and so on between rivers and floodplains depending on hydrological flow conditions (Figure 2); for example, during high flow periods, the river generally connects with the floodplain via overbank flow and during lower flow periods floodplain groundwater sustains the river's base flow,
- 4) »longitudinal connectivity,« as connections from upstream (headwaters) to downstream (the lowland river network) that facilitate the unidirectional movement of water and sediments, and bidirectional movement of organisms along channel networks, and
- 5) »stream-lake connectivity,« where lakes (Figure 3), reservoirs, and ponds reduce transport velocities, residence times are longer, and sedimentation is greater.

However, because of the interconnections of all forms of hydrological connectivity, one cannot be managed in pure isolation from another (Covino 2017). Also in landscape diverse Slovenia (Perko, Ciglič, and Hrvatin 2017; Perko, Ciglič, and Zorn 2020), the forms of hydrological connectivity are intertwine and change rapidly over short distances (Figures 1 to 3).

4 How can connectivity be determined?

The majority of studies on hydrological connectivity have focused on conceptual frameworks, indices, and modeling. The conceptual frameworks and models describe the components of catchment con-

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Figure 2: Jovsi are a miniature protected cultural landscape of wet meadows along the meanders of the Sotla river, surrounded by the stream Sušica. It is an example of hydrological river-floodplain connectivity.

nectivity. The indices and metrics used to describe connectivity were mostly based on topography using DEMs, soil moisture, or a combination of DEM-based and field-based studies. Connectivity can be described as a nominal variable, as a scalar vector, or as complex vectors. The problem, however, with these types of descriptions is that they need to be measured or assessed at a single scale level, and then they are not always suitable for application over an entire catchment (Masselink 2017).

Currently there is a consensus among the hydrological and geomorphological research community that connectivity as such cannot be measured directly, but must be inferred from measurements of other variables. Structural connectivity can be inferred from measurements of topography and landscape structure, whereas functional connectivity needs to be inferred from measurements of fluxes and sediment tracing (Masselink 2017). Although many studies have quantified connectivity, most have used approaches developed for a specific question and only a few have tried to develop metrics that would be more widely applicable (Bracken et al. 2013; 2015).

Wohl et al. (2019) write that one approach to measuring connectivity is to determine the fundamental temporal and spatial scales for the phenomenon of interest and to make measurements at a sufficiently large multiple of the fundamental scales to reliably capture a representative sample. Another approach seeks to characterize how connectivity varies with a scale by applying the same metric over a wide range of scales or using statistical measures that characterize the frequency distributions of connectivity across scales.

Most studies of connectivity are primarily motivated by understanding how connectivity affects specific aspects of landscape dynamics. Hence, a straightforward approach is to quantify fluxes directly and to use those measurements to infer the degree of connectivity in the transport system. This can be done at a single point such as a catchment outlet or at many locations distributed through the

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Figure 3: Lake Bohinj is an example of hydrological stream-lake connectivity, and at the same time its tributary Savica is an example of hydrological longitudinal upstream-downstream connectivity and stream-hillslope connectivity.

system. In contrast to quantifying the bulk system output at a single point in space, metrics for the local effects of connectivity at many locations across the landscape are more complex. Numerical models can overcome this challenge by predicting outcomes for every point in the landscape. Modeling approaches (Baartman et al. 2020) include cellular automata, process-based modeling, statistical models, and GIS approaches based on network theory (Wohl et al. 2019). One example of modeling is the index of connectivity (Borselli, Cassi, and Torri 2008), which expresses relative sediment transport efficiency upstream and downstream of any point in the landscape using topographic attributes such as drainage area, mean slope, and travel distance between elements. For more metrics and indices of hydrological connectivity, see Bracken et al. (2013), Wohl (2017), and Wohl et al. (2019).

5 Importance

The concept of connectivity is helpful for understanding the occurrence and routes of water and sediment within a system. The concept is »useful to identify the dominant processes that reflect the effective fluxes in models« (Keesstra et al. 2018, 1568).

Wohl (2017) argues that connectivity can help in several aspects of hydrological process:

- 1) in understanding the spatial and temporal scales of different types and degrees of connectivity to reconcile disparities between direct measurements of fluxes and inferred rates of landscape change,
- 2) to understand the resistance and resilience of rivers to natural and human-induced disturbances,
- 3) to identify processes that cross traditional disciplinary boundaries as well as spatial boundaries within landscapes,
- 4) to identify the factors and processes that affect the retention or storage of diverse materials (e.g., water, solutes, sediment, and organic matter),
- 5) to provide critical insights into how nonlinear behaviors occur in watercourses, and
- 6) to identify factors that facilitate or limit effective management of rivers.

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HIDROLOŠKA POVEZLJIVOST – TEMELJNI KONCEPTUALNI OKVIR

1 Osnovni pojmi

Povezljivost kot strokovni izraz in pojem se na področju ved o Zemlji in okolju uporablja kot konceptualni okvir za obravnavo prostorske ter časovne spremenljivosti v pretoku vode in prenosu gradiva (na primer Lexartza-Artza in Wainwright 2009; Michaelides in Chappell 2009; Reaney 2010; Bracken s sod. 2013; 2015; Parsons s sod. 2015; Masselink 2017; Wohl, Magilligan in Rathburn 2017; Wohl 2017; 2020). V tem pogledu se je zgodil premik od razmišljanja o prenašanju snovi med različnimi deli pokrajine k pristopu, ki temelji na nenehnem prenašanju (premikanju, prehajanju) gradiva ter se osredotoča na razumevanje poti in obsega njegovega prenašanja (Bracken s sod. 2015; Masselink 2017).

Značilnosti pokrajine pospešujejo ali zavirajo gibanje vode. Voda lahko teče po pobočju, se zadržuje v kotanjah, ponikne v tla, izhlapi ali pa jo zajamejo živa bitja. Premika se lahko nad površjem, po površju (po pobočju) ali pod površjem (skozi prst ali vodonosnik).

Povezljivost lahko opredelimo kot »*učinkovitost prenašanja gradiva med deli sistema*« (Wohl s sod. 2019, 5) ali »*… stopnjo, pri kateri se snov (voda, topljenci, sedimenti in organske snovi) in organizmi lahko premikajo med prostorsko opredeljenimi enotami naravnega sistema …*« (Wohl 2017, 345–346). Bracken in Croke (2007, 1751) navajata, da »*… se v najsplošnejšem pomenu povezljivost nanaša na vse nekdanje in prihodnje položaje in čase, povezane s premikanjem vode ali sedimentov skozi točko v pokrajini …*«. Keesstra s sod. (2018, 1557, 1560) izpostavlja, da se lahko pojem povezljivosti uporablja za »*… opisovanje in kvantificiranje vplivov na pretok vode in sedimentov na različnih prostorskih ravneh, od strukturnih skupkov, prereza prsti, dela pobočja in pobočja do porečja in povodja …*«, ter navajajo, da »*… pojem povezljivosti zagotavlja okvir za razumevanje prenašanja vode in sedimentov skozi pokrajine …*«. V določeni meri je povezljivost omejena s časom in prostorom, zato je enako pomembno razumevanje druge skrajnosti tega kontinuuma, to je nepovezljivosti. Prvine ali procesi, ki niso povezljivi, so drug od drugega prostorsko ali časovno preveč oddaljeni, da bi sprememba ene prvine ali enega procesa lahko vodila do spremembe druge prvine ali drugega procesa, ali pa so to prvine ali procesi, pri katerih je treba preseči določen prag, da postanejo povezljivi (Wohl s sod. 2019).

Pristop, ki temelji na povezljivosti, se uporablja na različnih področjih, od geologije, geomorfologije, pedologije, hidrologije, ekologije in ved o ozračju (Keesstra s sod. 2018), do ved o socialnih mrežah in nevroznanosti (Masselink 2017). V ekologiji se povezljivost nanaša na »*vse funkcionalne in učinkujoče povezave, potrebne za dolgoročno delovanje, stabilnost in prožnost ekosistemov*«, v geografiji pa na »*vse povezave med dvema krajema*« (Cossart, Lissak in Viel 2017, 4).

Pojem prenašanja snovi ter energije na različnih prostorskih in časovnih ravneh je povezan s fizično geografijo, denimo prek vodnega in kamninskega kroga ali pa so, kot navaja Brierley s sod. (2006, 173), »*analize pokrajinskih odnosov in modeliranje biofizičnih pretokov osrednji predmet geografske tradicije*«. V naravnogeografskih raziskavah o prenašanju sedimentov, odtoku, rečni mreži, podtalnici in podobnem so geografi določali in kvantificirali tudi povezljivost, čeprav dejansko tega izraza niso uporabljali (Wohl 2017), zmeda okoli njegove uporabe in opredelitve pa vlada še danes.

V hidrologiji in geomorfologiji razlikujemo tri glavne vrste povezljivosti (Bracken in Croke 2007):

- 1. pokrajinsko povezljivost, ki se nanaša na fizične povezave med različnimi reliefnimi oblikami (na primer pobočji in rečnimi strugami) v porečju,
- 2. hidrološko povezljivost, ki se nanaša na prenašanje vode z enega dela pokrajine na drugega, ter
- 3. sedimentološko povezljivost, ki se nanaša na prenašanje sedimentov skozi porečje.

2 Zgodovinski pregled

Izraz »povezljivost« je bil v vede o Zemlji prenesen iz ekologije in predvsem biološkega konteksta (na primer prenos genov med subpopulacijami izbrane metapopulacije). Začetki preučevanja povezljivosti v vedah o Zemlji izhajajo iz upravljanja porečij zaradi varstva pred poplavami, namakanja in oskrbe z vodo ter opazovanj povezav med procesi na Zemljinem površju in dinamiko preoblikovanja površja (na primer povezav od izvira do izliva). Navedeni začetki segajo več tisočletij v preteklost. Morda je bilo najosnovnejše takratno vprašanje, zakaj vodotok ob odsotnosti padavin še naprej teče. Pojem vodnega kroga, ki je to pojasnil, je bil prvič opisan šele konec 16. stoletja (Wohl s sod. 2019). Renesančni učenjaki so preučevali procese erozije ter prenašanja in odlaganja gradiva na ravni pokrajine ter njihovo vlogo pri oblikovanju rečnih mrež v pokrajini in večjih rečnih dolinah. V 19. stoletju so spoznanja o povezljivosti med vodotoki in pokrajinami, iz katerih odvajajo vodo, vodila do ugotovitve, da se lahko geomorfološki učinki širijo skozi pokrajino ter na primer povezujejo redčenje gozda na pobočjih in poplavljanje vodotokov. V 70-ih letih 20. stoletja je bil razvit koncept procesno-odzivne spojenosti, in sicer na podlagi predpostavke, da proces pokrajinskih sprememb temelji na sposobnosti pokrajine, da med sestavnimi deli sistema prenaša impulze, to sposobnost pa uravnavata povezanost sestavnih delov in stopnja oziroma moč njihove spojenosti. Občutljivost pokrajinskih sprememb se nato določi na podlagi stopnje odziva. Močno povezani in spojeni sistemi se hitro odzovejo ter so običajno morfološko kompleksnejši, medtem ko se slabše povezani in spojeni sistemi odzovejo počasneje in so manj kompleksni (Wohl s sod. 2019). Več raziskovalcev priporoča uporabo izraza »spojenost« (angleško *coupling*) za preučevanje elementarnih povezav in izraza »povezljivost« (*connectivity*) za preučevanje več tovrstnih povezav skupaj (Cossart, Lissak in Vie 2017).

Izraz »povezljivost« je bil v hidrologiji prvič uporabljen v poznih 80-ih letih 20. stoletja, ko sta Amoros in Roux (1988) hidrološko povezljivost opisala kot »… *izmenjavo snovi, energije in biote med različnimi prvinami rečne pokrajine prek vodnega medija* …« (Wohl 2017, 345).

3 Uporaba v hidrologiji

»… *Hidrološke povezave vključujejo povezave med pobočji in rečnimi mrežami, vodotoki in jezeri, podzemljem in površjem, kopnim in ozračjem, kopnim in vodami ter zgornjim in spodnjim tokom rek. Lahko se razvijejo v navpični, prečni ali vzdolžni smeri ter na prostorski ali časovni ravni. Te smeri in ravni so med sabo povezane, kar ustvarja mozaik prepletenih hidroloških povezav in z njimi povezanih procesov. Ti součinkujoči in prepleteni procesi pa vplivajo na prenašanje, kroženje in preobrazbo organskih snovi in anorganskih hranil skozi porečja in vzdolž rečnih mrež* …« (Covino 2017, 133). Ker izraz »hidrološka povezljivost« pokriva široko področje, zanj (še vedno) ni enotne definicije (glej Ali in Roy 2009 ter Wohl s sod. 2019 za sintezo definicij). Kot navaja Pringle (2003, 2685), se hidrološka povezljivost nanaša na »… *prenašanje snovi, energije in/ali organizmov prek vode znotraj ali med prvinami vodnega kroga* …«, Hooke (2003) pa jo opredeljuje kot fizično povezanost vode in sedimentov v rečnem sistemu. Bracken s sod. (2013, 18) hidrološko povezljivost opisuje kot povezavo med obvodnim območjem in vzpetim zaledjem, ki se pojavi, ko gladina podtalnice doseže mejo med vzpetim in obvodnim pasom nad vododržno plastjo, Masselink (2017, 12) pa kot »… *fizično spojenost (povezanost) različnih prvin v pokrajini z vidika (pod)površinskih tokov* …«. Ne glede na definicijo ponuja uporaben okvir za razumevanje prostorskih razlik pri odtoku (Bracken s sod. 2013). Covino (2017, 133) navaja, da »… *se lahko hidrološka povezljivost vzpostavi prek nadzemnih ali podzemnih poti in se pojavlja v štirih razsežnostih* …«. Tri razsežnosti so prostorske (prečna, navpična in vzdolžna), četrta razsežnost pa je čas. Hidrološke povezave niso enosmerne, ampak obsegajo več razsežnosti ter delujejo na različnih časovnih ravneh (od sekund do tisočletij) in prostorskih ravneh (od milimetrov do več tisoč kilometrov).

Hidrološka povezljivost je lahko strukturna (statična) ali funkcionalna (dinamična ali procesna). Strukturna povezljivost se nanaša na prostorske vzorce v pokrajini, kot so prostorska razporejenost pokrajinskih enot, ki vplivajo na vzorce vodnega prenašanja gradiva in poti pretoka, funkcionalna povezljivost pa se nanaša na to, kako ti prostorski vzorci delujejo na procese v porečjih, da omogočajo odtok, povezan pretok in s tem vodno prenašanje gradiva v porečjih (Turnbull, Wainwright in Brazier 2008; Bracken s sod. 2013). Skratka, »… *strukturna povezljivost se nanaša na obliko in arhitekturo pokrajine, funkcionalna povezljivost pa obsega vse procese, na katere ta struktura vpliva* …« (Masselink 2017, 3). V dosedanjih raziskavah so bile uspešno opisane prvine, ki določajo strukturno povezljivost, medtem ko je prvine funkcionalne povezljivosti težje izmeriti in kvantificirati. Kljub temu pri razumevanju hidrološke povezljivosti ne smemo pozabiti na pomen součinkovanja topografskih dejavnikov in procesov v porečjih (Bracken s sod. 2013). Wohl s sod. (2019, 8) navaja, da »… *statični okviri dajejo hiter vpogled v to, kako je pokrajina zgrajena in deluje v katerem koli trenutku. Dinamični okviri temeljijo na treh ključnih dejavnikih. Prvič, zgradba pokrajine se lahko spreminja, zato se lahko spreminjajo tudi vrsta, položaj in vzorci reliefa v pokrajini, kar nato spreminja povezljivost. Drugič, jakost funkcionalne povezljivosti se bo najverjetneje spremenila glede na spremembe v strukturni konfiguraciji. Tretjič, strukturna konfiguracija in funkcionalna povezljivost se lahko spremenita glede na razsežnost motenj, ki vplivajo na pretok vode in sedimentov skozi pokrajine* …«.

Covino (2017, 134) razlikuje pet oblik hidrološke povezljivosti:

- 1. povezljivost med vodotokom in pobočjem kot temeljno povezavo med kopenskimi in vodnimi okolji, ki se lahko vzpostavi prek nadzemnega pretoka ali podzemnih povezav, in je prostorsko in časovno spremenljiva;
- 2. povezljivost med vodotokom in podzemno vodo kot izmenjavo vodotoka in podzemne vode ali dvosmerno povezavo med vodotoki in podzemnimi vodami (slika 1);
- 3. povezljivost med vodotokom in njegovim poplavnim območjem kot dvosmerno gibanje vode, sedimentov, organskega gradiva ipd. med vodotoki in njihovimi poplavnimi območji glede na pogoje vodnega pretoka (slika 2); na primer ob visokem pretoku se reka s poplavnim območjem poveže tako, da prestopi bregove, ob nizkem pretoku pa podtalnica na poplavnem območju vzdržuje osnovni pretok reke;
- 4. vzdolžno povezljivost kot povezavo med vodotokovim povirnim in izlivnim (nižinskim) delom, ki omogoča enosmerno gibanje vode in sedimentov ter dvosmerno gibanje organizmov po rečni mreži, in
- 5. povezljivost med vodotokom in jezerom, pri kateri naravna (slika 3) in umetna jezera ter ribniki upočasnijo prenašanje gradiva, zadrževalni čas je daljši, sedimentacija pa se okrepi.

Ker so vse oblike hidrološke povezljivosti med sabo povezane, posamezne povezljivosti ni mogoče upravljati popolnoma ločeno od drugih (Covino 2017). Tudi v pokrajinsko raznoliki Sloveniji (Perko, Ciglič in Hrvatin 2017; Perko, Ciglič in Zorn 2020) se vse oblike hidrološke povezljivosti prepletajo in prostorsko hitro spreminjajo (slike 1 do 3).

Slika 1: Presihajoče Cerkniško jezero je zelo zanimiv primer hidrološke povezljivosti med vodotokom in podzemno vodo, saj se med različnimi letnimi časi izrazito spreminja in prepleta z drugimi povezljivostmi.
Glej angleški del prispevka.

Slika 2: Jovsi so miniaturna zavarovana kulturna pokrajina mokrotnih travnikov vzdolž okljukov reke Sotle, ki jih obkroža potok Sušica. So primer hidrološke povezljivosti med vodotokom in poplavnim območjem.
Glej angleški del prispevka.

Slika 3: Bohinjsko jezero je primer hidrološke povezljivosti med vodotokom in jezerom, njegov pritok Savica pa je hkrati primer hidrološke vzdolžne povezljivosti med povirjem in izlivom vodotoka ter med vodotokom in pobočjem.
Glej angleški del prispevka.

4 Kako se lahko določi povezljivost?

Večina raziskav hidrološke povezljivosti se osredotoča na konceptualne okvire, kazalnike in modeliranje. S konceptualnimi okviri in modeli se opisujejo sestavine povezljivosti v porečju. Večina kazalnikov in metod merjenja za opisovanje povezljivosti je temeljila na topografiji, pri čemer so bili uporabljeni digitalni modeli višin (DMV), podatki o vlažnosti tal ali kombinacije študij, ki so temeljile na DMV-jih in terenskih opazovanjih. Povezljivost lahko opišemo kot nominalno spremenljivko, skalarni vektor ali kompleksni vektor. Težava pri tovrstnih opisih je v tem, da slonijo na meritvah ali ocenah na samo eni ravni in da niso vedno primerni za uporabo v celotnem porečju (Masselink 2017).

Trenutno v hidrološki in geomorfološki strokovni javnosti vlada enotno mnenje, da se povezljivosti ne da neposredno meriti, ampak jo je treba določiti na podlagi meritev drugih spremenljivk. Strukturna povezljivost se lahko določi na podlagi meritev topografije in zgradbe pokrajine, funkcionalna povezljivost pa na podlagi meritev pretokov in sledenja sedimentov (Masselink 2017). Čeprav je bila povezljivost kvantificirana v številnih raziskavah, jih večina uporablja pristope, razvite za obravnavo točno določenega vprašanja, v le malo raziskavah pa so avtorji skušali oblikovati metode merjenja, ki bi bile širše uporabne (Bracken s sod. 2013; 2015).

Wohl s sod. (2019) navaja, da je eden izmed pristopov k merjenju povezljivosti ta, da se določijo temeljne časovne in prostorske ravni preučevanega pojava ter opravi dovolj meritev na izbranih temeljnih ravneh, da se zajame dovolj reprezentativen vzorec. Pri drugem pristopu se skuša določiti, kako se povezljivost spreminja z ravnjo merjenja, pri čemer se enaka metoda merjenja uporabi na najrazličnejših ravneh ali pa se uporabijo statistični kazalniki, ki prikažejo frekvenčno porazdelitev povezljivosti na različnih ravneh.

Cilj večine raziskav povezljivosti je predvsem razumeti, kako povezljivost vpliva na izbrane vidike pokrajinske dinamike. Preprost pristop, ki se za to lahko uporabi, je neposredno kvantificiranje pretokov in uporaba teh meritev za določanje stopnje povezljivosti v sistemu prenašanja gradiva. To se lahko izvede na samo eni izbrani točki, kot je odtok s prispevne površine, ali na več lokacijah, razporejenih po sistemu. V nasprotju od kvantificiranja odtoka iz celotnega sistema na samo eni točki v prostoru je merjenje lokalnih učinkov povezljivosti na več lokacijah v pokrajini bolj zapleteno. Ta izziv lahko uspešno premagamo z numeričnimi modeli, s katerimi predvidimo izide za vsako točko v pokrajini. Metode modeliranja vključujejo uporabo celičnih avtomatov, procesnega modeliranja, statističnih modelov in GIS-ov na podlagi teorije omrežij (Wohl s sod. 2019). Primer modeliranja je indeks povezljivosti (Borselli, Cassi in Torri 2008), ki kaže relativno učinkovitost prenašanja gradiva gorvodno ali dolvodno na kateri koli točki v pokrajini na podlagi topografskih značilnosti, kot so prispevna površina, srednji naklon in razdalja med prvinami. Za več kazalnikov in indeksov hidrološke povezljivosti glej Bracken s sod. (2013), Wohl (2017) ter Wohl s sod. (2019).

5 Pomen

Pojem povezljivosti je uporaben za razumevanje pojava ter poti vode in sedimentov v sistemu. »*… Uporaben je za določanje prevladujočih procesov, ki odražajo učinkovitost pretokov v modelih …*« (Keesstra s sod. 2018, 1568).

Wohl (2017) navaja, da je povezljivost uporabna z različnih vidikov hidrološkega procesa:

- 1. pri razumevanju prostorskih ter časovnih ravni različnih vrst in stopenj povezljivosti, na podlagi česar lahko uskladimo neskladja med neposrednimi meritvami pretokov in izpeljanimi stopnjami pokrajinskih sprememb;
- 2. pri razumevanju odpornosti in prožnosti vodotokov na naravne in antropogene motnje;
- 3. pri prepoznavanju procesov, ki presegajo tradicionalne meje med strokami in prostorske meje znotraj pokrajin;

- 4. pri določanju dejavnikov in procesov, ki vplivajo na zadrževanje ali odlaganje različnega gradiva (na primer vode, topljencev, sedimentov in organskih snovi);
- 5. pri pridobivanju kritičnega vpogleda v pojav nelinearnih učinkov vodotokov, ter
- 6. pri določanju dejavnikov, ki olajšajo ali omejujejo učinkovito upravljanje vodotokov.

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6 Viri in literatura

Glej angleški del prispevka.