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Time-lapse visualization of spatial and temporal patterns of stream network dynamics

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1 | DESCRIPTION

Temporary streams (i.e., streams that experience zero flow, at least in some branches of the network) represent a fundamental part of riverine systems. Conservative estimates indicate that they constitute more than 30% of the global river network (Tooth, 2000). Temporary streams are ubiquitous, as they are found in arid or semi-arid areas as well as in humid regions (Skoulikidis et al., 2017), providing unique habitats continuously shifting between lotic and terrestrial conditions (Datry et al., 2014). Nevertheless, huge efforts are needed for acquiring empirical data about active stream dynamics, which are typically obtained from field surveys by visual inspection (Durighetto et al., 2020; Jensen et al., 2017) or through the deployment of a network of sensors (Assendelft & van Meerveld, 2019; Jensen et al., 2019; Kaplan et al., 2019). Over the years, there have been several attempts to modelling the full spatial and temporal dynamics of stream networks (Jensen et al., 2018; Ward et al., 2018). These models supported the identification of the main drivers of network expansion/contraction in different climatic regions of the world. However, representing the dynamics of the active fraction of the stream network is not straightforward, because of the intertwined spatial and temporal dimensions of the problem and the limited resolution of empirical data. Developing techniques for visualizing empirical data on river network dynamics not only could help researchers to represent and communicate their data to the general public, but could eventually enhance understanding of the physical processes that underlie stream dynamics. To the best of our knowledge, Ward et al. (2018) is the only study that reproduced temporally and spatially continuous dynamics of the active network by means of a reduced-complexity mechanistic model. In this study, we describe a novel data-driven procedure to reconstruct and visualize the expansion/contraction dynamics of a river network by exploiting information derived from a limited number of field surveys. This procedure combines the statistical approach proposed by Durighetto et al. (2020) to predict the temporal dynamics of the flowing length and the hierarchical model developed by Botter and Durighetto (2020) to explain spatial patterns of flow persistency. The empirical nature of this approach and the reduced number of parameters make it particularly suited to handle highly heterogeneous networks where spatially discontinuous flow patterns are observed.

The model application refers to the Rio Valfredda, a 5.3 km^2 catchment in the Italian Alps. The heterogeneous physiology of the catchment generates a variety of persistent and dynamic reaches, in spite of the humid climate of the area. A total of 10 surveys of the active network were performed in the study catchment from July to November, 2018, encompassing hydrological conditions spanning from dry to very wet. Field surveys did not continue during winter because the network became static in response to the low temperatures and the snow cover. For more detailed information about the catchment, the experimental activities and how the study period fits into the longer-term climate, the reader is referred to Durighetto et al. (2020). For each node of the network we calculated the local persistency, P_i, as the fraction of surveys during which the node was active (i.e., presence of visible water flow, at least 10 *cm* wide). Note that the location of each node was not predetermined, but specifically selected to properly describe the spatial variability of P_i (see Durighetto et al., 2020). P_i was then linearly interpolated along the network to provide a reliable representation of the spatial patterns of the local persistency. Daily precipitation data were collected by a nearby weather station. The available data allowed the development of a simple empirical model for predicting the temporal evolution of the length of the active network, L (km), as a function of antecedent precipitation (see Durighetto et al., 2020):

$$L = L_0 + k_{T1} \cdot h_{T1} + k_{T2} \cdot h_{T2}, \quad (1)$$

where L_0 (km) is the length of the permanent network; h_{T1} and h_{T2} (mm) are the antecedent precipitation accumulated on $T1$ and $T2$ days, respectively; k_{T1} and k_{T2} are empirical parameters that dictate the increase of active length for a unit increase of cumulated precipitation. L_0, k_{T1}, k_{T2}, $T1$ and $T2$ have been calibrated on the available data (R^2 = 0.99) and the robustness of the estimate has been assessed using a leave-one-out approach, thereby ensuring that L is correctly evaluated by the model also between field surveys.

The Stream Length Duration Curve (SLDC) of the Rio Valfredda (i.e., the inverse of the exceedance probability of the active length see Botter and Durighetto (2020)) was obtained from the experimental data through a Weibull plotting position method. This curve, that is analogous to the Flow Duration Curve, indicates the fraction of time for which a given active length is equalled or exceeded. Given $L(t)$, the spatial pattern of network activity can be reconstructed by assuming that node activation takes place in a hierarchical way, from the most to the least persistent (Botter and Durighetto, 2020). Under this assumption, the SLDC can be interpreted as the relationship between the active length and the corresponding persistence threshold, P^*, that separates active ($P_i > P^*$) from dry ($P_i < P^*$) nodes. This step recreates the spatial pattern of the active network relying on empirical data alone, without any additional parameter calibration.

The embedded video represents the change in the active network during 5 months (from 1 July to 6 December 2018) simulated using the aforementioned approach. The speed of the animation was adjusted by imposing a constant rate of change of the active length within all the frames, to slow down the periods with faster dynamics (e.g., the network expansion induced by precipitation events). Video S1 shows that different modes of network expansion and contraction concur to determine the observed changes in the active network of our study catchment. During stream expansion, some branches lengthen upstream while other expand downstream, either connecting to the outlet or remaining disconnected from the main river. During network contraction, disconnections frequently appear along many tributaries, especially in the lower-east part of the catchment where the limited soil permeability supports a flashy activity of the streams, thus enhancing flow intermittency. Furthermore, network expansion is much faster than the subsequent contraction, mirroring the positive skewness of the hydrograph (e.g., Botter & Rinaldo, 2003). As an example, during the huge rain event that took place in late October, the network lengthened from approximately 7 to 17 km in only 3 days, while more than 1 month was necessary to go back to the average length of 8 km. Overall, the video emphasizes the spatial heterogeneity of network dynamics, highlighting once more the importance of capturing high-frequency dynamics of the active network. The continuous nature of the animation, both in space and time, facilitates the identification of many important features of network dynamics which are much harder to catch from a sequence of static maps.

This work shows how network dynamics can be reconstructed and visualized starting from precipitation data and using a limited number of field surveys. The approach is based on the assumption that the activation of the network nodes is hierarchical, and utilizes an empirical regression between active length and precipitation. The novel visualization technique presented in this contribution allows an optimized use of empirical data about active stream dynamics, providing useful information on the influence of precipitation on network expansion and contraction cycles. The approach is also useful to enhance the resolution of empirical data within a mathematically robust framework, in which the temporal and spatial dimensions of the problem are suitably connected through the persistence of the network nodes.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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