A theoretical approach to improve the applicability of the Catchment Connectivity Index

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Abstract

Several frameworks to evaluate the sediment connectivity - the physical linkage of sediment through the channel system - in a catchment have been proposed and verified in several environmental contexts. A simple but effective index (“catchment connectivity index”, CCI), considering the geomorphological characteristics of the channels and the connectivity between hillslopes and channels was proposed for estimating the sediment connectivity in Spanish rivers. The procedure to calculate the CCI is improved in this study, which suggest a modified index (“mCCI”) to make simpler and more realistic the hydrological and geomorphological description of the landscape elements influencing the sediment connectivity. The new procedure to calculate the mCCI reduces the need of many field surveys (whose output is often affected by errors when carried out by low-experience operators) and makes quicker the CCI application on a catchment scale (thanks to the large use of GIS).

Keywords: connectivity, sediment source, hillslope-channel connection, geo-morphological factor, CCI.

1 Introduction

The concept of connectivity is taken to mean the physical linkage of sediment through the channel system, which is defined as the transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system. Sediment connectivity of the river system depends on the spatial variability, organization and internal connectivity of landform elements as well as its adaptability and type of response to any change (Borselli *et al.*, 2008). Thus, it is possible to investigate the overall complexity and heterogeneity of a given river system, from the relationships between its components, such as their location and extension (Brierley *et al.*, 2006).

In the past decade the scientific literature has shown a large interest in studying sediment movement within a catchment. Sediment connectivity evaluates the sediment sources, transport and storage from hillslopes along the channels to the outlet point. Besides studying the sediment connectivity as resulting from natural processes, it is necessary to identify sediment barriers in channels, such as the retention sites due to check-dams and deposition areas between hillslopes and channels as well as the changes in the drainage area; these factors are partly responsible for the development of hillslope-channel connection (coupling), for the evolution of channel morphology (lateral erosion, bed incision, narrowing, aggradation, degradation) and for changes in the sediment balance at the catchment scale (Quiñonero-Rubio *et al.*, 2013). Such factors must be taken into account with particular care to study the sediment connectivity of the Mediterranean torrents, where the local meteorological drivers (precipitation and temperature) coupled with the climate (semi-arid), hydrology (intermittent flow regime) and geo-morphology (high gradient, steep and coarse-grained riverbed) make these water courses particularly prone to the hydrogeological and flooding risk.

A number of frameworks to evaluate sediment connectivity in a catchment have been proposed and widely verified (e.g. Borselli *et al.*, 2008; Cavalli *et al.*, 2013; Grauso *et al.*, 2018). A simple but effective index ("catchment connectivity index", CCI) was proposed by Quiñonero-Rubio *et al.* (2013). CCI considers geomorphological characteristics of the channels and the connectivity slope-channel. The developers tested CCI estimating the sediment connectivity of Alto Taibilla river (SE Spain) under different historical land use patterns including hydrological control works. Some of the strengths of this index are: the inclusion of geomorphological factors, the connectivity evaluation at different spatial scales, the inclusion of transversal and longitudinal connectivity and the combination of different data sources (modelling, field data and orthophoto-interpretation). However, the procedure to calculate this index can be improved by a more efficient description of the hydrological and geomorphological parameters composing CCI; moreover, the CCI applicability can be made easier for the operators with less field experience.

To achieve these goals, this paper proposes the "modified CCI" (mCCI) that is a revised version of the original CCI of Quiñonero-Rubio *et al.* (2013). The mCCI minimises the need of direct surveys (whose reliability strictly depend on the ability and experience of the field operators) thanks to the use of sub-indices directly determined by GIS software, with the possibility of future use of remote sensing data.

2 The original CCI of Quiñonero-Rubio *et al.* (2013)

Acknowledged the complexity and the importance of the movement of sediments within the hydrographic basin, Quiñonero-Rubio *et al.* (2013) developed an experimental index, mainly based on field surveys, which give a measure of the degree of sediment connectivity in a watershed. The proposed is based on a semi-quantitative assessment of hydrological and geomorphological factors (Eq. 1), using remote sensing (analysis of aerial photography), hydrological modelling (waTEM/SEDEM model [De Vente *et al.*, 2008]), GIS analysis and field observations. Thus, the authors defined the original CCI as follows:

$$CCI = \left(\frac{TC_{av}}{TC_{max}}\right) \cdot \left(\frac{100-TE_{av}}{100}\right) \cdot \left(\frac{GF_{av}}{GF_{max}}\right) \cdot \left(\frac{SP_{av}}{SP_{max}}\right) \cdot \left(\frac{FC_{av}}{FC_{av\_max}}\right) \tag{1}$$

where *TC* (Transport Capacity) is the sediment transport capacity within the catchment (hillslopes and channels), *TE* (Trap Efficiency) is the capacity of sediment retention behind check dams, *GF* is the Geomorphological Factor, *SP* (Stream Power) is the sediment transport capacity in channels, and *FC* (Flow Conditions) expresses the conditions of flow channels (continuous or ephemeral). The subscripts '*av*' and '*max*' indicate, respectively, the average and the maximum value of these factors within the catchment. The range of each factor is 0 to 1, that is, from a lower to higher connectivity, respectively.

TC (Eq. 2), has different values according to different land use scenarios by the ktc parameter. *TC* is given by the following equation:

$$TC = ktc \cdot R \cdot K \cdot A^{1.4} \cdot S^{1.4} \tag{2}$$

where *R* and *K* are RUSLE factors, determining rainfall erosivity and soil erodibility, *A* is the contributing area and *S* is the terrain slope. The values of *ktc* derive from a reclassification of the RUSLE C factor values, shown by a related map according to the C distribution for each land use (Borselli *et al.*, 2008). The area covered by the channels is considered in the analysis. Values of *ktc* are calibrated assuming as optimal those obtained in previous works where the model was calibrated by WaTEM/SEDEM (optimizing values: *ktc*-low = 2 x 10-6 and *ktc*-high = 2 x 10-5) (Boix-Fayos *et al.*, 2008; Quiñonero *et al.*, 2016).

TE (Eq. 3), limits the transfer of sediment downstream, since the material is stored into drainage areas artificially created by the check dam; this factor is the trap efficiency proposed by Brown (1943):

$$TE = 100 \cdot \left(1 - \frac{1}{1+0.0021 \cdot D \cdot \frac{C}{W}}\right) \tag{3}$$

where C is the reservoir storage capacity (m^3), W is the catchment area (km^2), D is a value ranging from 0.046 to 1 (with a mean value of 0.1), all of them being dependent on the characteristics of the artificial reservoir.

GF explains the degree (that is, the fraction) of sediment connectivity of a sub-catchment due to geomorphological conditions at the confluence of a tributary channel with the main channel of a catchment. It can have values of 1 or 0.5 depending whether the tributary channel is connected or not to the main channel, respectively.

SP (Stream Power, Eq.4), unlike *TC* slopes, does not consider changes in land use, being only oriented to sediment transport through the channels, not from hillslopes. As suggested by Prosser and Rustomji (2000):

$$SP = A^m \cdot S^n \tag{4}$$

SP is proportional to the drainage area (*A*) and terrain slope (*S*); *m* and *n* are two empirical values, equal to 1.4 in the work of Quiñonero-Rubio *et al.*, (2013)

FC expresses the continuity and persistence of flow in the channels, with values of 1 or 0.5 depending whether flow is permanent or ephemeral, respectively.

Thanks to the standardization, the range of possible values for each factor is 0 to 1, from a lower to a higher connectivity, respectively.

3 Suggested improvements of CCI (mCCI)

Modifications are made on all CCI factors (*TC*, *TE*, *GF*, *FC*), except *SP*, which is implemented only by a different standardization.

The use of WaTEM/SEDEM model provides only two values for the subfactor *ktc* of TC (*ktc*-low and *ktc*-high), which do not express in detail the variability of land cover of an area. For this reason, in the mCCI the USLE-C factor (better consolidated in literature) is instead proposed in the mCCI to obtain more than two classes.

For TE factor, Brown (1943) proposed values of *D* close to 1 (i.e., high *TE*) for reservoirs in regions with smaller and more variable runoff). More specifically, the original *TE* of Brown (1943) depends on the C/W ratio. However, the use of this ratio could lead to very different *TE* values (Brune, 1953), since *TE* depends on runoff volumes or other hydrological characteristics (whose values are often not available in the Mediterranean catchments). Since the *TE* of CCI may be affected by a large error, which weighs on the overall CCI value, the *TE* expression of Brown is replaced in the mCCI by an index (*TE* = 1 - *Vs*) that provides a more accurate estimate of the ability of an artificial reservoir (such as a check dam) to store sediment in the channel. TE expresses the residual capacity of a barrier to store sediment, that is, the difference between the total trap capacity (equal to 1) and the volume of sediment effectively retained behind the barrier (*Vs*). This sedimentary zone can be considered as a prism with a trapezoidal section. Based on the height and surface area, the parameter *Vs* can be estimated by Eq. (5) (Castillo *et al.*, 2007; Zema *et al.*, 2014).

$$V_s = \frac{1}{2}\, w_s \cdot l_s \cdot h = \frac{1}{2}\, Sh \tag{5}$$

where Vs (m^3), l_s (m), w_s (m), S (m^2), h (m) are the volume, the longitudinal length, the average width, the surface area and the height of the sedimentary zone, respectively.

The limit of the sedimentary wedge/area can be identified upstream of each barrier by the changes in longitudinal gradients or surface grain size. The surface of this sediment wedge can be mapped by GPS (Fig. 1).

Fig. 1 Sedimentary zone behind a check dam in a Mediterranean ephemeral torrent.

Whereas the equation for calculating *TE* in the original expression of CCI has an empirical nature (mainly in the estimation of the parameter *D*, *C* and *W*), the *TE* proposed in the mCCI can be derived from the actual feature (shape and geometry) of a geomorphological feature of a channel and estimated by aerial maps or, in its absence, by field surveys with low possibility of errors.

In the CCI the *GF* and *FC* factors are calculated in fieldwork and, as explained above, the errors in their estimation (depending on the ability and experience of the field operators) can be high when the surveyor has low skills and experience. In order to make more realistic the evaluation and reduce the errors for the *GF* sub-index, the use of the terrain profile curvature (longitudinal and tangential directions) is proposed in the mCCI. Longitudinal curvature belongs to the vertical plane parallel to the slope direction, identified by Shary (1995) and Florinsky (1998) as "vertical curvature". It measures the slope variability and influences the surface water flow velocity and thus the downstream flow of water and sediment.

GF values can be easily calculated by a common GIS based on a DEM of the study catchment. GIS calculates longitudinal curvature as the second derivative of the terrain local slope, in a 3 x 3 moving window surrounding a given cell of DEM. The tangential curvature is calculated as for the longitudinal value, but it is estimated in the perpendicular direction to the steepest slope. After the standardization, *GF* ranges from 1 (negative values of curvature, that is, concave terrain) to 0 (for higher values of curvature, that is, convex shape of terrain). Therefore, *GF* factor gives information about the local shape of the terrain (convexity or concavity) using the values of longitudinal and tangential curvatures. There is a reduction or a lack of connectivity in correspondence of sediment accumulation (buffers) originated by natural (floodplain areas or areas with very low slope) or artificial (flat agricultural areas occupying and filling ephemeral channels) conditions (Quiñonero-Rubio *et al.*, 2013).

The terrain profile curvature by GIS procedure in the mCCI, is able to better discriminate - compared to the CCI, relying to field observations - the connections between main channel and tributaries at the pixel scale. Furthermore, GIS approach is able to overcome the limit reported by Heckmann *et al.* (2018), who stated that (dis) connectivity operates at landform scale and not at raster cell scale.

Perennial rivers are characterized by a permanent water flow, while intermittent torrents typically alternate prolonged periods of minimum flow to flash flood events in response to the large temporal variability of precipitation. In CCI the *FC* factor discriminates permanent (*FC* = 1) and discontinuous flow (*FC* = 0.5). The original *FC* factor of Quiñonero-Rubio *et al.*, 2013 is replaced in the mCCI by the difference (if positive, otherwise *FC* has a value of 0.5) of: (a) short-term precipitation given by flow duration curves at a return interval of two years (which determines the most frequent hydrological regime in Mediterranean torrents) and a duration equal to the catchment concentration time, *tc*; (b) the initial abstraction (*Ia*), calculated by SCS-CN method. In other words, when the precipitation depth exceeds *Ia*, the channel has permanent flow and *FC* = 1, otherwise *FC* is set to 0.5.

As outlined above, the CCI requires the standardization of all factors, made by Eq. (6). If this equation is applied to the factors of the mCCI, in some cases (extreme values of DEM), the standardization provides very small values, which may become unrealistic. In the mCCI a different standardization method (Eq. 7) is proposed for all factors, except for *GF*, where the Eq. (8) is assumed, and for *TE*, which, unlike the other factors, is directly expressed as a percentage.

$$\frac{x_{avg}}{x_{max}} \tag{6}$$

$$\frac{x-x_{min}}{x_{max}-x_{min}} \tag{7}$$

$$\frac{x_{max}-x}{x_{max}-x_{min}} \tag{8}$$

Contrarily to the range of values of the CCI, the mCCI index is expressed as the binary logarithm of the product among the factors, in order to reproduce the very large range of values of the sediment connectivity. All mCCI factors being in the range [0, 1], the binary logarithm is in the range [-∞, 0]. To avoid negative values, the absolute value of the mCCI is taken. Accordingly, the mCCI is calculated using equation (9):

$$mCCI = \left| log_2 \left[\left(\frac{TC - TC_{min}}{TC_{max}-TC_{min}} \right) \cdot \left(\frac{GF_{\tan\_norm}+GF_{prof\_norm}}{2} \right) \cdot \left(\frac{SP-SP_{min}}{SP_{max}-SP_{min}} \right) \cdot \left(\frac{FC-FC_{min}}{FC_{max}-FC_{min}} \right) \cdot TE \right] \right| \tag{9}$$

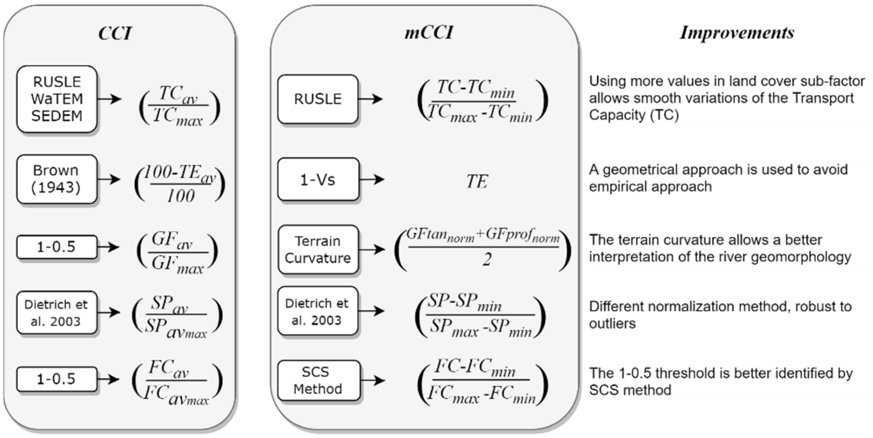

Fig. 2 Comparison of methods to calculate CCI and mCCI.

Fig. 2 compares the sub-factors and the calculation procedures of CCI and mCCI, while Table 1 explains the main differences between the two indexes.

Table 1 Main differences between CCI and mCCI.

CCI	mCCI
Gives the sediment connectivity at the catchment or sub-catchment scales	Gives the sediment connectivity for each cell of DEM with the possibility to calculate at different spatial scales
Requires geomorphological training	Does not require experience for field operators
Some factors are binary in nature and left to the evaluation of operators	Every factor is continuous
Not automatable calculations for some factors	Quick and automatable calculation of all factors

4 Conclusions

This study reports a theoretical approach to improve the applicability of the CCI of Quiñonero-Rubio *et al.* (2013). A modified CCI (mCCI) is suggested by improving the calculation methods of CCI. Some factors of the original index are replaced by alternative methods, which are based on DEM. This reduces the need of field surveys and allows the almost complete automation of the procedure. The proposed mCCI may be used not only for the analysis of sediment connectivity of the individual elements of a catchment (spatial domain), but it allows also the possibility to catch the evolution of river connectivity from a diachronic perspective (temporal domain). The mCCI can be used as analytical tool to evaluate the influence of past or future changes in land use, climate and anthropogenic actions by comparing scenarios of torrent connectivity.

Practical applications in different environmental contexts are expected in order to verify the efficacy and efficiency of the suggested improvements. Finally, the mCCI could be more reliable in the case of high-resolution DEM availability (e.g., LIDAR), which may allow a more realistic estimation of the geomorphological factors of the index.

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