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Flow connectivity in active volcanic areas: Use of index of connectivity in the assessment of lateral flow contribution to main streams

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ABSTRACT

Connectivity analysis is an important geomorphological and hydrologic tool that can be used to identify spaces that are prone to removal of primary sediments which are eventually assimilated into granular flows and related epiclastic processes. Studies of connectivity have been made in various areas, but to date, not in active volcanic areas, where such studies can be very useful due to the constant presence of loose volcanic material easily removed by epiclastic processes. Mobilization of loose pyroclastic sediments can trigger phenomena such as lahars, which are among the most dangerous in nature.

In this study, the index of connectivity (IC) (Borselli et al. 2008) was calculated by obtaining a weight coefficient (W) combining two elements: the coefficient C related to the universal soil loss equation and the revised universal soil loss equation (USLE-RUSLE) proposed by Borselli et al. (2008) for areas with vegetation cover or crops, and the roughness index (RI) developed by Cavalli et al. (2013), which characterizes bare soil areas. Combining both methods, we propose a new joint index of connectivity (IC_J) that does not overestimate the degree of connectivity in bare areas, while areas with vegetation cover are characterized based on their well-recognized hydrologic impedance properties. This methodology may enable better characterization in highly dynamic environments such as active volcanic areas.

We also propose a new lateral hydrological efficiency index (LHEI) that increases the ability to identify watersheds that supply major amounts of sediment to main streams in ravines.

The application of this methodology in the active volcanic area of Volcán de Colima, the most active volcano in Mexico, is of great importance, because of the constant supply of new pyroclastic material from the top of the edifice, the high dynamicity of geomorphological processes, and the widespread presence of bare soil areas consisting of loose materials easily sourced, or assimilated, into epiclastic processes.

1. Introduction

Sediment transport along flow channels is the main process that determines the evolution of a landscape (Harvey, 2001). In active volcanic areas, this evolution is highly dynamic due to the constant generation of new material and its subsequent remobilization. These processes, defined as epiclastic, represent the major phase of volcanic activity both in terms of duration and the volumes involved (Cas and Wright, 1987).

Lahars are one of the most important epiclastic processes in volcanic areas (Cas and Wright, 1987; Pierson and Costa, 1987). In order to produce lahars, a supply of water, poorly consolidated sediments, slope, and a trigger mechanism are needed (Francis and Oppenheimer, 2004; Vallance and Scott, 1997). These simple elements may combine at any time and can produce rivers of mud and rock that travel dozens of kilometers from the source through already existing channels (Tarbuck and Lutgens, 2005).

One of the reasons why lahars are dangerous is because they can also occur even during quiescent phases of the volcano. The dangerous behavior and high fatality rate related to lahars in volcanic areas explain why they have been considered the most dangerous of volcanic phenomena throughout the course of history (Schmincke, 2004).

The removal of material has a close relationship with the characteristics of the environment. The concept of connectivity provides conceptual and methodological tools to quantitatively and spatially analyze the efficiency of the natural context in providing and transport-

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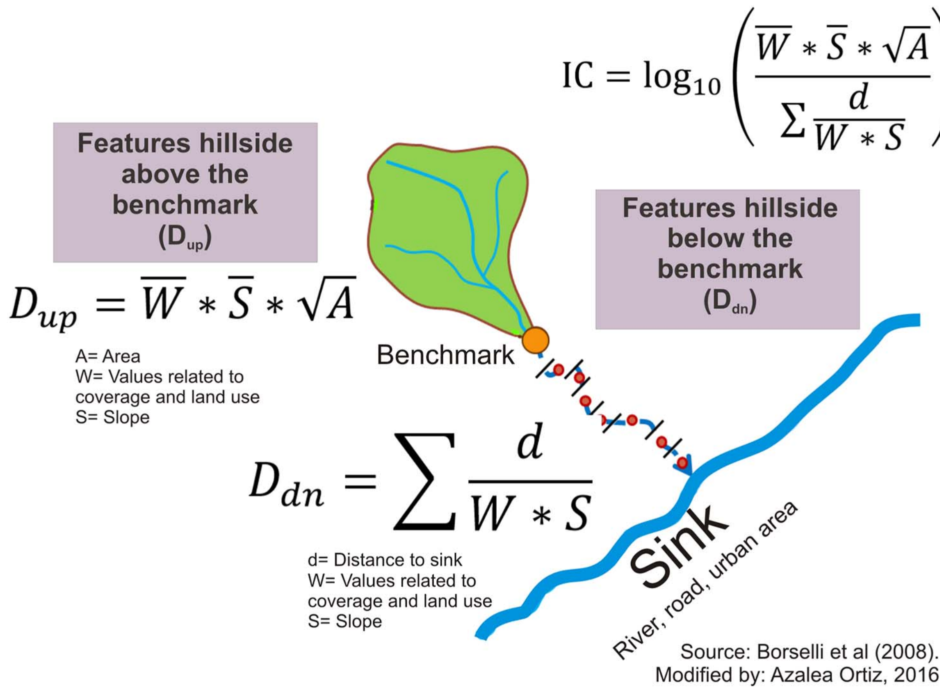

Fig. 1. Elements that constitute the connectivity index.
Source: Borselli et al. (2008).

Table 1
Values of the W factor used in calculating the connectivity index proposed by Borselli et al. (2008).

Level 1	Level 2	Level 3	W
1. Artificial cover	1.1 Urban areas		n.a.
	1.2 Industrial areas		n.a.
	1.3 Mines, landfills and construction sites	1.3.1 Mining sites	1
		1.3.3 Construction sites	1
	1.4 Natural areas and agricultural areas	1.4.1 Urban greening	0.05
		1.4.2. Sports and recreation areas	0.05
2. Agricultural areas	2.1 Farmland	2.1.1 Non-irrigated farmland	0.1
		2.1.4.1 Vegetable gardening	0.1
		2.1.4.2 Nurseries and cultivation of crops under plastic	0.001
	2.2 Perennial crops	2.2.1 Vineyards	0.451
		2.2.2 Fruit trees and cereals	0.296
		2.2.3 Olive groves	0.296
	2.3 Grasslands	2.3.1 Pasture	0.15
		2.3.2 Pasture with shrubs	0.13
	2.4 Heterogeneous agricultural areas	2.4.4 Agroforestry spaces	0.05
3. Forests and semi-natural areas	3.1 Forests	3.1.3.1 Mixed forest	0.001
		3.1.3.2 Discontinuous forest	0.006
		3.1.4 Gallery forest or riparian vegetation	0.006
	3.2 Plant associations of shrubs and/or grasses		0.04
	3.3 Open spaces with little or no vegetation	3.3.2 Bare rock	0.9
4. Wetlands	4.2 Coastal wetlands	4.2.3 Tidal flats	1
5. Water bodies	5.1 Inland water bodies	5.1.1 Watercourses	n.a.
		5.1.2 Water bodies	n.a.

ing sediment from the source to sedimentation areas (Croke et al., 2005).

The concept of connectivity can be applied to a wide range of different research areas and it provides a solid and constantly expanding frame of reference. The issues addressed from the point of view of connectivity are very broad and range from analysis of soil erosion (López Vicente et al., 2013; Sougnez et al., 2011; Vigiak et al., 2012); the study of debris flows (Cavalli et al., 2013); fluvial distribution of pollutants (Chartin et al., 2013); morphometric modeling of landscapes with GIS assistance (Messenzehl et al., 2014); analysis of the genesis, provenance, distribution and amount of sediment produced (D'Haen et al., 2013; Jamshidi et al., 2014); assessment of the impact of civil engineering construction works on the natural connectivity and flow of water and sediments (Kumar et al., 2014); changes in sediment transport caused by modification in vegetation cover (Foerster et al., 2014); to the analysis and characterization of basins and watersheds and their geomorphological dynamics (Gay et al., 2016; Heiser et al., 2015; Schneider et al., 2013), among others. However, the concept of connectivity has not been applied to volcanic environments until now. In volcanic environments, the constant and rapid geomorphological evolution present in active volcanic areas suggests that the application of this type of analysis may be relevant and useful.

Connectivity is a term often used to describe internal linkages between runoff and sediment sources in upper parts of catchments and the corresponding sink (Croke et al., 2005; Hooke, 2003). In other words, it refers to the degree of connection between sediment source