Quantifying Hydrologic Connectivity with Measures from the Brain Neuro-Sciences

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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 neuro-science.

Connectivity	Hydrology	Brain Neuro-Sciences
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 time series (e.g., Electro Encephalogram EEG)
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

Objectives

- Similarities in the terminology of connectivity in hydrology and the neuro-sciences (Figure 1).
- Idea: Brain neuro-science connectivity measures can potentially capture properties of hydrological connectivity (Table 2).

1) Applying brain-connectivity measures in hydrology
2) Feasibility study and recommendations for future research

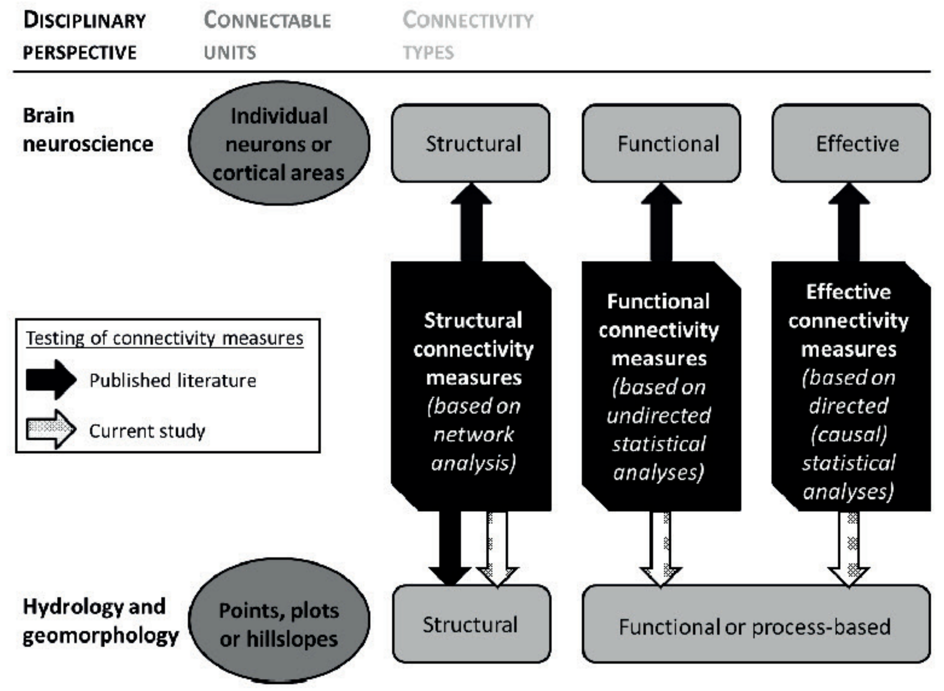

Figure 1: Similarities in the connectivity concepts in hydrology and the brain neuro-sciences.

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)

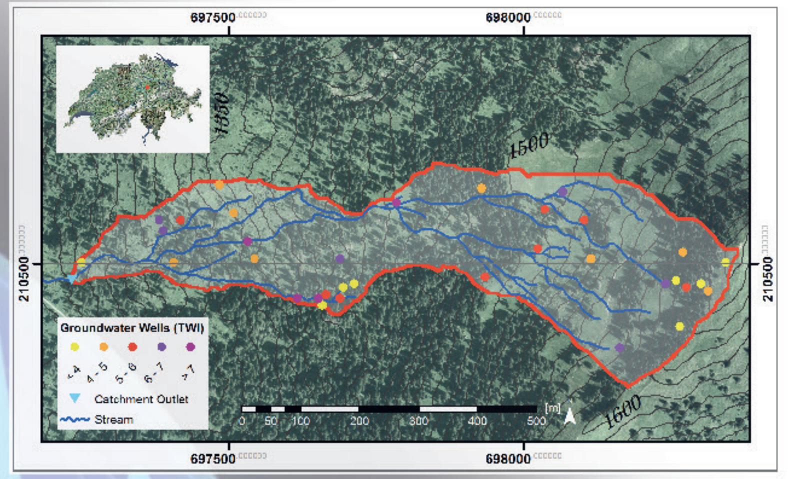

Figure 2.: (right): Map of the study catchment showing the location of the 34 groundwater wells, (above): steep slopes and stream in the upper part of the catchment.

Functional & Effective Connectivity

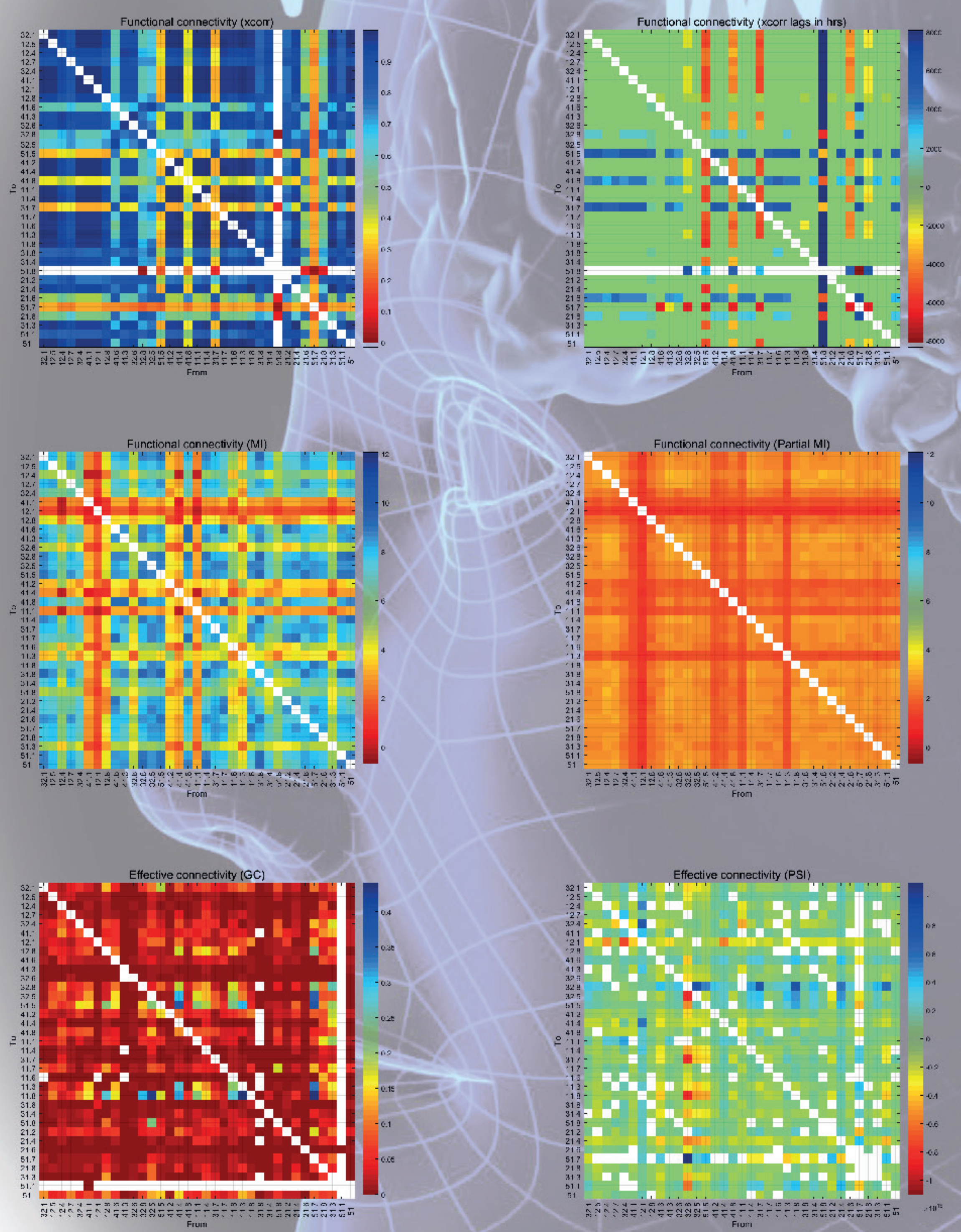

Figure 3.: Functional and effective connectivity matrices for the 34 groundwater wells and the catchment outlet. Cells are color-coded according to the value of the connectivity measure calculated between the source site (x-axis) and the target site (y-axis); blank cells: computed connectivity is not 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

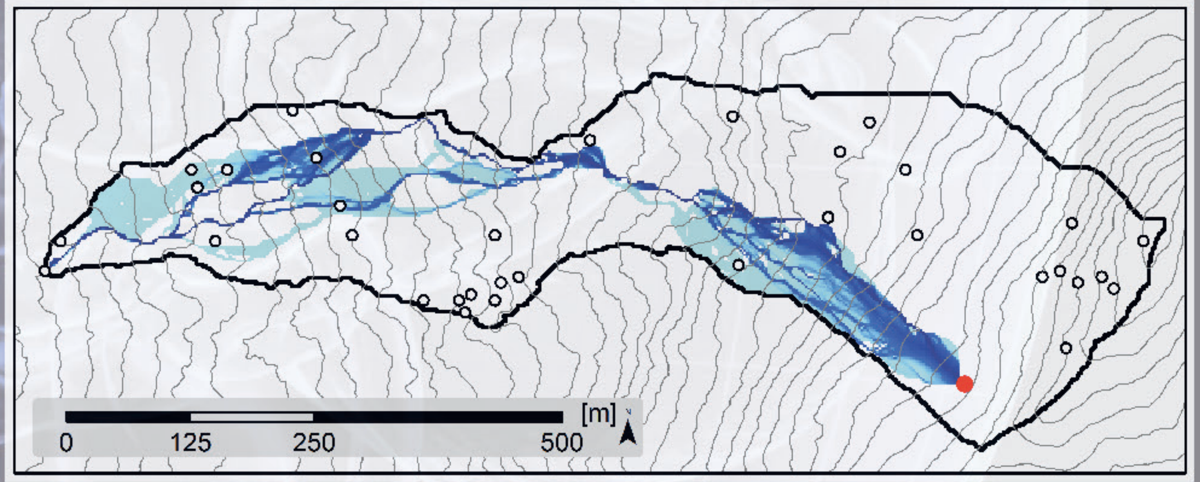

Figure 4.: Example of an influence map between a source site (red circle) and any groundwater or streamflow monitoring location (black circles). Shades of blue illustrate the degree of structural connectivity, i.e., the percentage of flow from the source pixel that is likely to reach any target pixel.

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

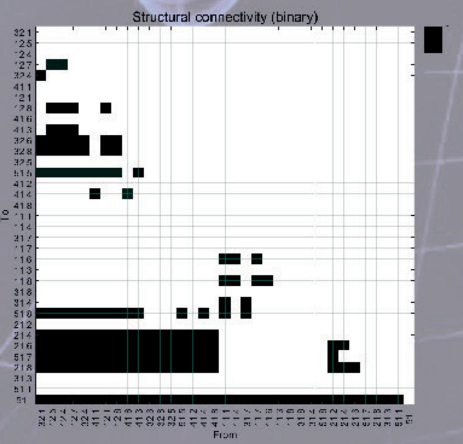

Figure 5.: Structural connectivity matrix for the 34 groundwater monitoring locations and the catchment outlet.
Black Cells indicate that there is flow from the source point (x-axis) that is likely to reach the target point (y-axis);
White cells signal the absence of structural connectivity (no flow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

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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 neuro-sciences to hydrology (*: connectivity values above which two sites are considered to be connected)

Brain Connectivity Measures

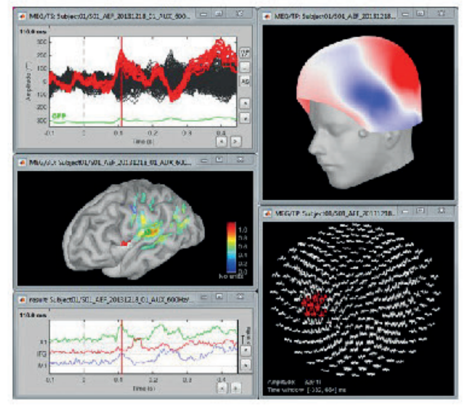

Figure 6.: Time series of electric currents in the human brain (magnetoencephalogram MEG) are analysed in terms of connectivity between neuronal elements when a person is performing certain activities. (Figure taken from Tadel et al., 2011)

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

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