Quantifying hydrological connectivity using a brain neuroscience framework

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Introduction

Hydrology

- Concept of connectivity has gained popularity
- Little agreement exists on its definition & quantification

Neuro-Sciences

- Clear conceptualization of connectivity
- Clear approaches to quantify connectivity

Table 1: Structural, functional and effective connectivity in hydrology and the brain neuroscience.

Connectivity	Hydrology	Brain Neuroscience
Structural	Structural elements of a catchment that can facilitate flow of water, solutes and sediment between landscape units (e.g., drainage network)	Brain anatomy i.e., physical connections linking sets of neurons or neuronal elements (e.g., neural network)
Functional	Magnitude, frequency, duration, timing and rate of water transfer that links disparate locations	Statistical dependencies between neural electric timeseries (e.g., magnetoencephalogram MEG)
Effective	Actual movement of water, sediment, nutrients between a source and a target site	Causal (directed) relations between timeseries assuming that "true" interactions occur with a certain time delay

Rationale and Objectives

- Similarities in the terminology of connectivity in hydrology and the brain neurosciences (Figure 1).
- Idea: Connectivity measures used in brain neuroscience can potentially capture properties of hydrol connectivity (Table 2).

1) Application of brain connectivity measures in hydrology
2) Feasibility study and recommendations for future research

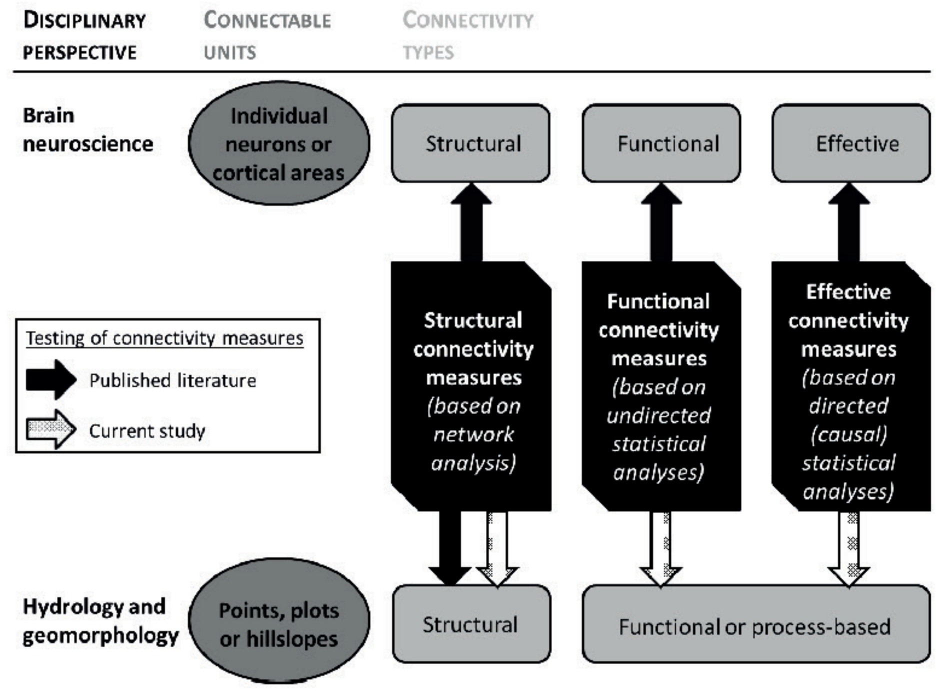
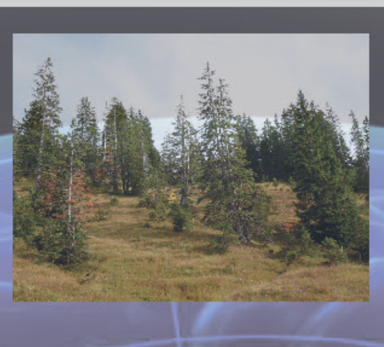


Figure 1: Similarities in the connectivity concepts in hydrology and the brain neurosciences.

Case Study

- 20 ha experimental catchment, Pre-Alpts, Switzerland
- Steep terrain (average slope 35%)
- Low-permeability soils (Gleysols)
- 2300 mm/yr precipitation, frequent rainstorms
- 34 groundwater and 1 streamflow time series
- 5 min time interval (August 2013 to May 2014)



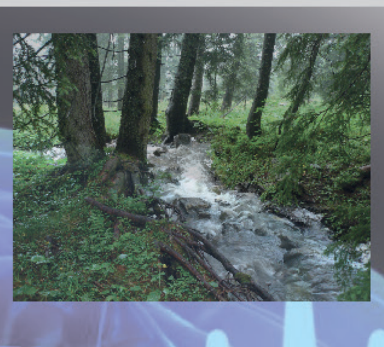
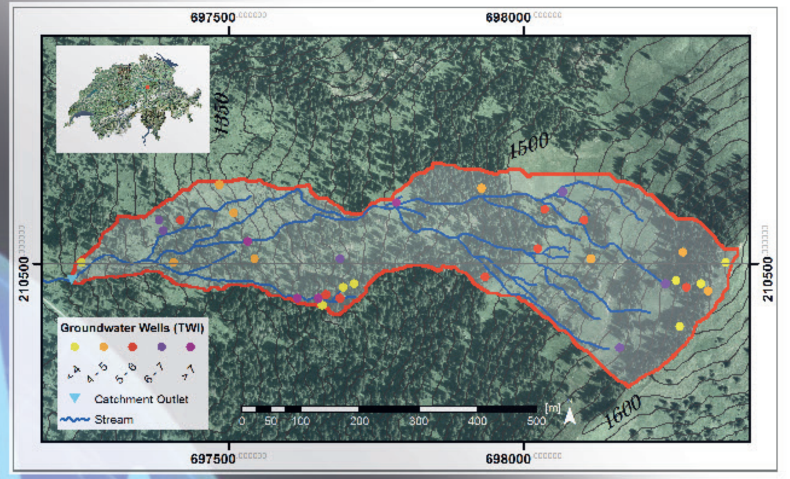


Figure 2.: (right): Map of the study catchment showing the location of the 34 groundwater wells, (above): steep slopes and stream in the upper part of the catchment.



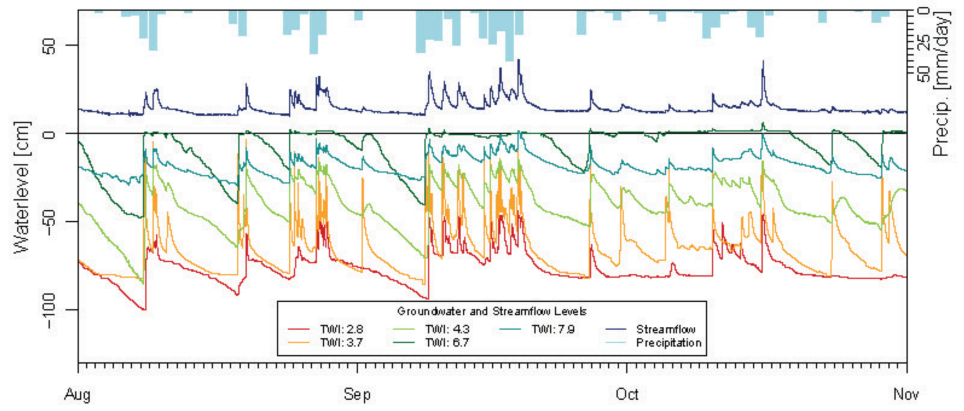


Figure 6.: Selected groundwater and streamflow timeseries unsed in the case study. The assumption is that the amplitude, response frequency and timing can be interpreted in terms of connectivity between individual monitoring sites.

Functional & Effective Connectivity

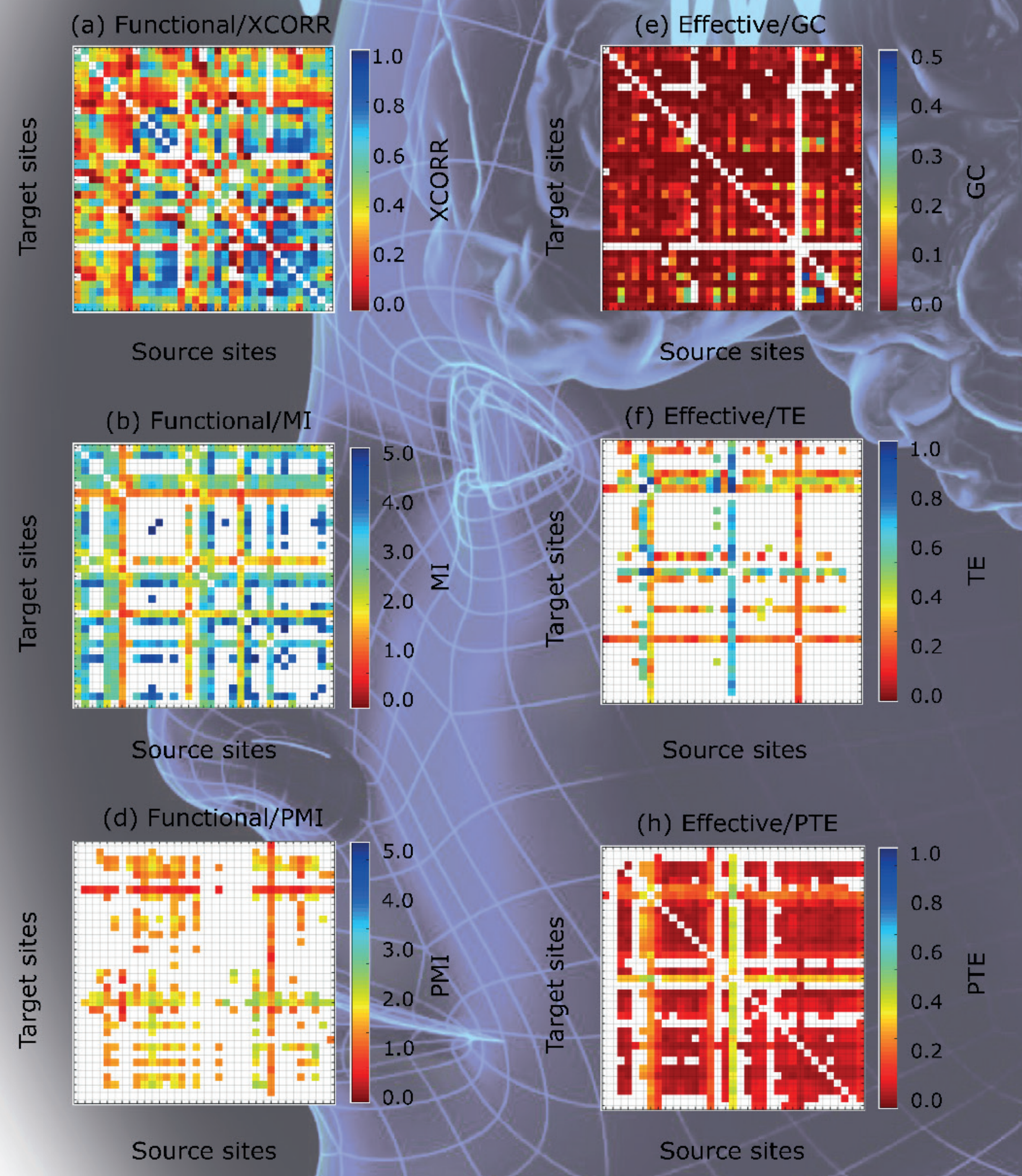


Figure 3.: Functional and effective connectivity matrices for the 34 groundwater wells and the catchment outlet. Cells are color-coded according to the value of the connectivity measure calculated between the source site (x-axis) and the target site (y-axis); blank cells: computed connectivity is not statistically significant. "Partial" measures (PTE and PMI) account for the effect of antecedent wetness (estimated as 24-hour antecedent precipitation minus evapotranspiration) on connectivity. (For abbreviations see Table 2).

Structural Connectivity

- Influence map quantifying structural connectivity. Cell value express the percentage of flow from a source pixel (red) to downslope pixels using a multi-flow direction routing algorithm

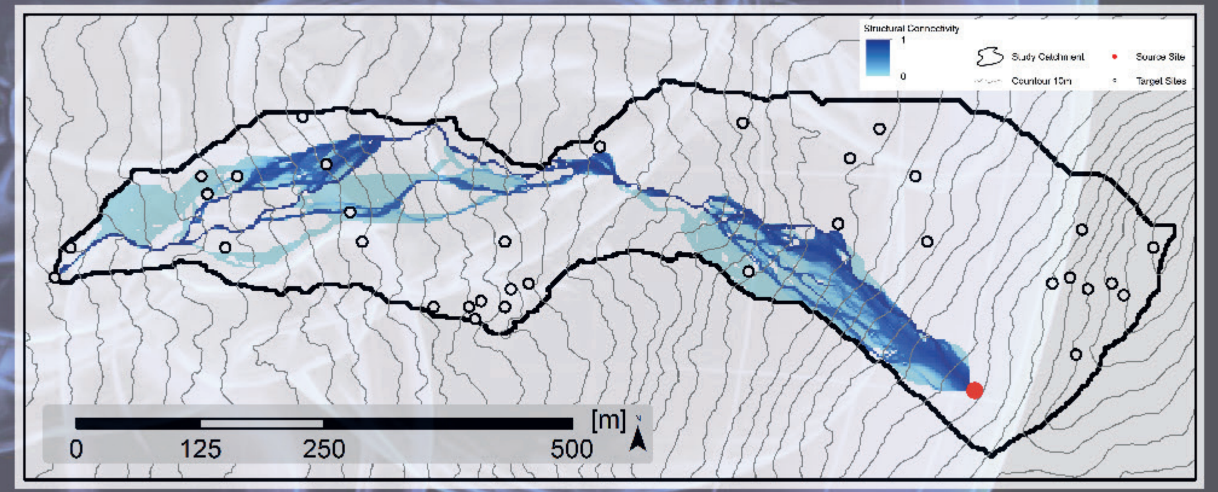


Figure 4.: Example of an influence map between a source site (red circle) and any groundwater or streamflow monitoring location (black circles). Shades of blue illustrate the degree of structural connectivity, i.e., the percentage of flow from the source pixel that is likely to reach any target pixel.

- Point-to-point and point-to-stream connectivity can then be expressed as a structural connectivity matrix

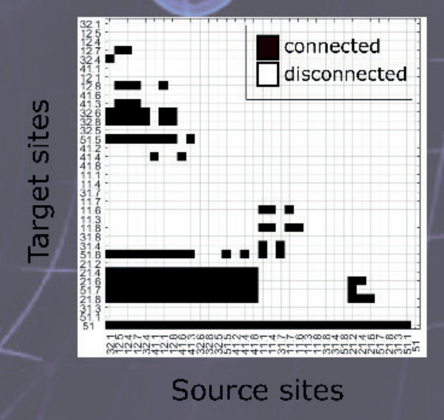


Figure 5.: Structural connectivity matrix for the 34 groundwater monitoring locations and the catchment outlet. Black Cells indicate that there is flow from the source point (x-axis) that is likely to reach the target point (y-axis). White cells signal the absence of structural connectivity (no flow path).

Brain Connectivity Measures

Table 2.: Theoretical ability of brain connectivity measures to capture specific properties of the hydrologic fluxes that support hydrologic connectivity. (the specific property can be captured if the spectral (or frequency domain) version of the connectivity measure is used; ** the specific property can be captured if the values can be standardized against a known maximum value).*

Connectivity measure	Acronym	Type	Frequency	Magnitude	Timing	Duration	Rate
Cross-correlation	XCORR	FC	Yes*	Yes	Yes	No	No
Mutual Information	MI	FC	No	Yes**	No	No	No
Partial Mutual Information	PMI	FC	No	Yes**	No	No	No
Transfer Entropy	TE	EC	No	Yes**	No	No	No
Partial Transfer Entropy	PTE	EC	No	Yes**	No	No	No
Granger Causality	GC	EC	Yes*	Yes**	No	No	No
Phase Slope Index	PSI	EC	Yes	Yes**	Yes	No	No

Conclusions

- The application of brain connectivity measures in hydrology is promising when constrained by structural connectivity measures.
- Not one "best" connectivity measure but individual measures capture different characteristics of hydrological connectivity.
- Some point-to-point connections were functionally or effectively connected despite the absence of a structural connection.
- Challenge to transfer connectivity thresholds* from the neurosciences to hydrology (*: connectivity values above which two sites are considered to be connected)

- See recently published paper in Earth-Science Reviews

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