Computing structural and functional flow and sediment connectivity with a new aggregated index: A case study in a large Mediterranean catchment

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HIGHLIGHTS:

Structural flow and sediment connectivity was mapped in detail with the new AIC

Values of connectivity with the AIC followed a normal distribution with a wide range

The new AIC allowed estimating the spatio-temporal dynamic of functional connectivity

Temporal changes of connectivity in the Vero River were higher than in the hillslopes

Simulated functional connectivity and river flow dynamics differed during the summer

GRAPHICAL ABSTRACT:

ABSTRACT:

Hydrological connectivity in large catchments is influenced by natural and human-induced heterogeneities and dynamic processes. In this study, a new aggregated index (*AIC*) based on topography, C-RUSLE factor, RUSLE2 rainfall erosivity, residual topography and soil permeability, was proposed to model structural and functional flow and sediment connectivity (FSC). It was tested in a large Mediterranean catchment (Vero River, NE Spain, 380 km²) with contrasted physiographic and climatic conditions (19 land uses and 15 types of lithology). Twelve weather stations were used and simulations were done at 5 m of pixel resolution using a LiDAR-derived DEM and the D-Infinity algorithm. Structural FSC (FSC-st) was computed with both an updated version of Borselli's index (*IC*) and the *AIC*. Values of connectivity with *AIC* followed a normal distribution with a wider range of values compared with the non-normal distribution obtained with Borselli's approach. The differences in the values of FSC-st between

the different land uses were similar with the two indices and in agreement with the soil erosion rates reported in comparable landscapes. The spatial characteristics at sub-catchment scale were better reflected with *A/C* although values of *FSC-st* in the river and outlet were similar between both indices. Functional *FSC* (*FSC-fn*) was computed with *A/C* during 96 months (September 2009 – August 2017) characterising the spatio-temporal dynamic at catchment scale (18% of coefficient of variation). *FSC-fn* was higher in September, October, June and July and lower during the period December – February. Variation of connectivity in the stream was higher than in the hillslopes. Modelling testing with river flow was satisfactory between November and March, and during the months with high discharge values and weak during the summer, suggesting different runoff and sediment responses over the year. The new *A/C* appeared as a suitable tool for geomorphic and hydrological studies at catchment scale.

Keywords: *Structural connectivity; Functional connectivity; Rainfall erosivity; Soil permeability; Spatio-temporal dynamic; Aggregated Index of Connectivity*

1. Introduction

The description of the overland flow pathways at catchment scale is a complex task that depends on the organization of local links and the interactions of the network structure of overland flow cascades (sources, local storage, nested sub-catchments and outlets, and transportation agents) (Cossart and Fressard, 2017). Forest- and shrub-dominated slopes, croplands and terraced fields, pastures and areas with rock outcrops produce different hydrological responses and storm-flow discharge over the entire year. Thus, the different compartments of a river basin show large hydrological heterogeneities (Lana-Renault et al.,

2018). Among the natural factors affecting soil erosion and runoff yield, rainfall erosivity has a paramount importance. In the Mediterranean landscapes, rainfall (depth and intensity) variability is significant, ranging from semiarid to subhumid and humid conditions and thus mapping rainfall erosivity at regional and basin scales becomes necessary for an accurate assessment of the hydrological response (Angulo-Martínez et al., 2009). Spatial heterogeneities of soil surface components, such as lithology, rock fragments, bare soil, texture, litter and surface crusts, have highly variable effects, in both space and time, on soil hydrological behaviour, such as infiltration-excess runoff (Ruiz-Sinoga and Martínez-Murillo, 2009).

In tilled soils, soil roughness has influence on whether diffuse or concentrated runoff dominates, especially during low- and medium-intensity rainfall events (López-Vicente and Álvarez, 2018a). Soil surface crusting in cultivated soils partially depends on the initial soil roughness (Taboada-Castro et al., 2015). Also at field scale, the use of plant covers in the inter-row area of woody crops, such as vineyards, olive and almond groves, increases the soil water content along the year, promotes higher infiltration rates, and reduces runoff generation and coefficients and soil erosion rates (Gómez et al., 2011; López-Vicente and Álvarez, 2018b; Vicente-Vicente et al., 2017). In spite of these advantages, mechanical tillage and bare soil after using herbicides still represent common techniques of soil management in woody crops within the Mediterranean Basin, mainly to avoid competition between the plant community in the inter-row area with the crops for the scarce soil water.

The term 'Hydrologic connectivity' (HC) is used in different disciplines to refer to water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle (Pringle, 2001; Bracken et al., 2013). Over the last decade, HC has emerged as a significant conceptual framework within which to address the spatial and temporal variability in runoff and sediment transport (Parsons et al., 2015). This concept, originated in ecology

(Pringle, 2001), is widely used in surface hydrology, geomorphology, soil erosion and sedimentation research at different spatial scales, from small sub-catchments to large basins, and implies sediment movement on hillslopes, between hillslopes and channels and within channels (Caraballo-Arias et al., 2018). The sediment delivery ratio (SDR; %) is defined as the ratio between gross soil erosion and catchment sediment yield during a period, usually one year. Thus, flow and sediment connectivity (FSC) is a concept implicit in the approach using the SDR because low values of SDR imply a lack of connectivity (structural and/or functional). The structural connectivity evaluates the properties (topography, surface roughness, soil properties, vegetation types and patterns, drainage network, etc.) of a system (catchment, landscape) that control the processes of water- and sediment-transfer, and the functional connectivity results from the way those processes operate (e.g. runoff and sediment delivery) and evolve through time at a specific spatio-temporal scale (Nunes et al., 2018). On the other hand, human-impacted fluvial systems, such as croplands and sub-urban areas, show a different response owing to changing inputs in comparison with natural systems. Moreover, geomorphic response of fluvial systems to human disturbance is determined by system-specific boundary conditions (incl. system history, related legacy effects and lag times), vegetation dynamics and human-induced functional relationships between the different spatial dimensions of connectivity (Poeppel et al., 2017).

Several approaches have been published in the literature to assess HC, such as the Network Index by Lane et al. (2009), the Relative Surface Connection (RSC) function proposed by Antoine et al. (2009), and the Reaney et al.'s (2014) Connectivity of Runoff Model, 2D version. Sediment cascades have also been explored using graph theory, such as by Heckmann and Schwanghart (2013) in the Austrian Alps, and by Cossart and Fressard (2017) in the French Alps. One decade ago, Borselli et al. (2008) developed the index of flow and sediment connectivity (IC) and successfully tested their approach against field observations in a large catchment in central Italy. For each pixel, this qualitative index $[-\infty, +\infty; \text{dimensionless}]$

accounts for the combined effect of the upslope topographic and land-use characteristics and these parameters' values throughout the flow path line a soil particle must travel to reach the nearest defined stream or sink. Afterwards, modified versions have appeared in the literature related to the slope computation, flow accumulation algorithm, and the weighed landscape parameter (*W* factor). The *IC* versions' capacity has been demonstrated in different fields and catchments around the world, e.g., in Australia (Vigiak et al., 2012), India (Singh et al., 2017), Japan (Evrard et al., 2013; Chartin et al., 2017; López-Vicente et al., 2017a), Turkey (D'Haen et al., 2013), Belgium (de Walque et al., 2017), France (Gay et al., 2016), Mexico (Ortíz-Rodríguez et al., 2017), Italy (Cavalli et al., 2013; Persichillo et al., 2018), and even in an artificially-created catchment in Germany (Schneider et al., 2013). In Spain, the studies by Sougnez et al. (2011), López-Vicente et al. (2013a; 2017b), Foerster et al. (2014), Calsamiglia et al. (2017) and Martínez-Murillo and López-Vicente (2018) proved its capacity to map runoff and sediment connectivity under different land uses and topographic conditions.

The published scientific studies based on Borselli's approach have used one, two or several parameters, such as the C-RUSLE factor, the residual topography, the overland flow Manning's roughness value, the drainage density, the rainfall erosivity, the USLE soil erosion equation, and even though the fire severity, to estimate the *W* factor. However, none of these studies have combined residual topography, any soil permeability parameter, the C-factors and the rainfall erosivity, and their temporal dynamics, to model structural and functional connectivity at large catchment scale with an aggregated index of FSC (*A/C*). We hypothesise that the use of the new *A/C* will improve the characterization of the actual processes of FSC at large catchment scale where multiple heterogeneities appear. To achieve this goal we planned two main tasks: (i) to run an updated version of Borselli's index and the new *A/C* under average year conditions (structural FSC) in a large Mediterranean catchment (Vero River, 380 km²) that has different land uses, topographic conditions, soil types and a clear climatic gradient; and (ii) to run the *A/C* at monthly scale to model the spatio-temporal dynamics of FSC during a 96-

month period (functional FSC). The spatial variability analysis was done considering all land uses, and the main catchment compartments and geomorphic units. The temporal evolution of the predicted values of functional connectivity was tested by using river flow values observed near the outlet. The new *AIC* aims to refine the modelling ability of the current indices of FSC based on Borselli's approach and will contribute to hydrological, soil and agricultural studies at catchment scale.

2. Materials and methods

2.1. Study area

The Vero River catchment (380 km²) was selected to perform this study. It is located in the External Ranges of the Spanish Pyrenees, in the province of Huesca (Aragon autonomous community), and within the Ebro River basin (NE Spain). The largest settlement is the town of Barbastro (17,000 inhabitants; 42° 02' 10'' N; 0° 07' 42'' E) that is located in the southern part of the catchment and near the outlet. The Vero River (81.7 km length; Strahler's order up to 12) is tributary of the Cinca River which is one of the main tributaries of the Ebro River (Fig. 1.a). The Vero River is not regulated by any dam and thus the stream flow at the outlet reflects the natural hydrological response of the entire catchment. The topography is characterised by steep slopes in the northern part with presence of deep ravines (typical alpine mountainous landscape), whereas alluvial terraces and low and medium steep slopes appear in the southern part. The mean slope gradient (*S*) is 20.8% with gentle (*S* < 8%) and steep (*S* > 20%) areas occupying 26% and 46% of the total area, respectively (Fig. 1.b). The shape of the catchment is lengthened from the north to the south and narrows from the east to the west.

The southern part is mainly devoted to agriculture whereas the northern part is mainly covered by forest (Fig. 1.c). The main crops are rainfed cereal (barley and wheat) fields,

vineyards and a mosaic of crops (cereal with olive and almond groves). Irrigated farmland, mainly vineyards, occupies 5.2% of the total area. The forest species include oaks (*Quercus faginea* Lam., 1785), holm oaks (*Quercus ilex* L., 1753), Scots pine (*Pinus sylvestris* L., 1753), crack willow (*Salix fragilis* L., 1753), European nettle tree (*Celtis australis* L., 1753), Mediterranean shrubs, such as thyme (*Thymus vulgaris* L., 1753), rosemary (*Rosmarinus officinalis* L., 1753), European box (*Buxus sempervirens* L., 1753), juniper (*Juniperus communis* L., 1753) and *Genista scorpius* (L.) DC. (1805), and grasses. Urban and peri-urban areas cover 1.4% of the total area, and boulders, areas with sand (near the outlet) and sparse vegetation occupy 1.1%. Concerning lithology, the soil's pattern material in the southern part is mainly composed by sandstones with conglomerates and alluvial materials surrounding the Vero River, and outcrops of clay with gypsum near the outlet. In the northern part, outcrops of limestone and marls are the predominant rocks together with conglomerates and levels of clay and sand (Fig. 1.d). Soils are classified as Leptosols and Cambisols in the northern mountainous part, and as Regosols and Calcisols in the southern part. Besides, Fluvisols appear in the southern part surrounding the Vero River and its main tributaries, and small areas near the outlet present Gypsisols (Badía-Villas et al., 2006). These authors analysed 174 soil samples in the study area obtaining loam texture in 62% of the samples, sandy-loam texture in 21% of the samples, whereas clay-loam (6.4%), silty-loam (4.2%) and silty-clay-loam (4.2%) textures were less frequent.

Climate is Continental Mediterranean, with two humid periods, in spring and autumn, and a dry and hot summer with occasional thunderstorms. Owing to the geographic location of the study area, between the External Ranges of the Pyrenees and the Central Ebro Basin Depression, there is a clear climatic gradient from the south (semiarid conditions) to the north (subhumid conditions). The average annual rainfall ranges between $662 \pm 10\%$ ($\pm$ coefficient of variation) and $794 \pm 17\%$ mm / yr in the weather stations located in the northern part, and between $360 \pm 16\%$ and $477 \pm 13\%$ mm / yr in the southern part (period September 2009 –

August 2017). The average annual temperature ranges between 10.6 and 14.4 °C in the northern and southern parts, respectively, and the average potential evapotranspiration was 1045 mm / yr near Barbastro.

2.2. Index of flow and sediment connectivity

We used Cavalli et al.'s (2013, 2015) modifications to the index of runoff and sediment connectivity (IC), originally proposed by Borselli et al. (2008), regarding the flow accumulation algorithm and maximum slope threshold. The index accounts for the drainage area and flow path characteristics. The downslope module (D_{dn}) contemplates the probability that runoff and sediment arrive at a defined sink along the flow path. The upslope module (D_{up}) represents the potential for downward routing of overland flow occurring upslope and also implements a "stream power"-like approach, taking into account the slope and size of the contributing area:

$$IC_K = \log_{10} \left(\frac{D_{up,K}}{D_{dn,K}} \right) = \log_{10} \left(\frac{\overline{W_K} \cdot \overline{S_K} \cdot \sqrt{A_K}}{\sum_{i=K,n_K} \frac{d_i}{W_i \cdot S_i}} \right) \quad (1)$$

where A is the upslope contributing area (m^2), $\overline{W}$ is the average weighing factor of A (dimensionless), $\overline{S}$ is the average slope gradient of A (m / m), d_i is the length of the i th cell along the downslope path (m), W_i is the weight of the i th cell (dimensionless), and S_i is the slope gradient of the i th cell (m / m). The weighting factor W was introduced to model the impedance to runoff and sediment fluxes due to properties of the local land use and soil surface. In the original version of the index, as well as in other studies (e.g., Vigiak et al., 2012; D'Haen et al., 2013; Ortíz-Rodríguez et al., 2017; and Singh et al., 2017), the W factor of Eq. (1) is equal to the C-factor (cover-management) of the RUSLE (Renard et al., 1997) and RUSLE2 (USDA, 2008) soil erosion model. This factor reflects the effect of cropping and management

practices of the different land uses on the soil erosion rates. Besides, the C-factor allows comparing the relative impacts of vegetation management options on soil and water conservation policy (López-Vicente et al., 2011).

In Eq. (1), slope steepness of less than 0.005 must be adjusted to $S_i = 0.005$ and those higher than 1 must be set to a maximum value of 1. The subscript K indicates that each cell “ i ” has its own IC value. This index is defined in the range of $[-\infty, +\infty]$ and connectivity increases when IC grows towards $+\infty$. The weighted flow path length, the $\overline{W}$, $\overline{S}$ and A factors were calculated with the D-infinity flow accumulation algorithm (Tarboton, 1997) available in the software SAGA® 2.1.2 64 bit (Conrad et al., 2015), instead of using the D8 single-flow algorithm of the original connectivity model. It is vital that a suitable algorithm is selected to model overland flow processes in hilly landscapes in order to obtain accurate simulations (López-Vicente et al., 2014). The D-infinity approach is recommended by the European SedAlp sediment transport in mountain basins research group (Cavalli et al., 2015) and also used in the TauDEM 5.2 tools suite for the extraction and analysis of hydrological information from topographical data (Tarboton, 2013). According to these authors, the D-infinity approach better captures the actual flow paths, especially on hillslopes where divergent flow predominates, than the multiple-flow (MD) algorithm. Besides, the D-infinity algorithm provides a better approximation of channel width by partitioning flow over the entire cross section than the single-flow (D8) algorithm. The D-infinity algorithm therefore produces a more representative pattern of the IC at sub-basin and hillslope scales (Martínez-Murillo and López-Vicente, 2018). The stream of the Vero River was chosen as the user-specified target for the IC computation.

2.3. Modifications on the IC tool

Regarding the W factor in study areas with homogeneous land uses, Cavalli et al. (2013) and Crema and Cavalli (2018) applied the IC equation using the roughness index (RI) that refers to topographic variations. This index is computed as the residual irregularity resulting from subtracting a moving average over 5 cells by 5 cells of a DEM from the original DEM region:

$$RI = \sqrt{\frac{\sum_{i=1}^{25} (X_i - X_m)^2}{25}} \quad (2)$$

where X_i is the pixel value in the original DEM, and X_m is the pixel value in the 5 x 5 moving average DEM. The relationship between the RI and IC is inverse: higher values of RI correspond to lower connectivity, because irregularities in terrain restrict sediment transport. Hence, the proposal to include the RI as the W factor involves the inverse normalization of the values obtained by the following mathematical expression:

$$W = RI_N = 1 - \left(\frac{RI}{RI_{max}} \right) \quad (3)$$

However, Trevisani and Cavalli (2016) observed that equations (2) and (3) generate a skewed distribution of the RI_N values characterized by a small range of variation, with values packed toward a weighting factor of 1. To increase the spatial variability of RI_N , these authors proposed normalizing the natural logarithm of RI_N as follows:

$$W = RI_{NLn} = 1 - \left(\frac{\ln(RI) - \ln(RI_{min})}{\ln(RI_{max}) - \ln(RI_{min})} \right) \quad (4)$$

where the minimum RI values are trimmed to 0.001.

In a recent study, Persichillo et al. (2018) estimated the W factor by using the overland flow Manning's roughness value (n). The n coefficient represents a simplified solution for studying overland flow behaviour along a natural or anthropic stream network. In a Mexican site, Ortíz-Rodríguez et al. (2017) combined two of the above methodologies (C -factor and RI) for estimating the W factor to better characterize the IC in active volcanic areas where the

constant supply of material and destruction of vegetation cover generate large areas of unconsolidated bare soil. Other authors have modified the original Borselli's approach by adding more factors to assess the W landscape weighting factor, such as Gay et al. (2016) for studies in France, Eq. (5); Chartin et al. (2017) for studies in Japan, Eqs. (6) and (7); and de Walque et al. (2017) for studies in Belgium, Eq. (8):

$$IC_{revised} = \log_{10} \left(\frac{\overline{W} \cdot \overline{IDPR} \cdot \overline{S} \cdot \sqrt{A_K}}{\sum_i \frac{d_i}{W_i \cdot S_i \cdot IDPR_i}} \right) \quad (5)$$

$$IC_{rev} = \log_{10} \left(\frac{\overline{C} \cdot \overline{S} \cdot \overline{R_t} \cdot \sqrt{A}}{\sum_i \frac{d_i}{C_i \cdot S_i \cdot R_{t_i}}} \right) \quad (6)$$

$$R_t = \frac{EI_{30t}}{EI_{30max}} \quad (7)$$

$$IC_{K, revised} = \log_{10} \frac{\left(\sum_i R_i \cdot K_i \cdot LS_i \cdot C_i \cdot S_{pixel} \right)_k}{\left(\sum_j \frac{n_j \cdot d_j}{S_j} \right)_k} \quad (8)$$

where $IDPR$ is the index of development and persistence of the drainage network, R_t is the normalized rainfall erosivity factor during a period t (value between 0-1), EI_{30t} (MJ mm / ha h t) is the rainfall erosivity during a period t , EI_{30max} is the maximum rainfall erosivity during the whole study period, R_i is the annual rainfall erosivity (MJ mm / ha h yr), K_i is the soil erodibility (Mg h / MJ mm), LS_i is the slope length and steepness factor, j is the number of erosive events for the n number of years and k is the temporal interval. Martínez-Murillo and López-Vicente (2018) chose the product between the C-RUSLE factor, the maps of burn severity, salvage logging and the different levels of vegetation recovery after the fire to calculate the W factor.

2.4. New aggregated index of flow and sediment connectivity

In this study, we introduce the aggregated index of flow and sediment connectivity (AIC) to study spatial and temporal dynamics of FSC at (large) catchment scale:

$$AIC_k = \log_{10} \left(\frac{D_{up,k}}{D_{dn,k}} \right) = \log_{10} \left(\frac{\overline{R_t} \cdot \overline{RT} \cdot \overline{C_t} \cdot \overline{K_P} \cdot \overline{S} \cdot \sqrt{A_k}}{\sum_{k=1}^n \frac{d_i}{AWC_i}} \right) \quad (9)$$

$$AWC_i = R_{ti} \cdot RT_i \cdot C_{ti} \cdot K_{Pi} \cdot S_i \quad (10)$$

where AWC is the aggregated weighting factor at catchment scale, R_t is the normalized rainfall erosivity factor for the period t (values between 0-1), RT is the residual topography factor (normalized values between 0 and 1), C_t is the vegetation and crop management factor for the period t (values between 0-1), K_P is the soil permeability factor (normalized values between 0 and 1) and S is the slope gradient (m / m). The K_P factor allows evaluating the influence of the soil physical properties on the runoff and sediment connectivity at catchment scale where significant spatial changes appear between the values of soil water infiltration and the soil water retention capacity. Rainfall erosivity, El_{30t} , is computed at monthly scale as the sum of the rainfall erosivities at event scale:

$$El_{30} = (E)(I_{30}) = \left(\sum_{K=1}^m e_r \Delta V_r \right) I_{30} \quad (11)$$

where m is the number of temporal intervals established for each storm; e_r (MJ / ha mm) is the kinetic energy of a storm for the r period; ΔV_r (mm) is the volume of rainfall registered during the r period; and I_{30} (mm / h) is the maximum rainfall intensity of each storm. In Eq. (7), El_{30t} values lower than 0.01 must be adjusted to $El_{30t} = 0.01$ in order to avoid computational errors. The kinetic energy is assessed in the RUSLE2 model following the approach of [McGregor and Mutchler \(1976\)](#) such as:

$$e_r = 0.29[1 - 0.72\exp(-0.082i_r)] \quad (12)$$

$$i_r = \frac{\Delta V_r}{\Delta t_r} \quad (13)$$

where i_r (mm / h) is the rainfall intensity for the r period; and Δt_r (min) is the duration of the r period. Eq. (12) was adopted in the development of RUSLE2 (USDA, 2013) and it is the energy-intensity equation currently recommended by the RUSLE and RUSLE2 development teams (Nearing et al., 2017). When the temporal subscript t in Eq. (10) is equal to one average year, the values and maps represent the structural FSC (AIC_{ST}). When this subscript is equal to a specific month, week or runoff event, the values and maps reflect the dynamic processes of functional FSC (AIC_{FN}).

2.5. Data acquisition and pre-processing

A LiDAR-based DEM was freely obtained from the Spanish National Centre of Geographic Information (IGN; <http://centrodedescargas.cnig.es/CentroDescargas/>) at a spatial resolution of 5×5 m of grid cell size. Before computing the IC and the AIC , the continuity of the flow path lines across the entire hillslopes and in the Vero River was guaranteed by removing the local depressions using the Planchon and Darboux algorithm (2001) (available in SAGA® 2.1.2 64 bit). This algorithm imposes a gradient to avoid the typically unrepresentative flat surfaces induced by other sink-filling tools. We considered that a minimum gradient of 0.01° would enable flow routing across the filled sinks. The boundary of the Vero River catchment was then automatically calculated upwards from the outlet using ArcGIS® 10.3. The residual topography factor, RT in Eq. (10), was estimated as the normalized and inverse values of the standard deviation of the slope gradient (S_{SD}). The map of S_{SD} was generated with the 'Residual Analysis (Grid)' tool (SAGA® 2.1.2 64 bit), with a radius of 2 cells (including the centre cell). We selected this approach instead of using the roughness index or any of the different techniques that have emerged over the years to describe quantitatively the surface roughness, because the S_{SD}

approach correctly identify smooth sloping areas and breaks of slope, and provides accurate results for geomorphological analysis (Grohmann et al., 2011; Berti et al., 2013). We considered a minimum RT value of 0.001 to avoid computational errors.

Rainfall data was obtained from 12 weather stations located inside and near the study area covering a period of eight agronomic years (September 2009 – August 2017). As cereal fields are usually ploughed in September and sowed in October, we set the beginning of the agronomic year in September. Eight of these stations belong to the Ebro River Basin water authorities (CHE: 15 minutes of temporal resolution; <http://saihebro.com/saihebro/index.php>) and three to the irrigation main office of the Regional Government of Aragon (Oficina del Regante: 30 minutes of temporal resolution; <http://aplicaciones.aragon.es/oresa/>) (Fig. 1b). We used the guide of the RUSLE model that establishes a period of six hours with a rainfall volume lower than 1.27 mm to distinguish between two different storm events. Rainfall depth, maximum intensity and erosivity were calculated at event, monthly and average annual scales keeping the original temporal resolution of the data (Fig. 2; Sup. Fig. 1). Then, 97 maps of rainfall erosivity were generated by spatial interpolation (spline type with tension; ArcGIS® 10.3) related to the average annual value and of the 96-month period. Values of the Vero River flow (Q ; m^3 / s) were obtained from the gauging station located in Barbastro, near the outlet (source: CHE; 15 minutes of temporal resolution).

The CORINE Land cover map (year 2012) was freely obtained from the IGN and 19 land uses were distinguished with 318 polygons. Annual RUSLE C-factors were obtained from Panagos et al. (2015) and Karydas and Panagos (2018) for the CORINE Land Cover classes 21x, 22x, 24x, 31x, 32x and 33x; these authors estimated these factors in the 28 countries of the European Union, and in five study sites in South East Europe and Cyprus, respectively. The C-factors for the urban areas (classes 1xx) were obtained from Schwab et al. (1996). In those cases where information was available, we used monthly RUSLE C-factors for computing the maps of

functional FSC. Monthly C-factors were estimated by using the previous annual values and the values obtained by [Martínez-Casasnovas et al. \(2016\)](#) in vineyards, [Gómez et al. \(2003\)](#) in olive groves, and [Renschler et al. \(1999\)](#) in cereal fields. We assumed that all woody crops (e.g. vineyards, olive and almond groves and other fruit trees) were managed following reduced tillage (RT) practice, that is non-tillage (NT) under the tree canopies and conventional tillage (CT; plough and herbicide) between the tree rows. Thus, 13 different maps of the RUSLE C-factor were generated. Although the C-factors could change over the 8-year test period owing to several reasons (e.g. plant growth and different canopy covers of the deciduous trees during the wet and dry years), we did not consider temporal changes in the C-factors, as we did not observe any significant evolution of the vegetation cover. Thus, constant C-annual and C-monthly factors were used during the 96-month test period. As C-factors are calculated every 15 days in RUSLE and at daily scale in RUSLE2, functional connectivity assessment with *A/C* can be adapted to these resolutions where data is available. The soil permeability factor (K_p) map was obtained by means of: (i) combining the regional maps of lithology (15 types in the study area) and soil types (6 groups following the FAO classification) (source: CHE); and (ii) using the field data obtained by [Badía-Villas et al. \(2006\)](#). These authors estimated the soil water retention capacity (SWRC; l / m^2) in 191 soil samples by using the values of soil water content at field capacity ($pF = -33$ KPa) and permanent wilting point ($pF = -1500$ KPa), and the values of bulk density, soil depth (up to 1.5 m) and the percentage of fine particles (< 2 mm). The values of SWRC ranged between 29 and 333 l / m^2 with a mean value of 188 l / m^2 (more details in [Sup. Fig. 2](#)). High values of SWRC were associated with potential low values of runoff depth and thus of FSC. Therefore, K_p was estimated as the normalized and inverse values of SWRC. We considered a minimum K_p value of 0.001 to avoid computational errors. As soil water infiltration capacity (K_f) varies in a specific site with the different values of rainfall intensity ([Dunne et al., 1991](#); [Hiraoka et al., 2010](#)) and ground cover ([Loch, 2000](#); [López-](#)

Vicente and Álvarez, 2018b), we selected the SWRC as a temporal stable parameter of soil permeability.

2.6. Simulated scenarios, spatial variability analysis and modelling testing

The two maps of structural FSC were obtained by running (i) the updated version of Borselli's index and (ii) the new AIC_{ST} with average annual values of the C-factors and rainfall erosivity. The 96 maps of functional FSC were generated with the new AIC_{FN} at monthly scale and using the interpolated maps of rainfall erosivity (September 2009 – August 2017) and the monthly values of the C-factors in the CORINE land cover codes 2xx (croplands), 311 (forest: deciduous trees) and 313 (forest: mixed). The remaining inputs (DEM, physical soil properties and the residual topography) were set as time-independent for all computations.

The spatial variability analysis was done estimating the values of structural and functional FSC in the 19 land uses and in the main geomorphic features, such as the headwater areas (Strahler's order equals to 1), the steep hillslopes ($S > 30\%$), the rolling slopes ($8\% < S < 30\%$), the alluvial terraces ($S < 8\%$), the banks of the Vero River, and near the outlet. Differences between all of these values were statistically analysed. Neither the IC nor the AIC include coefficients to adjust/calibrate the indices' predictions. Thus, the temporal dynamic of functional flow connectivity over the 96-month test period and predicted with AIC_{FN} was tested at the Vero River flow gauging station that is located in Barbastro (6 km upwards from the outlet) with the mean river flow values (Q ; m^3 / s) calculated at monthly scale. We used the unique gauging station located in the Vero River. Unfortunately, this station did not measure sediment concentration and/or load in the river flow and thus functional sediment connectivity could not be tested.

3. Results

3.1. Structural connectivity

The estimated map of structural FSC (FSC-st) with the Borselli's index had a mean value of -7.571 (± 1.559 of standard deviation) at catchment scale with a range of values of 15.2. The *IC* map showed clear differences in the values of connectivity along the catchment showing a patched distribution of the areas with high, medium and low FSC. Six areas with values above the mean were clearly identified: in the lower part (in the vicinity of the town that covers ca. one sixth of the total area), along the whole course of the Vero River and all its tributaries, in two areas in the middle of the catchment and in two areas located in the upper section of the catchment (Fig. 3.a). The histogram of this map showed a non-normal distribution with a positive skew to the values of low FSC and five peaks: two sharp peaks in the lowest and highest values associated to the divides, and the Vero River and the river banks, respectively, and three round peaks with low, medium-low and medium-high values of FSC. The largest area with high values of connectivity was located in the lower section of the Vero River catchment where cropland is the main land use and thus the C-RUSLE factors of the different patches (polygons in the input map) had higher values than the average (Table 1). In this area, the left and right riversides of the Vero River look somehow symmetric between them and the overland flow length to the stream is shorter than in the eastern middle part and in the western upper part of the catchment where the flow path lengths are much longer. The C-RUSLE map at catchment and annual scales had a mean value of 0.1438 (± 0.1642 of standard deviation; more details in Sup. Fig. 3). In the two areas in the middle part of the catchment where cropland appear in rolling slopes with medium values of slope gradient ($4\% < S < 8\%$), the *IC* reached high values. However, in the middle eastern part of the catchment and despite the main land uses are rainfed and irrigated vineyards, the values of FSC were around the mean value at catchment scale owing to (i) the longer distance to the river of these fields, and

(ii) the gentle topography with low slope gradient ($S < 3\%$) (Fig. 3.c). In the northern middle part of the catchment and downwards the headwater of the Vero River, very high and low values of FSC appeared in a patched distribution (Fig. 3.d). This spatial pattern was explained by the mix of agricultural and forestry areas in a landscape with steep slopes ($S > 10\%$) and numerous nested sub-catchments that favour the presence of many drainage divides that are characterised by low values of FSC. Near the headwater of the catchment, connectivity was high because of the high slope gradient (S ca. 10%) and the short distance from the slopes to the Vero River due to the geometry of the catchment in this section.

The map of FSC-st generated with the AIC_{ST} had a mean value of $-10.462 (\pm 2.566 \text{ of s.d.})$ at catchment scale with a range of values of 19.7. The variability of values of FSC along the catchment was 30% higher with the new index than with the IC . The histogram of the AIC_{ST} map was similar to a normal distribution with most of the values concentrated near the mean, and with seven peaks distributed along the curve: two sharp peaks with the lowest and highest values, respectively, although these peaks were smaller than the sharp peaks observed in the histogram of the IC map. Two small peaks appeared in the distribution of the low and high values of FSC, whereas three peaks appeared in the middle of the histogram and associated with medium-low, medium and medium-high values of FSC. The spatial distribution of annual rainfall erosivity, R_t in Eqs. (7) and (10), showed a clear pattern with the highest values in the northern part (more than $1000 \text{ MJ mm / ha h yr}$) and the lowest in the southern part (lower than $600 \text{ MJ mm / ha h yr}$; see Fig. 2.d). The minimum, mean and maximum average annual rainfall erosivity was 484, 894 and $1411 \text{ MJ mm / ha h yr}$; with a mean coefficient of variation of 57% at catchment scale. However, the influence of this input in the spatial distribution of the AIC_{ST} was apparently low and areas with high and low FSC with the stream appeared both in the upper, medium and lower part of the catchment. The map of the residual topography factor, RT in Eq. (10), showed a similar and inverse spatial pattern as the slope gradient map with a mean value of $0.933 (\pm 0.074 \text{ of s.d.})$. The histogram of this factor showed a strong bias

to the maximum value of 1, whereas few pixels had a RT value below 0.6. The highest RT values were observed in the gentle areas (mean $RT = 0.974$), whereas intermediate values appeared in the rolling slopes (mean $RT = 0.934$) and the lowest values in the steep areas (mean $RT = 0.897$). The map of the soil permeability factor, K_p in Eq. (10), had a mean value of 0.324 (± 0.348 of s.d.) with a strong biased distribution of the values in three peaks: 61% of the pixels had a K_p value lower than 0.14, 34% a K_p value higher than 0.76, and only 5% an intermediate value. This factor had a clear influence on the AIC_{ST} : the areas with the lowest and intermediate K_p values had an average FSC that was 25% and 5% lower than the average connectivity in the areas with the highest K_p values (mean $AIC_{ST} = -9.011$).

As the IC and AIC indices depend on the upslope weighting factors, and both indices are dimensionless, the comparison between the two maps of structural connectivity was done in detail after value normalisation ('Rescale by Function' tool in *ArcGIS*® 10.3; linear transformation from 1 to 10) (Table 1). As expected due to the clear differences in the distribution values of the two maps (see histograms in Fig. 3), the mean value of FSC-st with the new index was 17% higher than the mean value with the IC . Most of the areas characterised with high and low values of FSC were the same with both indices except one area located in the upper part of the catchment with different land uses (see details maps of Fig. 3.d and f). The original index predicted a scenario where areas with low, medium and high FSC are intersected whereas the new index predicted a more homogeneous scenario with predominant low and very low values of FSC, except in the valley bottoms of the gullies and gorges where both indices predicted high and very high values of FSC. Concerning the different land uses the highest values of FSC predicted with both indices were observed in the suburban areas (due to the high C-RUSLE factors assigned to the impervious surfaces) and in the vineyards (Table 1). The IC model also predicted very high values in the boulders and areas with sparse vegetation whereas the new approach predicted high values in the sand deposits near the river. The lowest values of connectivity were predicted by both models in the three

land uses devoted to forest. In the cultivated soils both models predicted higher values of connectivity in the vineyards and orchards than in the olive groves and cereal fields. Thus, similar patterns were obtained with both models on the basis of land use analysis although differences in FSC between the two models in the different land uses ranged between -17% and +37%. The spatial variability analyses considering the main geomorphic elements showed similar results with the highest values of FSC in the outlet and the Vero River and the lowest in the headwater areas and the steep and rolling slopes due to the presence of forest. Terraces and areas with gentle topography had intermediate values of FSC due to the predominant land use of crops (Table 1). The differences between both models were the highest in the terraces, up to 20%, high in the headwater areas and hillslopes, between 16% and 18%, and low in the river (6%) and outlet (4%).

3.2. Functional connectivity

The maps of functional FSC (FSC-fn) were generated with the AIC_{FN} approach for the 96-month period, appearing the lowest values of FSC in January and February 2012 and in December 2016, whereas the highest values were observed in September 2010, September 2014 and August 2015 (Fig. 4.a). At catchment scale, the mean values of AIC_{FN} ranged between -20.102 and -11.292 with an average standard deviation of 2.573 (18% of coefficient of variation). Over the test period, a linear, positive and very high correlation was observed between the monthly mean values of AIC_{FN} at catchment scale and those at the Vero River (Pearson's $r = 0.9971$) and at the outlet ($r = 0.9901$), and between the AIC_{FN} in Vero River and at the outlet too ($r = 0.9818$). The Pearson correlation coefficient between the AIC_{FN} at catchment scale and the mean rainfall erosivity was moderate ($r = 0.5725$), although high exponential correlations were found between the monthly rainfall erosivity and AIC_{FN} at catchment scale ($R^2 = 0.9583$), at the Vero River ($R^2 = 0.961$) and at the outlet ($R^2 = 0.9356$).

(Sup. Fig. 4). After analysing all the rainfall events recorded in the 12 weather stations over the 96-month period and calculating the corresponding rainfall erosivity, four types of rainfall events were identified: low, medium, high and very high erosivity (more details in Sup. Table 1). The most frequent events were those of low erosivity (67% of the total events) followed by the very high (14%), medium (12%) and high (7%) erosivity events. The highest monthly rainfall erosivity, El_{30max} in Eq. (7), was assessed in August 2011, in the northern part of the Vero River catchment ('El Coscollar' weather station; see Fig. 1.b) with a value of 2,364 MJ mm / ha h month.

On a monthly average basis the highest values of FSC were observed in September and high values were also obtained in June, July and October, whereas the lowest values were found in December (22% lower FSC than in September), January (19% lower) and February (20% lower) (Fig. 4.b). The coefficient of variation of the average monthly values of FSC was 7%. The mean values of the C-RUSLE maps at monthly and catchment scale ranged from 0.0961 (in June) to values between 0.1677 and 0.1838 during the period December – April (more details in Sup. Fig. 3). As expected a linear and negative correlation was found between the average monthly values of FSC-fn and those of the C-RUSLE factor (Pearson's $r = -0,607$).

Concerning the different land uses and geomorphic features, the spatial trends observed in the map of FSC-st were also observed in the values of FSC-fn over the twelve months of the year, although slight differences in these trends were found in the values of FSC-fn in spring and summer in the rainfed crops and the steep slopes (Fig. 5). These changes were associated with changes in the C-RUSLE factors. The highest coefficients of variation between the different land uses were found in April (14.8%), September (13.5%), October (13.8%) and November (13.6%), whereas the lowest variation (between 10% and 11%) was observed in the periods December – February and July – August (more details in Sup. Table 2). Regarding the different geomorphic elements, the highest coefficients of variation were estimated in

September (45.6%) and October (45.2%), and in April (43.8%) and June (44.8%). During the period December – February was found the lowest variations between the different geomorphic features. The headwaters, the steep and rolling slopes and terraces had coefficients of variation between 7.0% and 7.4%, whereas the coefficients of variation in the Vero River and at the outlet were clearly higher, up to 13.4% and 29.3%, respectively.

3.3. Modelling testing

During the test period the mean, median and maximum river flow (Q) was 1.28, 0.55 and 110.75 m³ / s, with 104 days with Q > 5 m³ / s (4% of the total period – T), 389 days with Q > 2 m³ / s (14% of T), 1280 days with Q < 0.5 m³ / s (44% of T) and only 116 days with a flow regime < 0.2 m³ / s (4% of T). The correlation between the 96 control points was weak ($r = 0.217$), although there was a general trend of increasing connectivity with increasing stream flow (Fig. 6.a). All points were drawn below this line and thus any point indicated a decrease of FSC with increasing river flow. Correlation between both variables improved up to $r = 0.348$ when the analysis was limited to the months with a river flow higher than 2 m³ / s. However, high values of connectivity were observed during months with low river flow. In order to refine the spatial variability analysis, the mean and standard deviation values of the monthly FSC-fn at the outlet and those of Q were plotted (Fig. 6.b). This figure showed different temporal dynamics between FSC-fn and Q. During the period November and March (5 months) both variables showed a similar pattern of decreasing and increasing values. Then, the river flow continuously decreased from March to July and remained at low values until October. However, FSC-fn showed a sinusoidal curve since March until October. These differences explained the high values of connectivity plotted in the graph with low values of stream flow.

4. Discussion

4.1. Original and aggregated index of connectivity

Recent studies have reported the necessity of developing accurate modelling tools for geomorphic investigation of sediment pathways, cross-scale connectivity processes and how overland flow inputs change from various sources, but keeping simplified mathematical and computational methodologies (Williams et al., 2016; Cossart and Fressard, 2017; Grauso et al., 2018). The new approach presented in this study to compute FSC kept the simple mathematical structure of the well known Borselli's index of FSC and increased the number of inputs at the same time. In addition to the land use factor, the *AIC* incorporated factors related to the soil water retention capacity, rainfall erosivity and residual topography by using spatially distributed maps and detailed databases. Thus, the new index fulfilled the current requirements of geomorphic and hydrologic studies at catchment scale. Besides, the inputs were prepared at high spatial and temporal scales taking into account the size of the study area.

The higher range of values of the map of FSC obtained with the new index in comparison with the map generated with the original *IC* model and the nearly normal distribution of the values represented in the histogram (characteristic of natural random variables) suggested that the new *AIC_{ST}* approach was more suitable to map spatially distributed values of FSC at large catchment scale. The differences in the values of FSC-st between the different land uses were similar with the two indices and in agreement with the different soil erosion rates reported in the literature in comparable Mediterranean landscapes. Olive groves had the lowest values of FSC, followed by the orchards and the cereal fields, whereas vineyards presented the highest values of FSC, up to 16% and 18% higher on average than the values estimated for the olive groves with the *IC* and *AIC*. Kosmas et al. (1997) found the same pattern along croplands located in Portugal, Spain, France, Italy and Greece, with the highest

rates of soil loss in vineyards, followed by wheat fields, especially during winter, and the lowest rates appeared in the olives grown under semi natural conditions. López-Vicente and Navas (2009) also found higher rates of soil erosion in rainfed cereal fields than in olive and almond groves in a small catchment located in the Spanish Pyrenees under similar physiographic conditions as those of the Vero River catchment. And recently, Rodrigo-Comino (2018) concluded in a review study that soil erosion rates in vineyards are higher than those in other land uses and represents a serious threat to landscape sustainability.

Concerning the geomorphic features, the highest differences between the two indices predictions were found in the terraces, up to 20%. The differences were also high in the headwater areas and hillslopes, between 16% and 18%, and low in the river (6%) and outlet (4%). It is also remarkable that all tributaries of the Vero River, such as ravines and gullies, had high values of FSC with the IC and the AIC_{ST} approaches both in the agricultural and forestry areas (see detail maps in Fig. 3). These differences can be explained by the more detail database used in the new approach, with more inputs reflecting the spatial characteristics of the different areas of the catchment, such as Chartin et al. (2017) found in two Japanese river catchments with a revised version of Borselli's index. The observed similarities in the river were explained because the Vero River was defined as the target of the simulation for both indices, and thus the effect of the different inputs were restricted.

The role of the RT factor in the new AIC was apparently opposite to the slope steepness because the highest values of RT (homogeneous slope gradient conditions) promoted higher FSC. The highest impedance for FSC was described by the RT factor in those areas where the slope gradient noticeably changed despite this fact happened in a steep or gentle area. However, the influence of the RT factor on the AIC_{ST} was limited, appearing slightly higher values of FSC in the areas with higher values of RT (> percentile 66) and lower values of FSC in those areas with intermediate (mean FSC 5% lower) and low values of RT (< Q33; mean FSC 4%

lower). This minor influence may be explained by the observed bias in the values of the RT map and thus a normalization procedure should be considered in a further application of the AIC approach in a similar way as Trevisani and Cavalli (2016) did with the roughness index, see Eq. (4), derived from the DEM. Finally, the high spatial heterogeneity of the soil physical properties explained the spatial distribution of the values of soil water retention capacity, K_p in Eq. (10), which is frequent in Mediterranean soils (Martínez-Murillo et al., 2017).

Although most of the AIC inputs appear in the RUSLE model, the results of the two approaches are different between them owing to six reasons: i) the new index does not include some of the RUSLE inputs, such as the soil organic matter, soil aggregate structure, soil texture and soil rock content; ii) the soil permeability factor of the AIC was calculated with the values of the soil water retention capacity that are not included in the RUSLE equation; iii) all AIC inputs used to calculate the weighting factor have normalized values between 0 and 1; iv) the combined assessment of the weighted upslope and downslope components at each pixel is only included in the connectivity indices whereas the RUSLE equation does not consider the weighted upslope contribution of its inputs (except for the slope length); v) the RUSLE equation estimates the soil erosion rates due to splash, rill, interrill and sheet erosion whereas the IC and AIC approaches are focussed on the runoff and sediment delivery processes linked to a defined target; and vi) the RUSLE's predictions cannot change as a function of different simulation targets, whereas the connectivity values calculated with IC and AIC strongly depend on the defined target and different maps and values are obtained in the same study area using different targets, such as the main river, the outlet, the ephemeral streams, wetlands, dams, different channel networks, etc. (more details in Renard et al., 1997; López-Vicente and Navas, 2009; Cavalli et al., 2013; and Persichillo et al., 2018). On the other hand, the combined application of RUSLE and SDR, such as the SEDD model (Burguet et al., 2017), requires discretization of a catchment into morphological units and the estimation of the β coefficient for each event and unit by using field-data of sediment yield. This data is not available in the

Vero River catchment. Thus, the results of the RUSLE and the flow and sediment connectivity indices give different and complementary information of the soil erosion, runoff and sediment delivery and connectivity processes at hillslope and catchment scales, and the numerical results of both approaches cannot be directly compared.

4.2. Spatial and temporal dynamics of flow and sediment connectivity

The low frequency of high (7%) and very high (14%) rainfall erosivity events observed in the Vero River catchment over the test period agreed with the review of daily soil erosion published in Western Mediterranean areas that suggested net soil loss and thus sediment delivery and connectivity depends on a few daily events (González-Hidalgo et al., 2007). The temporal dynamic of FSC-fn at catchment scale with the highest values in September, October, June and July, intermediate values in spring, and the lowest values between December and February agreed to a greater extent with the three erosive periods defined by López-Vicente et al. (2008) in a small agro-ecosystem located near our study area and after calculating the soil erodibility, the rainfall erosivity and the soil loss ratio for each month of the year.

Despite runoff responses are known to differ between the different sub-catchments of a river basin (López-Vicente et al., 2014) we considered that the overland flow generated within the entire Vero River catchment contributed to the river discharge during a period less than one month, because transfer distances of overland flow tend to be limited (Gomi et al., 2008). Thus, modelling testing of the AIC_{FN} with the monthly stream flow data was trustworthy. The differences between the river flow and the values of functional FSC estimated with the AIC_{FN} can be explained by the different hydrological and sedimentological response of the catchment over the twelve months of the year. In the relatively undisturbed Isábena River catchment (445 km²), that is a neighbour and similar catchment as our study site (also tributary of the Cinca River), Buendía et al. (2016) observed marked seasonality in water (Q)

and sediment load (SSC). These authors found that most of the discharge occurred in winter and spring as we observed in the Vero River flow patterns (Fig. 6.b), and most of the sediment was transported during summer and autumn as the AIC_{FN} predicted. According to these authors, Q-SSC hysteretic loops revealed the importance of sediment availability (whether stored in the channel or originating from wider catchment source areas) in the river's sedimentary response. Clockwise loops dominated during winter and spring, whereas counter-clockwise loops occurred mostly in summer and autumn, when in-channel storage reached its maximum. Despite the limitations of the AIC tool that cannot estimate soil water infiltration and runoff and sediment yields such as the process-based SWAT and WEPP hydrological and soil erosion models do (Al-Mukhtar et al., 2014; Vigiak et al., 2016), our tool can generate maps of structural and functional flow and sediment connectivity by using much less inputs and computational time than the complex models. Thus, the AIC appears as a suitable tool for hydrological studies in ungauged catchments.

4.3. Future research

It is known that runoff yield, stream flow, soil erosion and sediment yield are related between them with non-linear functions that depend on threshold values, numerous processes, the initial conditions and the spatial location of the source areas and the main overland and sub-surface flow networks (Mathys et al., 2005; Smets et al., 2011; Tena and Batalla, 2013; Lana-Renault et al., 2018). In the Vero River catchment, the values of functional connectivity and river flow over the test period showed different temporal dynamics. On the other hand, the IC and AIC tools do not include hydro-geological parameters, storage effects, evapotranspiration and other factors that influence on the hydrological connectivity processes at catchment scale. Moreover, Vogel and Sankarasubramanian (2003) illustrated that once a hydrological model is calibrated, the unavoidable model error can cloud our ability to validate

(or invalidate) the model. They emphasized that calibration is a complementary and subsequent task to the validation process. Thus, we propose to split the computation of runoff and sediment connectivity into two different approaches within the same index or isolated as two different indices that have to include calibration coefficients in order to refine the indices' simulation/prediction capability by using independent field-measured values of flow and sediment connectivity.

Further research activities will include the assessment of (specific) sediment yield in small sub-catchments within the Vero River catchment in order to test the functional sediment connectivity predictions of the AIC_{FN} tool. The potentiality of the tool as an index to describe the variations of the channel network for a mountainous catchment will be evaluated by means of correlation with the temporal variation of runoff yields. On the other hand, the use of cover crops in vineyards, almond and olive groves is becoming more frequent and provides an environmental-friendly alternative to conventional tillage for land management (Gómez et al., 2011). We will evaluate different land use scenarios in the woody crops of the Vero River catchment with the AIC in order to propose the best management scenario at local and catchment scales. The installation of grass buffer strips near the banks of the Vero River will be evaluated too.

5. Conclusions

The new aggregated index of runoff and sediment connectivity (AIC) successfully generated the maps of structural and functional flow and sediment connectivity in the large and heterogeneous catchment selected to test this index. Detailed information of topography, C-RUSLE land use factor, RUSLE2 rainfall erosivity and soil water retention capacity was incorporated in the new approach allowing generating more realistic maps of structural connectivity than the well known Borselli's index. Besides, the histogram obtained with the

new index followed a normal distribution, which is characteristic of natural random variables, with a wider range of values than the non-normal histogram derived from the original index. The spatial patterns of flow and sediment connectivity in the different crop types agreed with the soil erosion rates found in the literature from analogous Mediterranean landscapes and thus supporting the indices' predictions. The spatio-temporal dynamic of connectivity was identified with *AIC* during eight years at monthly scale. Different spatial and temporal changes were observed in the different land uses and geomorphic features, obtaining the highest variations in the stream. Modelling testing with the river flow values suggested different runoff and sediment responses of the catchment over the year, with predominant runoff production between November and March and sediment delivery during the summer associated to occasional thunderstorms. Further research is required to split the runoff and sediment connectivity processes and modelling testing with independent field- and model-based results. The new index fulfilled the current requirements of geomorphic and hydrologic studies at catchment scale and it appeared as a suitable and easy-to-run tool for studying spatio-temporal dynamics and different land-use and climatic scenarios.

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Appendix A. Supplementary content

Supplementary Table 1: Average annual values of rainfall events, depth and intensity, and of erosivity (R-RUSLE) calculated in the 12 weather stations during the period September 2009 – August 2017. Supplementary Table 2: Mean monthly values of A/C_{FN} in the different land uses (LU) and geomorphic features (GF) estimated during the 96-month test period. Supplementary Figure 1: Boxplot of the monthly values of maximum rainfall intensity (I_{30} ; mm / h) measured in the 12 weather stations during the test period. Supplementary Figure 2: Location of the soil profiles defined by [Badía-Villas et al. \(2006\)](#) within the Somontano designation of origin of wine, and mean values of the soil water retention capacity (SWRC) estimated in these profiles. Supplementary Figure 3: Maps of the RUSLE C-factor at average annual (a) and monthly (b) scales. Evolution of the monthly C-factors at catchment scale (c) and in the main land uses affected by temporal changes (d). Supplementary Figure 4. Correlation between the values of the monthly rainfall erosivity and those of the A/C_{FN} at catchment scale (a), in the Vero River (b) and at the outlet (c) during the 96-month test period.

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Table 1. Values of IC and AIC_{ST} in the different land uses (LU) and geomorphic features (GF).
CORINE2012_Codes: 112: discontinuous urban; 121: industrial and commercial; 211: rainfed farmland; 212: irrigated farmland; 221: permanent crop: vineyard; 222: permanent crop: orchard; 223: permanent crop: olive grove; 241: mixed cereal and permanent crop; 242: mosaic of crops; 243: mixed farmland and forest; 311: forest: deciduous trees; 312: forest: coniferous; 313: forest: mixed; 321: natural grassland; 323: scrubland; 324: mixed scrubland and forest; 331: sand; 332: boulder; and 333: sparse vegetation.

LU (code) & GF	Area	IC				AIC_{ST}				
	(%)	min	mean	max	sd	min	mean	Δ^* (%)	max	sd
112	0.7	-9.332	-4.813	2.170	0.899	-15.618	-6.755	+14%	0.840	2.092
121	0.6	-8.638	-5.527	2.536	1.185	-10.444	-7.003	+20%	1.066	1.271
211	11.4	-12.222	-7.170	1.443	1.045	-17.175	-10.043	+15%	0.411	1.823
212	5.2	-11.019	-5.787	1.919	1.031	-13.897	-7.695	+18%	0.460	1.360
221	8.4	-11.999	-7.339	1.983	1.066	-14.864	-9.651	+22%	0.517	1.416
222	0.7	-11.456	-7.280	-4.555	0.883	-14.223	-9.869	+19%	-7.278	0.828
223	0.5	-11.101	-7.774	-4.911	0.989	-13.909	-10.571	+20%	-7.815	0.970
241	0.3	-10.958	-7.030	-1.939	0.909	-13.929	-9.304	+21%	-4.007	1.067
242	11.5	-12.456	-7.122	0.970	1.128	-17.327	-9.928	+16%	0.308	1.794
243	2.1	-11.076	-6.401	1.123	1.305	-17.399	-9.496	+10%	0.295	2.737
311	12.7	-12.668	-8.916	1.216	1.223	-18.306	-11.959	+25%	0.055	2.240
312	5.3	-12.717	-9.228	0.827	1.193	-18.434	-12.140	+30%	-1.365	2.431
313	9.1	-12.716	-9.096	0.149	1.018	-18.647	-13.200	+11%	-0.675	2.630
321	1.2	-11.806	-7.510	-3.447	1.126	-16.863	-9.845	+23%	-4.330	1.743
323	24.0	-11.523	-7.073	1.518	1.419	-17.497	-9.734	+17%	0.272	2.536
324	5.1	-12.202	-7.427	1.599	1.234	-16.903	-10.844	+11%	0.088	2.100
331	0.1	-8.922	-7.189	1.410	0.892	-9.981	-8.068	+37%	0.235	0.872
332	0.2	-10.274	-6.107	-1.521	1.147	-16.821	-10.087	+0.2%	-3.610	3.896
333	0.8	-9.921	-5.480	1.424	1.066	-16.067	-11.211	-17%	-2.559	1.379
Vero catchment	100.0	-12.717	-7.571	2.476	1.559	-18.647	-10.462	+17%	1.066	2.566
Headwater**	64.1	-12.717	-7.676	2.197	1.546	-18.647	-10.583	+18%	0.847	2.586
Steep slope	31.0	-11.300	-7.648	2.536	1.653	-17.061	-10.619	+17%	1.066	2.844
Rolling slope	43.0	-11.820	-7.652	2.173	1.552	-17.870	-10.683	+16%	0.863	2.566
Terrace	25.9	-12.717	-7.269	1.620	1.439	-18.647	9.788	+20%	0.399	2.101
Vero River	0.1	-10.022	-1.870	2.439	2.161	-15.484	-3.672	+6%	1.066	2.920
Outlet***	<0.1	ND	1.055	ND	ND	ND	-0.084	+4%	ND	ND

*After value normalization (from 1 to 10) of the IC and AIC_{ST} maps; **Strahler's order equals to 1; ***This feature corresponds to only one pixel in the map.

Fig. 1. Location of the Vero River catchment in the Ebro River basin (NE Spain) (a); and maps of the slope gradient with location of the weather and river flow stations (b) land uses (c) and lithology (d).

Weather stations: CHE: Ebro River Basin water authorities; OR: irrigation main office of the Regional Government of Aragon. CORINE2012_Codes: 112: discontinuous urban; 121: industrial and commercial; 211: rainfed farmland; 212: irrigated farmland; 221: permanent crop: vineyard; 222: permanent crop: orchard; 223: permanent crop: olive grove; 241: mixed cereal and permanent crop; 242: mosaic of crops; 243: mixed farmland and forest; 311: forest: deciduous trees; 312: forest: coniferous; 313: forest: mixed; 321: natural grassland; 323: scrubland; 324: mixed scrubland and forest; 331: sand; 332: boulder; and 333: sparse vegetation.

Fig. 2. Monthly values of rainfall depth (a), and erosivity (b) measured in the twelve weather stations and daily values of the Vero River flow near the outlet (c) during the eight-year test period. Map of the mean ($\pm$ coefficient of variation) annual rainfall erosivity calculated in the Vero River catchment (d).

Fig. 3. Maps and histograms of FSC estimated with Borselli's IC (a) and the new AIC_{ST} (b) indices. Detail of the IC (c, d) and AIC_{ST} (e, f) maps in the southern (c, e: croplands, trails and roads) and northern (d, f: forest) parts.

Fig. 4. Graph of the monthly values of AIC_{FN} at catchment scale, in the Vero River and at the outlet during the 96-month test period (a). Maps of the average AIC_{FN} in May, September and December (b).

Fig. 5. Monthly values of the AIC_{FN} in the different land uses (a) and geomorphic features (b) during the 96-month test period.

Fig. 6. Correlation between the mean monthly values of the AIC_{FN} at the outlet and of the Vero River flow at the stream gauging station (a), and monthly temporal dynamic of the AIC_{FN} at the outlet and of the Vero River flow (b).

Supplementary Table 1. Average annual values of rainfall events, depth and intensity, and of erosivity (R-RUSLE) calculated in the 12 weather stations during the eight-year period September 1, 2009 – August 31, 2017.

Weather station			Rainfall depth (mm / yr)		Rainfall events (n: mean)					I ₃₀ (mm / h)			R-RUSLE (MJ mm / ha h yr)	
ID#	Name	Source	mean	CV	Total	Type 1	Type 2	Type 3	Type 4	mean	median	CV	mean	CV
1	<i>Ara_Boltaña</i>	SAIH-Ebro	746.6	21%	104	64(62%)	14(13%)	7(7%)	20(19%)	4.24	2.15	21%	1055.0	43%
2	<i>EMA_Mediano</i>	SAIH-Ebro	794.2	17%	103	63(61%)	12(12%)	8(8%)	20(19%)	5.14	1.83	25%	2044.3	51%
3	<i>El Coscollar</i>	SAIH-Ebro	754.2	16%	105	66(63%)	13(12%)	8(8%)	18(17%)	4.24	1.65	19%	1408.3	66%
4	<i>Rodellar</i>	SAIH-Ebro	661.9	10%	105	68(65%)	13(12%)	8(8%)	16(15%)	3.96	1.85	17%	966.5	37%
5	<i>EMA_Guara</i>	SAIH-Ebro	668.2	19%	98	59(60%)	15(15%)	8(8%)	17(17%)	4.74	1.93	15%	1412.7	40%
6	<i>Alquézar</i>	SAIH-Ebro	500.0	14%	95	63(66%)	12(13%)	7(7%)	14(15%)	4.04	1.68	29%	708.5	66%
7	<i>EMA El Grado</i>	SAIH-Ebro	548.8	16%	92	60(65%)	10(11%)	7(8%)	15(16%)	4.49	1.70	18%	1004.1	41%
8	<i>Antillón</i>	SAIH-Ebro	360.2	16%	92	69(75%)	10(11%)	5(5%)	9(10%)	3.08	1.25	22%	469.4	59%
9	<i>Vero_Barbastro</i>	SAIH-Ebro	415.6	12%	86	59(69%)	11(13%)	6(7%)	10(12%)	3.41	1.48	19%	485.7	55%
10	<i>Barbastro</i>	Ofi.Reg.	477.0	13%	110	80(73%)	11(10%)	6(5%)	12(11%)	2.74	0,85	19%	684.3	51%
11	<i>Huerta</i>	Ofi.Reg.	409.1	25%	105	79(75%)	12(11%)	6(6%)	8(8%)	2.70	0.85	23%	630.9	76%
12	<i>Selgua</i>	Ofi.Reg.	425.5	18%	106	80(75%)	11(10%)	6(6%)	10(9%)	2.68	0.83	24%	621.5	63%

CV: coefficient of variation; SAIH-Ebro: Automatic System of Hydrologic Information of the Ebro River Basin water authorities

(<http://saihebro.com/saihebro/index.php>); Ofi.Reg.: 'Oficina del Regante': irrigation main office of the Regional Government of Aragon

(<http://aplicaciones.aragon.es/oresa/>). Type 1: low erosivity, between 0 and 4 mm / event; Type 2: medium erosivity, between 4 and 8 mm / event; Type 3: high erosivity, between 8 and 12 mm / event; Type 4: very high erosivity, more than 12 mm / event or with an intensity equal or higher than 6 mm / 15 min.

Supplementary Table 2. Mean monthly values of AIC_{FN} in the different land uses (LU) and geomorphic features (GF) estimated during the 96-month test period (September 1, 2009–August 31, 2017).

LU (code) & GF	AIC_{FN}												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	cv
112: Discontinuous urban	-11.954	-12.040	-10.100	-9.436	-10.338	-9.355	-10.317	-10.353	-9.126	-9.562	-9.607	-12.185	-10.6%
121: Industrial and commercial	-12.173	-12.240	-10.346	-9.632	-10.566	-9.593	-10.693	-10.794	-9.401	-9.504	-9.836	-12.494	-10.7%
211: Rainfed farmland: cereal	-14.792	-14.923	-13.331	-13.149	-13.666	-13.005	-13.102	-13.496	-12.613	-12.705	-12.953	-15.153	-6.5%
212: Irrigated farmland: vineyard	-12.823	-12.851	-10.888	-10.118	-11.098	-10.488	-11.205	-11.388	-10.137	-10.302	-10.612	-13.157	-9.8%
221: Permanent crop: vineyard	-14.645	-14.674	-12.913	-12.310	-13.050	-12.424	-12.633	-13.026	-11.964	-12.196	-12.560	-15.005	-8.0%
222: Permanent crop: orchard	-14.753	-14.839	-13.373	-13.098	-13.443	-12.654	-12.601	-13.092	-12.208	-12.215	-12.616	-15.012	-7.6%
223: Permanent crop: olive grove	-15.452	-15.588	-14.047	-13.636	-14.304	-13.402	-13.544	-13.868	-12.786	-12.916	-13.299	-15.751	-7.3%
241: Mixed cereal and permanent crop	-14.116	-14.303	-12.574	-12.148	-13.016	-12.255	-12.704	-13.025	-11.871	-11.758	-12.088	-14.488	-7.5%
242: Mosaic of crops	-14.792	-14.870	-13.223	-12.865	-13.503	-12.843	-13.011	-13.411	-12.389	-12.467	-12.760	-15.114	-7.1%
243: Mixed farmland and forest	-14.269	-14.481	-12.830	-12.566	-13.182	-12.347	-12.760	-12.978	-12.077	-12.125	-12.409	-14.621	-7.0%
311: Forest: deciduous trees	-16.705	-16.890	-15.414	-15.270	-15.570	-14.641	-14.681	-15.015	-14.317	-14.634	-14.984	-17.157	-6.2%
312: Forest: coniferous	-17.085	-17.198	-15.641	-15.372	-15.583	-14.614	-14.712	-15.122	-14.423	-14.824	-15.199	-17.426	-6.8%
313: Forest: mixed	-18.029	-18.197	-16.719	-16.553	-16.733	-15.728	-15.775	-16.162	-15.521	-15.960	-16.309	-18.439	-6.1%
321: Natural grassland	-14.793	-14.890	-13.260	-12.874	-13.321	-12.413	-12.725	-13.082	-12.192	-12.394	-12.797	-15.158	-7.8%
323: Scrubland	-14.644	-14.784	-13.235	-13.041	-13.183	-12.216	-12.379	-12.756	-12.141	-12.442	-12.825	-14.996	-7.7%
324: Mixed scrubland and forest	-15.800	-15.900	-14.321	-14.004	-14.287	-13.352	-13.494	-13.925	-13.150	-13.482	-13.860	-16.130	-7.3%
331: Sand	-13.042	-13.072	-11.430	-10.821	-11.650	-10.809	-11.348	-11.537	-10.307	-10.382	-10.922	-13.515	-9.3%
332: Boulder	-14.991	-15.128	-13.598	-13.426	-13.526	-12.566	-12.663	-13.052	-12.474	-12.849	-13.227	-15.353	-7.6%
333: Sparse vegetation	-16.269	-16.293	-14.731	-14.466	-14.479	-13.638	-13.631	-14.272	-13.610	-13.925	-14.308	-16.537	-7.4%
<i>Coefficient of variation</i>	-10.8%	-10.8%	-13.1%	-14.8%	-12.4%	-13.0%	-10.6%	-11.1%	-13.5%	-13.8%	-13.6%	-10.6%	
<i>Vero River catchment</i>	-15.345	-15.465	-13.867	-13.576	-13.975	-13.135	-13.308	-13.676	-12.863	-13.113	-13.453	-15.708	-7.1%
Headwater*	-15.467	-15.588	-13.990	-13.700	-14.095	-13.250	-13.425	-13.793	-12.981	-13.233	-13.575	-15.831	-7.0%
Steep slopes ($S > 30\%$)	-15.490	-15.631	-14.101	-13.903	-14.108	-13.167	-13.272	-13.648	-12.987	-13.319	-13.684	-15.865	-7.2%
Rolling slopes ($8\% < S < 30\%$)	-15.561	-15.685	-14.091	-13.804	-14.209	-13.360	-13.540	-13.904	-13.085	-13.333	-13.671	-15.925	-7.0%
Terraces and flat areas ($S < 8\%$)	-14.693	-14.780	-13.093	-12.685	-13.307	-12.606	-12.853	-13.216	-12.229	-12.379	-12.692	-15.041	-7.4%
Vero River	-8.501	-8.675	-7.064	-6.836	-7.167	-6.312	-6.545	-6.827	-6.165	-6.374	-6.722	-8.877	-13.4%
Outlet**	-5.013	-5.086	-3.431	-2.914	-3.504	-2.718	-3.070	-3.386	-2.462	-2.560	-3.038	-5.443	-29.3%
<i>Coefficient of variation</i>	-36.6%	-36.6%	-41.9%	-43.8%	-41.6%	-44.8%	-43.2%	-42.1%	-45.6%	-45.2%	-43.3%	-35.4%	

*Strahler's order equals to 1; **This feature corresponds to only one pixel in the map; cv: coefficient of variation.

Supplementary Fig. 1. Boxplot of the monthly values of maximum rainfall intensity (I_{30} ; mm h⁻¹) measured in the 12 weather stations during the eight-year period September 2009 – August 2017. Mean values appear in red.

Supplementary Fig. 2. Location of the soil profiles defined by Badía-Villas et al. (2006) within the Somontano designation of origin of wine, and mean values of the soil water retention capacity (SWRC) estimated in these profiles.

Supplementary Fig. 3. Maps of the RUSLE C-factor at average annual (a) and monthly (b) scales. Evolution of the monthly RUSLE C-factor at catchment scale (c) and in the main land uses affected by temporal changes (d).

Supplementary Fig. 4. Correlation between the values of the monthly rainfall erosivity and those of the AIC_{FN} at catchment scale (a), in the Vero River (b) and at the outlet (c) during the 96-month test period.