A network theory approach for a better understanding of the dynamics of overland flow on hillslopes

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1. Introduction

Hydrological connectivity describes the physical coupling or linkages of different elements within a landscape regarding (sub)surface flows (Croke et al., 2005; Pringle, 2003; Stieglitz, 2003). A network approach where the elements are represented as nodes and the linkages or pathways between the elements are represented as edges would seem like an intuitive approach to study hydrological connectivity. There are examples of network theory for e.g. sediment connectivity (Heckmann and Schwanghart, 2013) or for channel patterns (Marra et al., 2014), but not for explaining runoff patterns on hillslopes or catchments. Network theory might provide a good way of analysing the behaviour of a hillslope or a catchment as a whole. The main objective of the STSM was to setup a network theory approach for analysing overland flow patterns on a hillslope in Northern Spain.

2. Work carried out during the STSM and main results

During the STSM in Eichstätt we looked at what the best way would be for creating graphs or networks using high resolution Digital Surface Models (DSM's) and data from overland flow sensors. For the largest part of the stay discussions were the most important part of the work carried out. The discussions were mainly on the approach to be taken to create the networks and how these should be analysed. The results of this discussion are discussed below.

Methods

Study Areas and data

The study area 'Latxaga' is situated in north Spain within the province of Navarre (Figure 1). 48 overland flow sensors were placed on a hillslope which is largely used for growing winter wheat, while a small portion of the hillslope has natural shrub vegetation. The slope is furthermore subdivided into a steep part and a relatively flat part (Figure 1). Soils are high in clay and silt content and mean annual precipitation is 840 mm of which the majority falls in winter.

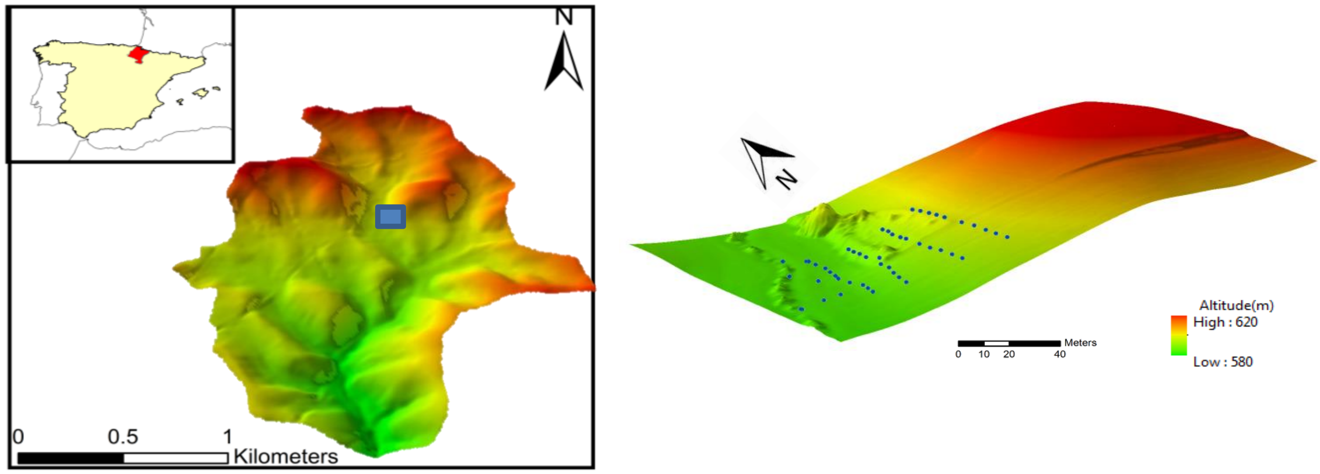

Figure 1: The Latxaga catchment in Navarre, Spain (left) and the hillslope with the locations of the overland flow sensors (right)

The overland flow sensors register every 10 seconds whether or not overland flow is present (Boolean system). A high resolution Digital Model (DSM) from the area was created using structure from motion stereo photogrammetry. The photos needed for the process were taken with a Panasonic Lumix GX1 on board a Mavinci Sirius 1 Unmanned Aerial Vehicle. The DSM has a resolution of 25 cm.

Structural and functional graph creation

A graph of the hillslope was constructed using a Multiple Flow Direction matrix calculated from the DSM, using the algorithm by Freeman (1991). Then using the procedure used by Schwanghart and Heckmann (2012) a probability matrix P of m*n rows, where m is the total number of pixels in the DSM and n is the number of sinks (sensors) was created. This matrix indicates for every pixel the probability that overland flow from the pixel reaches the overland flow sensors. Every pixel was assigned to an area corresponding to a sensor which has the highest probability of receiving overland flow from that particular pixel (Figure 2).

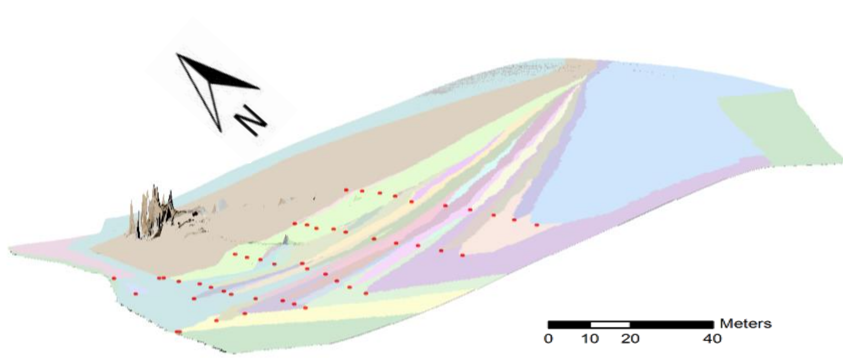

Figure 2: Delineation over contributing areas for the different sensors

After the delineation of the contributing areas a node for the graph was assigned to each of the areas. The flux between the two areas was then calculated as the sum of all probabilities of one area to reach the second sensor. If the sum of probabilities is higher than zero, a connection between the two areas exists and an edge is created with a ‘flux’ and ‘weight’. The flux is calculated as the equivalent catchment area of area 1 to reach sensor 2 ($ECA_{1,2}$). The equivalent catchment area is defined as the equivalent surface within the area that contributes to the sensor. The weight is calculated as the ratio between this flux and the total equivalent catchment area of area1.

$$W_{1,2} = \frac{ECA_{1,2}}{ECA_{1,2} + ECA_{1,1} + ECA_{1,i}}$$

Where $ECA_{1,I}$ is the sum of all other equivalent catchment areas within area 1.

Likewise the flux and weight from area 2 into area one can be calculated with the same equation by exchanging the numbers in the subscripts.

Of this structural graph, which is solely based on elevation information, 3 versions were created which will be used to analyse the data from the overland flow sensors. Firstly a full, directed graph as described in the text above (Figure 3). Secondly, a directed graph where only edges exist if the second sensor is downslope of the first and thirdly an undirected version of the full directed graph. Three versions of the graph were chosen to aid in the analysis of the graphs, while some algorithms to describe graph characteristics are only applicable to directed graphs and others only for undirected graphs.

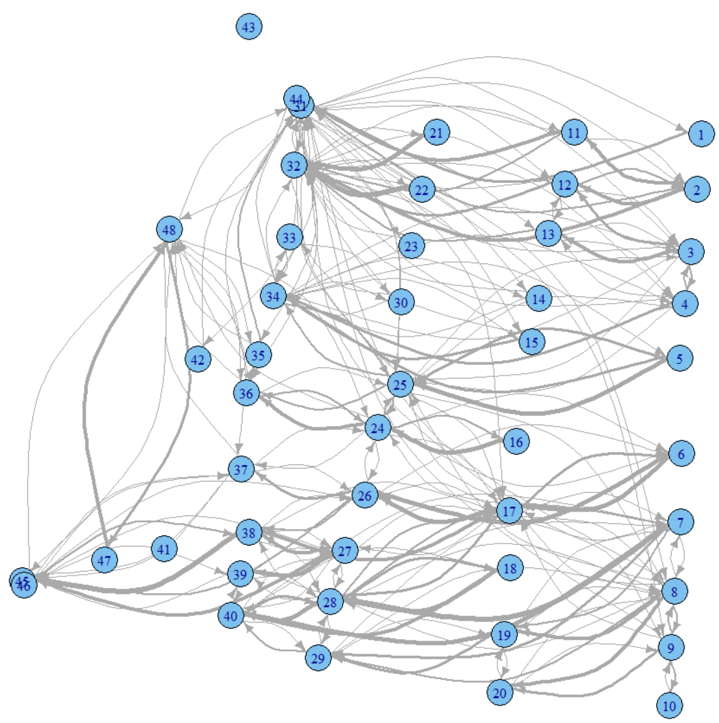

Figure 3:Structural Graph of the hillslope. Edge widths indicate the weight of the edge,

For every time step in the overland flow sensor data (t=10s) a graph will be created using the structural graph. Whenever a sensor detects overland flow, all outgoing edges of the corresponding node of the structural graph exist and are added to the functional graph for that time step (Figure 4).

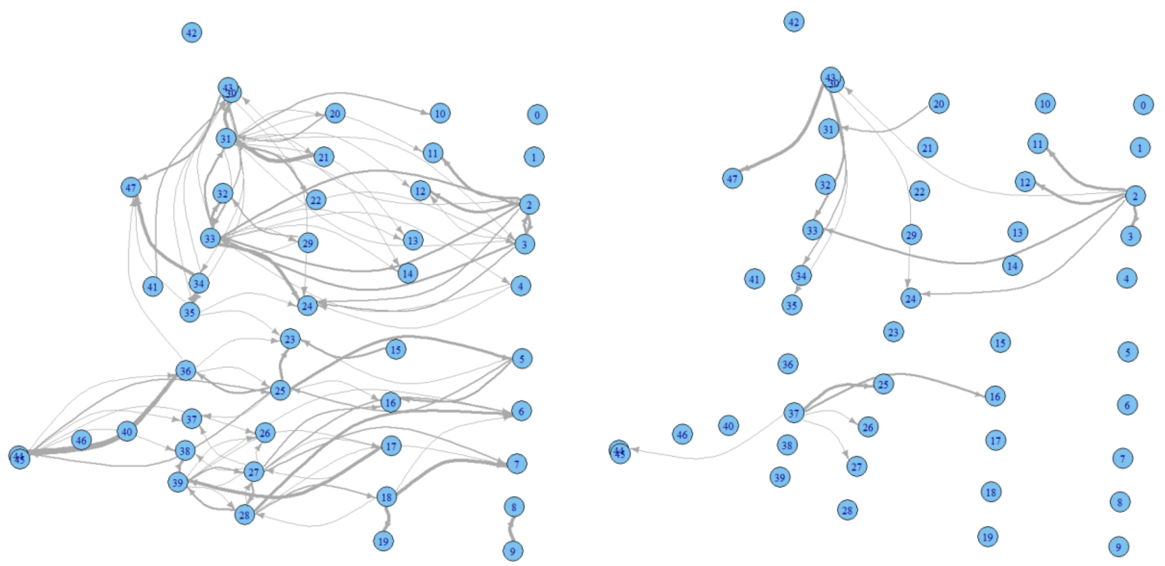

Figure 4: Examples of two functional graphs for two time steps in the overland flow data

Future work

All sensor data will be analysed by creating graphs from every time step in the data. These graphs will then be analysed by analysing the nodes and edges separately and the graph as a whole. From this we hope to assess existing overland flow patterns and determine the most important factors influencing these patterns, e.g. precipitation sum/intensity, landuse, roughness and/or antecedent soil moisture.

We will write a paper on this topic which will be most likely submitted to Hydrological Processes or Hydrology and Earth Systems Sciences.

3. The contribution of this and future work to the actions aims

The work that was carried out during this STSM and the work that will be carried out in the (near) future contribute to the main aim of the action, which is to share expertise between scientists. Dr Heckmann already had experience in working with graphs in geomorphology, which helped a great deal in the advancement of using these methods for assessing hydrological connectivity. Next to contributing to the main aim of the action the STSM contributed to the objectives for Working Group 2: Measuring Approaches and WG3: Modelling connectivity. Ultimately the graph representation is a model of the processes on the hillslope which were measured using overland flow sensors. Depending on the results this STSM might contribute to WG1: Theory when measured patterns can be explained using the network theory approach.

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