Quantifying Hydrologic Connectivity with Measures from the Brain Neuro-Sciences

Michael Rinderer (1,2), Genevieve Ali (3,4), Laurel Larsen (5)
michael.rinderer@hydrolgy.uni-freiburg.de

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 relative connectivity in hydrology and the brain neuro-science

<table>
<thead>
<tr>
<th>Connectivity</th>
<th>Hydrology</th>
<th>Brain Neuro-science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>Structural elements of a catchment that the hydraulic flow of water, solutes and sediment between landscape units (e.g., drainage networks)</td>
<td>Brain anatomy, i.e., physical connectivity and routing of networks or neuronal elements (e.g., neural networks)</td>
</tr>
<tr>
<td>Functional</td>
<td>Spatial, frequency, duration, timing and rate of water movement that links discharge locations</td>
<td>Statistical dependencies between water fluxes at different time scales (e.g., Delta DrylandSoil03)</td>
</tr>
<tr>
<td>Effective</td>
<td>Spatial and temporal variations between discharge locations that express water interactions occur with a common time delay</td>
<td>Transport processes between sources, sediments and nutrients between a source and target site</td>
</tr>
</tbody>
</table>

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

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

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

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

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 no relationships considered to be connected

Brain Connectivity Measures

Table 3: Theoretical study of brain connectivity measures to capture specific properties of the hydrologic system that support hydrologic connectivity. (*: the specific property can be captured if the specific connectivity measure is used) **: the specific property can be captured if certain criteria can be satisfied against a known neuroscientific validation.

<table>
<thead>
<tr>
<th>Connectivity</th>
<th>Measure</th>
<th>Acronym</th>
<th>Type</th>
<th>Frequency</th>
<th>Magnitude</th>
<th>Timing</th>
<th>Scale</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>SCRM</td>
<td>CR</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Functional</td>
<td>FC</td>
<td>FC</td>
<td>No</td>
<td>No</td>
<td>No**</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Effective</td>
<td>E</td>
<td>E</td>
<td>Yes</td>
<td>Yes**</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Figure 1: Definition of the connectivity concepts in hydrology and the brain neuro-sciences

Figure 2: Envelope of the spatial extent showing the location of the 34 groundwater wells, stream, topographic contours and the boundaries of the catchment

Figure 3: Functional and effective connectivity values for the 34 groundwater wells and the catchment outlet. Darker color indicates a higher connectivity. The functional connectivity (FC) expresses the functional connectivity, i.e., the connectivity between two variables, considering both spatial and temporal dependencies (Table 2).

Figure 4: Distance or flow map between a cell (or node) and any groundwater or stream outlet expressing the connectivity. Darker cells indicate a higher structural connectivity (the higher path, the darker cells indicate the absence of structural connectivity (the lower path).

Figure 5: Structural connectivity matrix for the 34 groundwater wells considering both the catchment outlet (Source) and spatial dependencies (flow from the source point, i.e., the location of the catchment outcrop). The matrix expresses the connectivity between all variables (Table 3).

Acknowledgments
Field assistance: S. Cerviño, J. Deak, S. Krueger, M. Bautista, N. Hoxingas, S. Pfeifer, B. Scherer
Keywords: hydro-geomorphology; brain neuro-science; connectivity

Figure 6: Time series of electric current in the human brain (MaxPlanck-Institute SCI) are analyzed in terms of connectivity measures to identify the existence of specific connectivity matrices that support certain activities. (Figure taken from Taft et al., 2015)