Calculation of Side-Separated Contributions to Stream Networks – A New Tool to Characterize Riparian Zones

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1. Introduction

Streams play a key role in many environmental studies and research areas. From a hydrological perspective, streams and other flow pathways carry the spatio-temporally convoluted signal of all upstream, hydrologically-connected processes. Modern tools for GIS-based hydrological landscape analysis (HLA) embrace this concept for calculating values of upslope area or for aggregating upslope terrain indices. Recent studies, however, suggest that not all upslope processes contribute equally to the observed stream signal and that particularly riparian zones hold the key for a better understanding of stream responses. Riparian zones are, by nature, elongated strips of land directly adjacent to a stream network and located on both of its sides. Being the last stage before a drop of water enters a stream network, the potential imprint left by riparian zones is likely to be considerably larger than indicated by their actual extend. However, traditional HLA methods used to characterize these zones are mostly inapplicable because most methods fail to account for small extend of riparian zones and for the fact that they are located on opposite sides in a stream network.

To overcome limitations of traditional HLA methods, we developed a novel method to calculate side-separated contributions from adjacent hillslopes. Water table and elevation data from the 22 km^2 Tenderfoot Creek catchment, Montana, demonstrated clearly the importance of the new method. Separating contributions from the two sides produced significantly different results than produced by standard HLA methods. More importantly, only upslope area calculated by the new method was able to predict the hydrological connection between hillslope and riparian water tables as observed in 24 transects along the stream network.

2. Material and Methods

Our new algorithm determines the side of contributing hillslopes relative to a stream network based on geometric calculations. Since these calculations are performed separately, this method can be combined with virtually any existing flow accumulation algorithm for calculating upslope area (UA). The algorithm requires an elevation map and a stream direction map (SDM). The SDM is composed of connected stream vectors while the elevation map can be represented by various data structures such as regular grids, triangular irregular networks or contours. At this stage, we implemented the algorithm in the open-source tool SAGA GIS (Böhner et al., 2008) for use with regular grid data. Correspondingly, stream vectors in the SDM are grid cells with integer values representing different flow directions (Figure 1) and the used elevation map is a standard digital elevation model (DEM). The SDM was derived from the DEM using the "Channel Network" module in SAGA GIS (Böhner et al., 2008).

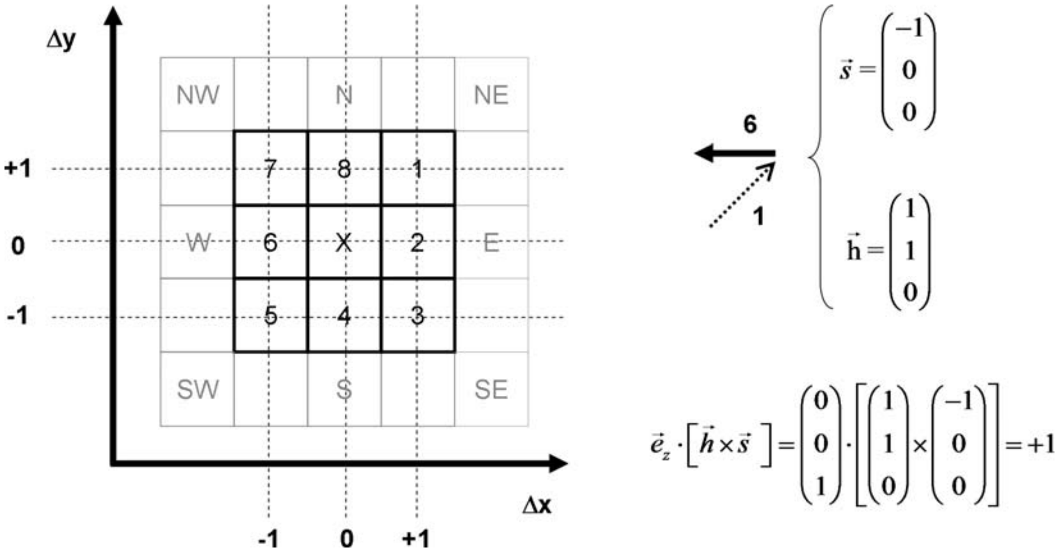

Figure 1. Directions relative to the center grid cell X are coded from 1 to 8 clockwise from northeast (NE) to north (N). The corresponding vector notation is illustrated for a hillslope vector $\vec{h}$ in direction 1 (dotted arrow) and for a stream vector $\vec{s}$ in direction 6 (plain arrow). Calculating the cross product $\vec{h}\times\vec{s}$ reveals a positive z-component and therefore the hillslope vector $\vec{h}$ is located on the left side relative to the stream vector $\vec{s}$.

The algorithm functions as follows. For every grid cell of the DEM that drains into a downslope SDM grid cell, the algorithm determines the corresponding hillslope vector $\vec{h}$ as well as the stream vector of the downslope SDM grid cell, $\vec{s}_0$, and all stream vectors $\vec{s}_{i+1}$ of upstream SDM grid cells that are directly connected to $\vec{s}_0$ (Figure 2). To find the position of the hillslope relative to the stream, the algorithm next calculates the cross products $\vec{c}_i$ of all pairs of the hillslope vector $\vec{h}$ with different stream vectors $\vec{s}_i$:

$$\vec{c}_i=\vec{h}\times\vec{s}_i\,,\quad i\geq 0 \tag{1}$$

Since $\vec{h}$ and $\vec{s}_i$ are horizontal vectors with z-components equal to zero, the resulting cross products, $\vec{c}_i$ are perpendicular to the map plane and only their z-components, $\vec{e}_z\cdot\vec{c}_i$, are normally different from zero. The sign of the z-components indicates the position of the hillslope relative to the considered stream vector. If left and right are defined looking in parallel direction to the stream vector $\vec{s}_0$, that is looking in downstream direction of the stream, then a negative z-component indicates that the hillslope is located on the right side relative to the stream vector. Similarly, a positive z-component indicates that the hillslope is on the left side of the stream vector. If all z-components of all cross products, $\vec{e}_z \cdot \vec{c}_i$, have the same sign the position of the hillslope can be directly inferred by from the sign of all $\vec{e}_z \cdot \vec{c}_i$. Exceptions occur when z-components have opposite signs, are equal to zero or in cases where the hillslope drains into endpoints of the stream network, which can be either sources, sinks or outlets (Figure 2). All exceptions are treated separately.

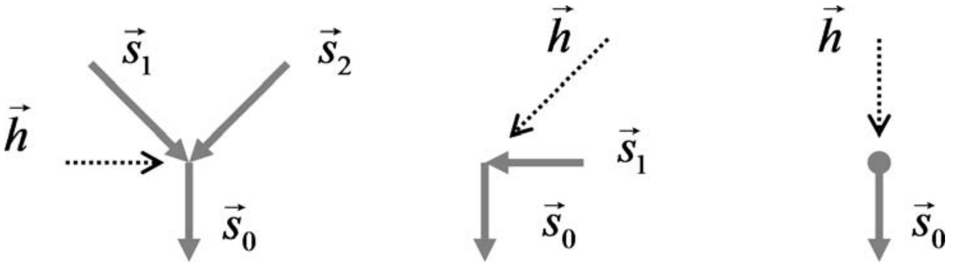

Figure 2. Different configurations of hillslope $\vec{h}$ (dotted arrows) and stream vectors $\vec{s}_i$, $i \geq 0$ (plain arrows). The left graph depicts a hillslope vector $\vec{h}$ pointing to a stream junction. In this case, the associated hillslope is attributed on the right stream side because it is on the right side relative to all stream vectors $\vec{s}_i$. A typical stream bend is shown in the middle graph. $\vec{h}$ is o the left side relative to $\vec{s}_0$ and on the right side relative to $\vec{s}_1$ and therefore on the outer side of the bend. Since the cross product $\vec{s}_1 \times \vec{s}_2$ has a negative z-component the inner bend must be located on the left stream side and hence on the right stream side. The graph on the right illustrates a hillslope upstream of a source. In this case the side of the hillslope is not definable.

3. Application and Results

We demonstrate the value of separating the stream into its left and right sides by comparing UA computed from a DEM of Tenderfoot Creek Experimental Forest (TCEF). TCEF is located in the Little Belt Mountains of the Lewis and Clark National Forest in Central Montana, USA. The research area consists of seven gauged catchments that form the headwaters of Tenderfoot Creek (22.8 km^2), which drains into Smith River, a tributary of the Missouri River. The 7 TCEF sub-catchment areas range in size from 3 to 22.8km^2. Catchment headwater zones are typified by moderately sloping (avg. slope ~ 8°) extensive (up to 1200m long) hillslopes and variable width riparian zones. Approaching the main stem of Tenderfoot Creek the streams become more incised, hillslopes become shorter (< 500m) and steeper (average slope ~20°), and riparian areas narrow compared to the catchment headwaters.

A preliminary comparison of inflows from the right side against inflows from the left side (Figure 3), all derived from a 10 m DEM of a 23km^2 catchment in (TCEF), showed no correlation between the inflows, which can be expected. This also illustrates that the total inflow is no suitable proxy for the lateral inflows from the two respective sides.

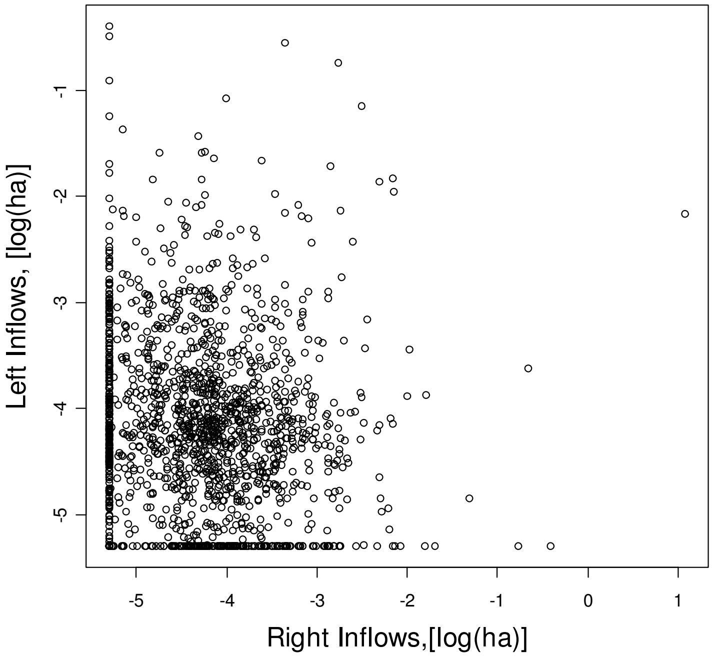

Figure 3. Scatter plot of inflows from the left versus inflows from the right side in the derived from a DEM of a 23km^2 catchment in TCEF

The distinction of opposite stream sides when calculating UA is theoretically plausible and also has practical implications. This was shown in a recent study by Jencso et al. (2009). Jencso et al. (2009) applied the suggested algorithm to same previously mentioned DEM. They compared UA to the yearly-cumulative Hillslope-Riparian-Stream (HRS) water table connectivity across twenty four transects of shallow groundwater recording wells. Hydrologic connectivity between HRS zones was inferred from the presence of saturation measured in well transects spanning the hillslope, toeslope, and riparian positions. A HRS hydrologic connection was defined as a time interval during which stream flow occurred and both the riparian and adjacent hillslope well recorded water levels above bedrock.

Meaningful relationships between UA and HRS water table connectivity were only found using side-separated UA whereas total UA seemed unrelated to HRS water table connectivity (Figure 4) which clearly demonstrates the importance of the new method.

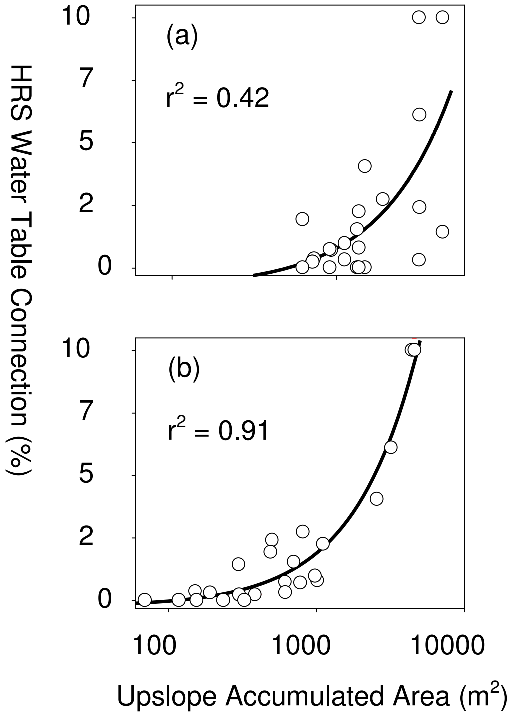

Figure 4. Hillslope UA regressed against the percentage of the water year that a hillslope-riparian-stream water table connection existed for 24 well transects. (a) Total hillslope UA from both sides of a transect cross-section. (b) Hillslope UA separated into left and right sides of the stream. A connection was recorded when there was stream flow and water levels were recorded in both the riparian and hillslope wells.

Riparian zones are also commonly referred to as buffer zones between streams and upslope areas. Any signal propagating from the upslope areas to the stream is modified, respectively buffered, by the intermediate riparian zone. To characterize the buffer capacity of riparian zones, McGlynn and Seibert (2003) introduced the ratio of riparian area to hillslope area as a new distributed terrain metric. High ratios are interpreted as high buffer capacities and vice versa. However, McGlynn and Seibert (2003) did not account for unequal lateral inflows when calculating buffer ratios. Redoing their calculations but using side-separated hillslope and riparian area ratios lead to significantly different results. For example, the catchment-wide median area-weighted buffer ratios are $1.7 \cdot 10^{-2}$ and $1.4 \cdot 10^{-2}$ for the lumped and side-separated calculations respectively, which corresponds to a relative error of about 26%. Local relative errors along the stream network even amount to 50% and more. Using the new method to compute side-separated inflows is thus an essential prerequisite for calculating realistic riparian hillslope ratios.

4. Concluding Remarks

Our findings highlight the importance and high potential benefits of using the new method to derive hydrologically meaningful characterizations of riparian zones. We are not aware of any other existing GIS-tool that allows discriminating lateral inflows.

While the need for such discrimination might depend on the type of index being calculated, it is crucial for calculating riparian-hillslope buffer ratios.

References

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