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Quantifying hydrological connectivity using a brain neuroscience framework: opportunities, challenges and ways forward

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The concept of connectivity is increasingly applied in hydrology and ecology despite a lack of universally agreed quantification framework. Conversely, brain neuroscientists use techniques to quantify connectivity, especially aspects related to structural connectivity (SC) (i.e. anatomical structure of the brain neural network), functional connectivity (FC) (i.e. statistical dependencies between neural signals), and effective connectivity (EC) (i.e. causal relations based on the assumption that "true" interactions occur with a certain time delay). The goal of the current study was therefore to borrow techniques from brain neuroscience so as to distinguish structural connectivity (i.e. physical adjacency of landscape elements that can facilitate material transfer) from functional or process/effective connectivity (i.e. interactions or causal relations between spatial adjacency characteristics and temporally varying factors). The focus was on groundwater and streamflow time series monitored across 35 individual sites in a 20 ha pre-alpine headwater catchment in Switzerland. Structural connectivity was assessed through influence maps that quantify the percentage of flow from an upslope site to a downslope site via a multiple flow direction algorithm. Functional connectivity between sites was assessed by cross-correlation, total, partial and lagged mutual information between pairs of groundwater and/or streamflow time series. Effective connectivity between sites was rather quantified by total, partial and lagged entropy and Granger causality between pairs of time series. Results show that many structural connections between sites were also expressed as functional or effective connections, which is reasonable in a catchment with shallow perched groundwater tables. However, some measures detected the presence of functional or effective connectivity despite the absence of structural connectivity, thus highlighting some of the limits of directly transferring brain connectivity measures to hydrology with no modification or data pre-processing. Interpretations about the presence/absence of connectivity, and the degree of connectivity, were also highly dependent on statistical significance tests as well as user-defined interpretation thresholds. Overall, the data analysis exercise performed here was useful to identify specific scenarios in which the application of brain neuroscience may prove difficult in hydrology: unbounded FC and EC measures made the assessment of weak versus strong connections uncertain; the length of time series has an influence on whether perennial or ephemeral connectivity is assessed; and there was limited possibility to distinguish direct connectivity from indirect connectivity (i.e. when two sites are indirectly connected via a third one). Still, we conclude that brain neuroscience methods for quantifying FC and EC can be powerful tools in assessing hydrological connectivity as long as they are constrained by SC measures.