European Water 57: 273-278, 2017.

Definition of critical support area revisited

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Abstract: Selecting the upslope contributing area threshold for channel initiation, herein termed as the Critical Support Area (CSA), is known to be crucial for extracting the hydrographic network from a Digital Elevation Model (DEM). Commonly, an arbitrary quantity is selected which is constant in both time and space. This study is aimed to investigate the spatio-temporal variation of CSA based on information from conventional maps. Specifically, maps at the scale 1:50000 for a Greek river basin are used to identify stream heads and the corresponding values of CSA for two seasons of the hydrological year: the wet and dry season. A DEM with a cell size of about 30 m is used for tests, which is based on the Shuttle Radar Topography Mission (SRTM). A Geographic Information System (GIS) is employed for data processing. For each stream head indicated on the map, raw data are extracted, which include CSA and statistics (mean and standard deviation) of the ground slope, square root of ground slope and height above the nearest drainage point (HAND) A variety of linear regression models were tested using untransformed data by regressing CSA on one or more of the remaining variables. No statistically significant relationship was found, which led us to propose the basin-wide median CSA for each season of the year as the best selection. The proposed CSAs are compared to the constant CSA of the common approach using multiple basin-wide geomorphometric characteristics.

Key words: Critical Support Area (CSA), upslope contributing area threshold for channel initiation, hydrographic network, Digital Elevation Model (DEM), geomorphometry

1. INTRODUCTION

Nowadays due to the availability of Digital Elevation Models (DEMs), the extraction of hydrographic networks and catchment delineation are typically performed in an automatic way. Identifying the extent of a hydrographic network based on a DEM is known to be of primary geomorphic and hydrologic importance (Montgomery and Dietrich, 1989; Montgomery and Foufoula-Georgiou, 1993). The hydrographic network affects the simulated hydrologic response of a catchment, which implies that the accurate estimation of stream heads is important for accurate runoff prediction.

The upslope contributing area threshold, herein referred to as the Critical Support Area (CSA), is the critical quantity that allows the extraction from DEMs of useful hydrological information. CSA is commonly selected as a constant quantity without consideration of its variation in time and space. Diverse methods have been proposed for automatically extracting channel networks from DEMs (O'callaghan and Mark, 1984; Tarboton et al., 1991; Band and Moore, 1995), the most common being the adoption of a value of CSA as the minimum drainage area required for a channel to initiate (Band, 1986; Morris and Heerdegen, 1988; Tarboton et al., 1988). In practice, this value is often selected on the basis of visual similarity between the hydrographic network extracted from a DEM and the blue lines depicted on topographic maps.

In this work, a mapped stream network from conventional maps is compared to a stream network derived from a DEM with a spatial resolution of 30 metres obtained from the Global Shuttle Radar Topography Mission (SRTM). The spatial variation of CSA is investigated by examining relationships between CSA and geomorphometric characteristics. Also, the temporal variation of CSA is investigated by adopting two seasons within each hydrological year: (i) the wet season in which both perennial and intermittent streams are considered, and (ii) the dry season in which only perennial streams are assumed to be present.

2. METHODOLOGY

2.1 General

As mentioned in the Introduction, in this work, relationships between the Critical Support Area (CSA) and various geomorphometric characteristics are sought, with the purpose to better define CSA in practical applications. The examined geomorphometric characteristics include: (i) the average ground slope; (ii) the standard deviation of ground slope; (iii) the average of the square root of ground slope; (iv) the standard deviation of the square root of ground slope; (v) the mean value of Height Above the Nearest Drainage (HAND); (vi) the standard deviation of HAND. All the above quantities refer to the upslope contributing area.

As also mentioned in the Introduction, in this study, the hydrographic network is considered as a dynamic feature of a drainage basin by focusing on two extreme situations: a first one for the wet season of the hydrological year and a second one for the dry season.

A Geographic Information System (GIS) is employed for data processing by implementing processing steps as a model in ModelBuilder. All datasets, i.e., conventional maps at the scale 1:50000 and the SRTM DEM data are projected in the same reference coordinate system so as to limit errors. Data pre-processing ensures that topographic depressions and flat areas are filled and each grid cell is linked to the catchment outlet by means of an uninterrupted flow path.

The employed methodology involves four steps. Step 1 involves the digitization of heads of perennial and intermittent streams from projected conventional maps. In step 2, the above mentioned information regarding the location of stream heads is transferred from the used map to the DEM-based hydrographic network using a snapping procedure. The need for such procedure arises from data geo-referencing and the imperfect ability of the DEM to accurately represent topography. The procedure ensures the selection of cells with high accumulated flow as the representations of channel heads. Step 2 is executed twice, i.e., separately for each season, using a vector-to-raster conversion. For all selected cells, the upslope contributed area is defined and the corresponding values of CSA are computed.

In step 3, a number of geomorphometric characteristics are assessed which are given in sub-section 2.2 and serve as the explanatory variables in a regression analysis with the upslope contributing area being the dependent variable. Only linear relationships are considered. Their statistical significance is checked using the well-known F-test. In this work, we provide the determination coefficient R^2, the value of F and the related probability, denoted as “significance of F” which is compared to a critical small value.

In step 4 of the methodology the final values for CSA are selected and the implications thereof on CSA-dependent basin-wide geomorphometric characteristics described in sub-section 2.2.

2.2 Geomorphometric characteristics

The definition of the employed geomorphometric characteristics of hydrological interest is necessary. This is given next.

Ground slope (Burrough and McDonell, 1998) is computed for the upslope contributed area for each stream head in the catchment, while the mean value and standard deviation of slope are selected to represent the frequency distribution of this variable. Slope is commonly computed in units of degrees as follows:

$$\text{Slope} = 57.29578 \times \tan^{-1} \sqrt{G_x^2 + G_y^2} \tag{1}$$

where G_x and G_y are terrain gradients in the x and y direction respectively.

The height above the nearest drainage point (HAND) is a new terrain feature that normalizes DEMs according to the vertical distances relative to drainage channels (Nobre et al., 2011; Papageorgaki and Nalbantis, 2013). HAND is calculated for each DEM cell, as the elevation difference from the nearest cell belonging to the drainage network, following the flow direction path. Evidently, HAND is directly affected by errors in the definition of the stream network.

The calculation of the upslope area depends on the way the accumulated area of upstream cells is routed to one or more downstream cells. In this work, the D8 flow direction algorithm (Jenson and Domingue, 1988) is used which involves conveying the area of each cell to its neighboring cell lying in the steepest downslope direction.

Basin-wide geomorphometric characteristics used for comparisons are the mean and standard deviation of ground slope, square root of ground slope, and HAND, as well as the total stream length.

3. STUDY AREA AND DATA

3.1 Description of the study area

One drainage basin was selected for tests, which is presented in Figure 1. Its watercourse is a tributary of the Acheloos River known as Krikeliotis River. The basin is located in western mainland Greece and has an area of 88.8 km^2. It is characterized by a mountainous topography, with a mean ground elevation of 1296 m and an average ground slope of 20.2 degrees.

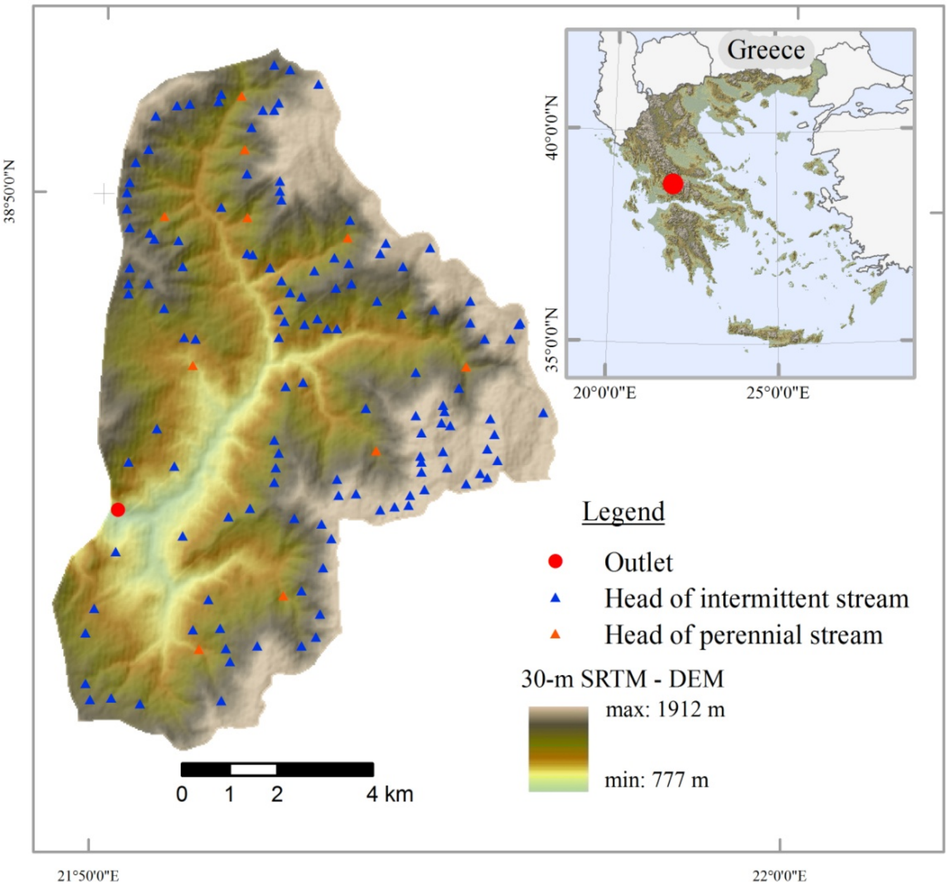

Figure 1. The study basin

3.2 Data used

Two kinds of spatial information are used for the definition of the Critical Support Area. These include the following: (i) conventional maps at the scale 1:50000 covering the study area; and (ii) an 1-arc-second Global coverage Shuttle Radar Topography Mission (SRTM) DEM. The National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) of the United States of America participated in an international project to acquire radar data which were later used to create the first near-global set of land elevations. The 1-arc-second Global SRTM product offers worldwide coverage of void filled data at the resolution of 30 m. It was tested in previous studies with regard to its accuracy and reliability (Nalbantis et al., 2017).

4. RESULTS

The methodology described in section 2 was applied to data presented in section 3. In the data preparation stage, it was revealed that the snapping distance required to achieve a successful transfer of information on stream heads from maps to the DEM-based hydrographic network was 120 to 150 m. The upslope contributing areas for the two seasons of the year were regressed on data for variables indicated in sub-section 2.2. Only cases with one and two explanatory variables were tested due to the small sample size, which was particularly restrictive for the dry season. Results are summarized in Table 1. By adopting the significance level of 0.05, only one regression relationship was found to be significant. Specifically, for the dry season and when using the mean and standard deviation of square root of ground slope, the significance of F fell below 0.05. Despite this fact, in this work, we consider that the sample size is very low (equal to 8), and we do not accept the regression relationship that was identified. In view of the fact that, in general, no significant dependence of the upslope contributing area to geomorphometric characteristics was found, we adopt the median value for this area for each season separately. For comparison purposes we examine also a third value for CSA which is the mean of the two CSAs for the two seasons. The implication on the basin-wide geomorphometric characteristics of sub-section 2.2 is shown in Table 2. A visual comparison of the hydrographic networks resulting from the various selected values of CSA is made in Figure 2. It is evident that the selected value of CSA exerts a significant influence on all geomorphometric characteristics selected for testing, the largest repercussion being observed for the total stream length.

Table 1. Results of regression analysis for the upslope contributing area using various explanatory variables

Explanatory variables	Dry season			Wet season		
	R^2	F	Significance of F	R^2	F	Significance of F
Mean ground slope	0.278	2.31	0.179	0.000	0.01	0.920
Mean of square root of ground slope	0.319	2.81	0.145	0.000	0.01	0.918
Mean HAND	0.204	1.54	0.261	0.025	2.10	0.151
Mean ground slope, Std of ground slope	0.683	5.39	0.057	0.057	2.48	0.090
Mean of square root of ground slope, Std of square root of ground slope	0.730	6.75	0.038	0.046	1.96	0.147
Mean HAND, Std of HAND	0.365	1.43	0.322	0.035	1.47	0.236

Std = standard deviation

Table 2. Basin-wide CSA-dependent geomorphometric characteristics as functions of the selected value of CSA

Geomorphometric characteristic	CSA of dry season	CSA of wet season	Average CSA
Mean ground slope (^{o})	7.25	14.92	8.27
Mean of square root of ground slope (^{o})$^{0.5}$	2.56	3.74	2.74
Mean HAND (m)	4.40	5.87	4.77
Std of ground slope (^{o})	4.31	6.28	4.73
Std of square root of ground slope (^{o})$^{0.5}$	0.81	0.94	0.85
Std of HAND (m)	5.26	7.16	5.59
Total stream length (m)	34265	246571	44973

Std = standard deviation

5. CONCLUSIONS

In this work the variation in both space and time of the upslope contributing area threshold for channel initiation, denoted as the Critical Support Area (CSA), was investigated with the purpose to assist the procedure for its selection. Results of our investigation allow for drawing the following conclusions:

- Conventional maps at coarse spatial scales (e.g., 1:50000) can be useful in providing information about stream heads and consequently about CSA.
- No statistically significant relationship was found between the CSA values from maps and typical geomorphometric characteristics such as the ground slope, square root of ground slope, and height above the nearest drainage point (HAND); it is therefore proposed to select the median value of CSA from maps by ignoring the spatial variation of CSA.
- As far as the temporal variation of CSA, heads for ephemeral and perennial streams allowed for roughly distinguishing between values of CSA for the wet and dry season of the hydrological year.
- It was demonstrated that selecting the CSA based on map information by simultaneously considering its temporal variation is crucial for assessing typical geomorphometric characteristics that depend on CSA.

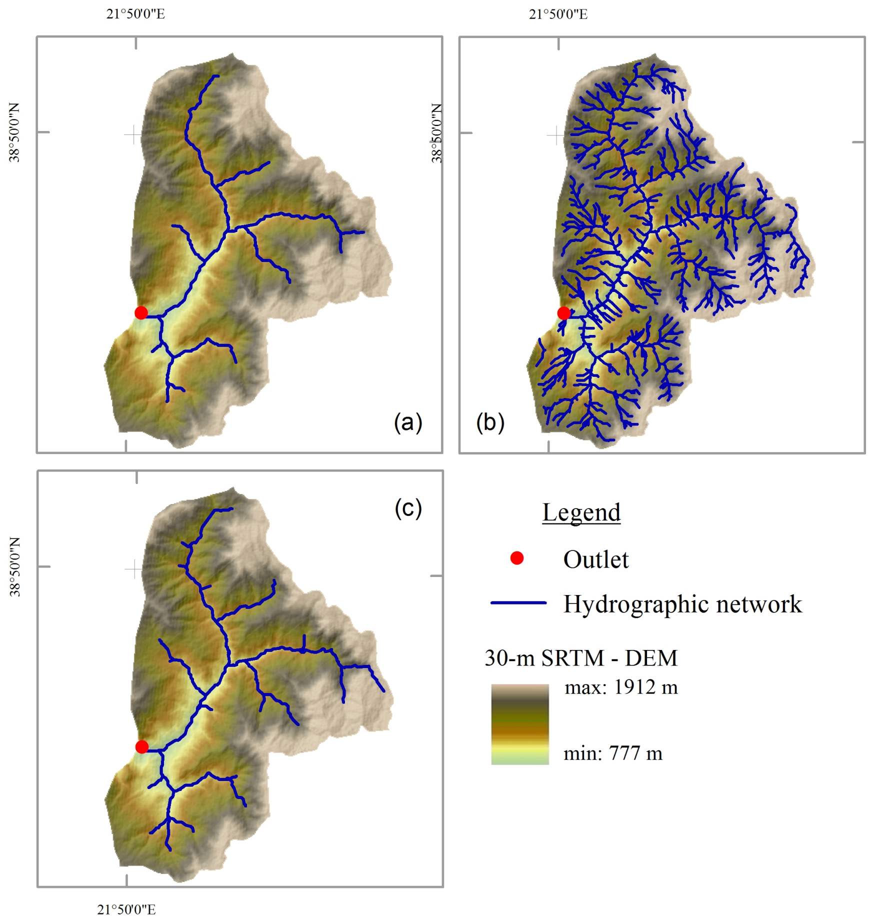

Figure 2. The hydrographic network of the study basin obtained by adopting (a) the dry season median CSA, (b) the wet season median CSA, and (c) the average of the two values

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