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A modified Catchment Connectivity Index for applications in semi-arid torrents of the Mediterranean environment

A modified sediment connectivity index for Mediterranean catchments

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Abstract

The importance of sediment connectivity for watershed management needs accurate quantification tools, particularly in Mediterranean torrents, where soil erosion and sediment transport are often not tolerable. This study proposes a modified version (*mCCI*) of the Catchment Connectivity Index (*CCI*), theorised by Quiñonero-Rubio et al. (2013). The modified index improves the calculation procedure, providing a more efficient description of the hydrological and geomorphological factors of *CCI* and making easier its applicability for the operators with less field experience.

The *mCCI* is applied to evaluate the sediment connectivity at the catchment scale in a torrent of Calabria (Southern Italy). This case study has shown how and by what extent the natural (climate changes) and human impacts (land-use changes and check dam installation) have influenced the geomorphic processes influencing sediment circulation in the studied basin throughout six decades. From 1955 to 2012, a general decrease in sediment connectivity has been caught by *mCCI*. This was the combined effects of greening-up processes of the catchment (due to both natural afforestation and human-induced reforestation) and the installation of check dams, which have decreased the catchment potential to circulating sediments. Overall, the *mCCI* can be used as an analytical tool to evaluate the influence of past or future changes in natural and human-induced changes in land use and climate actions by comparing scenarios of torrent connectivity.

Keywords: Soil erosion, sediment transport, sedimentation, connectivity index, land use change, check dams

1. INTRODUCTION

River management often requires proper restoration actions, in order to assure the geomorphological and ecological *equilibrium* at the catchment scale. Erosion control is one of the most important issues in river management planning and operation, particularly in catchments where huge amounts of sediments are mobilised by floods. The locations and distances to which the eroded sediments are transported depend on the connectivity within the catchment system (Sandercock and Hooke, 2003). Hooke (2003) defines the sediment connectivity as the physical linkage of sediment through the channel system or the potential for a specific soil particle to move through the river system. The related concept is taken to mean the physical linkage of sediment through the channel system. Thus, sediment connectivity becomes an emergent property of the river state, interpreting the continuity and strength of runoff and sediment fluxes at a given point of a catchment in time (Heckmann et al., 2018; Surian et al., 2009).

In the last decades, many studies have been targeted at evaluating the sediment connectivity in riverine channel systems at varied-detail scales, also supported by field observations (Grauso et al., 2018). However, sediment connectivity assessment and quantification is a quite difficult task (Harper et al., 2017), since (i) it cannot be measured explicitly (Turnbull et al., 2018) and (ii) the number of factors that can modify the sediment connectivity in a river system is very large, as mentioned above. To overcome these problems, a number of frameworks to evaluate sediment connectivity in a catchment have been proposed in the last decades and applied in several climatic and environmental contexts (e.g. Walling and Zhang, 2004; Borselli et al., 2008; Cavalli et al., 2013; Grauso et al., 2018; Quiñonero-Rubio et al., 2013; Lane et al., 2017), of which a comprehensive review is available in the paper of Heckmann et al. (2018). However, few of these indexes have been purposely prepared to study and evaluate the sediment connectivity of the ephemeral torrents of the Mediterranean areas, affected by particular meteorological drivers (precipitation and temperature), high soil erodibility, and flood risk (Fortugno et al., 2017). Therefore, the availability of simple but effective sediment connectivity indices to be applied in Mediterranean torrents may be helpful for evaluating of the hydrological response in terms of water and sediment flows.

Recently, the Catchment Connectivity Index (*CCI*) has been proposed by Quiñonero-Rubio et al. (2013) and applied in Alto Taibilla River (South-East Spain). Using *CCI*, these authors estimated the sediment connectivity in this ephemeral torrent of the Mediterranean environment, subjected to different historical land-use patterns including reforestation and control works. Some of the strengths of this index are: (i) the evaluation of the sediment connectivity at different spatial scales; (ii) the inclusion of transversal and longitudinal connectivity; and (iii) 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 study proposes the *modified CCI* (henceforth *mCCI*), which is a revised version of the original *CCI* of Quinonero-Rubio et al. (2013). The *mCCI* requires lower field surveys (whose reliability strictly depends on the ability and experience of the operators), thanks to a larger use of GIS software for calculating the *mCCI* factors. Moreover, its ability to interpret the sediment connectivity at the catchment scale is assessed in the Sant'Agata torrent (Calabria, Southern Italy), which exhibits the typical climatic and geomorphological conditions of the ephemeral watercourses of the Mediterranean environment. Applying the *mCCI*, the current connectivity degree of the catchment and the changes in the sediment connectivity over a period of fifty years - in which a decreasing hydrological trend, changes in land use, and check dam installation have occurred – have been evaluated.

2. MATERIALS AND METHODS

2.1. Outlines to the original index

The *CCI* proposed Quiñonero-Rubio et al. (2013) is based on a semi-quantitative assessment of hydrological and geomorphological factors (Eq. 1), using remote sensing (analysis of aerial photography), hydrological modeling (waTEM/SEDEM model [De Vente et al., 2008]), GIS analysis and field observations. More details about the structure and the calculation procedure of the *CCI* can be found in the related paper.

2.1.1. The equation for calculating the CCI

The authors defined the original *CCI* as follows:

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

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 and discontinuous flow condition). The subscripts *av* and *max* in the Eq. 1 for calculating *CCI* indicate, respectively, the average and the maximum value of these factors within the catchment. Since each factor is normalized, its range is 0 to 1, that is, from a lower to higher connectivity, respectively. Thanks to the standardisation, the range of possible values for each factor is 0 to 1, from a lower to a higher connectivity, respectively.

2.1.2. The factors composing the CCI

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

$$TC = k_{tc} RKA^{1.4} S^{1.4} \qquad (2)$$

where *R* and *K* are RUSLE factors (Wischmeyer and Smith, 1978), 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 = 2×10^{-6} and ktc-high = 2×10^{-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):

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

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 (Eq. 4), unlike *TC* slopes, does not consider changes in land use, being only oriented to sediment transport through the channels, not from hillslopes. *SP* is proportional to A and S; m and n are two empirical values, equal to 1.4 in the work of Quiñonero-Rubio *et al.* (2013), as suggested by Prosser and Rustomji (2000):

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

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.

2.2. Suggested improvements of *CCI* (*mCCI*)

In this study, modifications have been made on all *CCI* factors (*TC*, *TE*, *GF*, *FC*), except *SP*, which is implemented only by a different normalization.

2.2.1. The TC factor

The use of WaTEM/SEDEM model provides only two values for the subfactor k_{tc} of *TC* (k_{tc}-low and k_{tc}-high), which do not express in detail the variability of the 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.

2.2.2. The TE factor

For the *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 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 ($TE = 1 - V_s$) 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 (V_s). This sedimentary zone can be considered as a prism with a trapezoidal section.

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.

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.

2.2.3. The GF factor

In the *CCI* the *GF* factor is calculated in fieldwork and, as explained above, the errors in its 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* factor, the use of the terrain profile curvature (longitudinal and tangential directions) is proposed in the *mCCI*, in order to calculate and tangential *GF* factors. 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. In the following the two *GF* factors will be indicated as GF_{long} (along to the longitudinal profile direction) and GF_{tan} (along the perpendicular direction).

GF values can be easily calculated by a common GIS-based on a DEM of the study catchment. After the normalization, *GF* ranges from 1 (negative values of curvature, that is, concave terrain) to 0 (for higher values of curvature, that is, the 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 on field observations - the connections between the 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 a landform scale and not at a raster cell scale.

2.2.4. The FC factor

In *CCI* also the *FC* factor is determined by operators in fieldwork, which requires experience and can be time consuming. 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 (I_a), calculated by SCS-CN method. In other words, when the precipitation depth exceeds I_a, the channel has permanent flow and $FC = 1$, otherwise, *FC* is set to 0.5.

2.2.5. Calculation of the mCCI

As outlined above, the *CCI* requires the normalization of all factors, made by Eq. (5):

$$x_{norm} = \frac{x_{av}}{x_{max}} \tag{5}$$

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

$$x_{norm} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{6}$$

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

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):

$$mCCI = \left| \log_2 \left[\left(\frac{TC - TC_{\min}}{TC_{\max} - TC_{\min}} \right) \left(\frac{GF_{\tan\_norm} + GF_{prof\_norm}}{2} \right) \left(\frac{SP - SP_{\min}}{SP_{\max} - SP_{\min}} \right) \left(\frac{FC - FC_{\min}}{FC_{\max} - FC_{\min}} \right) \cdot TE \right] \right| \tag{8}$$

where the subscript *norm* refers to the normalized value of the factor. Overall, differently from *CCI, mCCI*: (i) estimates the sediment connectivity for each cell of DEM; (ii) provides the possibility to calculate connectivity on other spatial scales; (iii) consists of only continuous factors (and not binary, as in the *CCI*); (iv) makes the calculation of each factor quick and automatable. Furthermore, *mCCI* application does not require high experience for field operators (Figure 1).

2.3. Application of *mCCI* to the Sant'Agata catchment

2.3.1. Study catchment

The Sant'Agata torrent shows the specific morphological and hydraulic characteristics of many Mediterranean watercourses, such as: (i) small catchment area (usually with irregular perimeter); (ii) hypsographic curve with pronounced concavity; (iii) very erodible soils; (iv) short length of the main stream (usually few tens of kilometres); (v) high longitudinal slopes (more than 10% in the headwaters, 2% or less in the valley reaches); (vi) torrential and highly impulsive response to the meteorological stress. In Calabria and Sicily, these torrents are called *fiumaras*, seasonally flowing watercourses that drain the mountain chains of Southern Italy. In *fiumaras* heavy floods in the rainy season follow long periods of completely dry bed (Sabato et al., 2004; Bombino et al., 2007).

The sub-catchment under investigation is the mountain and middle part of the Sant'Agata torrent. It covers 17.43 km^2 within the Aspromonte mountain system (Figure 2). The studied main stream rises at 1.649 m above sea level and it is 11.2 km long. The outlet of the sub-catchment is located 744 m a.s.l. and the mean slope is 29%.

The geological units of the studied headwater are mainly composed of metamorphic rocks and sedimentary deposits of the Pleistocene. The prevalent soil texture is sandy loam, according to the soil map of Calabria (ARSSA, 2003).

The land use was monitored in 1955 and 2012. In 1955, the prevalent land use was forest (43.4% of the total catchment area, natural stands of beech and fir and artificial woods dominated by pine), shrublands (8.5%), agricultural areas (15%, mainly arable land), natural grasslands (15%) and residual not vegetated areas. In 2012 the prevalent land use is still forest (67.7%, with natural stands still of beech and fir as well as artificial woods of pine planted in the 1960s on degraded or deforested lands), shrubland (12%, with some species of shrubs covering partly or thoroughly the channel bed, not flooded for many years), agricultural areas (20%, still arable land and vegetable gardens, EEA, 2016) and natural grasslands in the remaining areas.

The average annual precipitation - recorded at Gambarie meteorological station (close to the upper portion of the sub-catchment perimeter) - was 1820 mm between 1930 and 1955 and decreased to 1571 mm between 1955 and 2012.

At the end of the 1950s, a series of check dams was built in the sub-catchment; moreover, heavy reforestation works were carried out in the same period and the land-use changed. In the main channel of the reaches under investigation 17 staggered check dams (made up of concrete or stone and concrete) were built in the 1950-60s to reduce erosion and the bedload transport capacity during flood events. These control works, 3 to 4 m high and 13.5 to 19 m wide, have a full body with a trapezoidal spillway (Bombino et al., 2009, Fortugno et al., 2017). No embankments were been built in the reaches under investigation (Bombino et al., 2007).

2.3.2. Implementation of mCCI in the studied sub-catchment

The modified *CCI* was applied to the Sant'Agata catchment, to evaluate the changes in sediment connectivity at the sub-catchment scale throughout a period of 60 years (from 1955 to 2012). Considering the check dam presence, reforestation and land-use evolution, four scenarios, consisting of a combination of check dam presence or not, and land-use changes or not, were simulated; under each scenario, the sediment connectivity was calculated using *mCCI*.

The four scenarios are:

(1) in 1955, before check dam construction (hereinafter indexed as *LU1955/NO-CD*, where LU indicates the land-use date and *NO-CD* indicates the absence of control works;

(2) at the end of the 1950s, that is immediately after check dam installation (*LU1955/CD*, where *CD* refers to the presence of check dams;

(3) in 2012 (*LU2012/CD*) with check dams, considering also the land-use evolution in the sub-catchment;

(4) in 2012 (*LU2012/NO-CD*), hypothesizing that check dams are absent.

The comparison of two scenarios *LU1955/NO-CD* and *LU2012/CD* evaluates the effects of the check dams and land-use changes (due to reforestation works and the general greening-up process) on the sediment connectivity in the sub-catchment. The analysis of the scenarios *LU1955/CD* and *LU2012/CD* allow the evaluation of the influence of land-use changes only (since in this case the check dams are present) on the connectivity. The comparison between *LU2012/CD* and *LU2012/NO-CD* provides an estimation of the check dam influence on the sub-catchment connectivity, assuming no historical variations in the land use.

It should be pointed out that the scenario *LU1955/CD* takes into account the presence of the check dams with a sediment retention capacity of 100% and that the land use and the original level of the channel bed were considered the same under the scenarios *LU1955/NO-CD* and *LU1955/CD*.

The scenario *LU2012/NO-CD* represents a hypothetical catchment, which underwent land-use changes, but was not regulated by installing check dams.

As regards the *mCCI* implementation in the studied sub-catchment, the land use of 1955 was drawn from black and white 1-m resolution orthophotos, taken by the Italian Military Geographic Institute (based on American flights). The original longitudinal profile of the channel bed in 1955 was reconstructed using the data of the previous study of Fortugno et al. (2017). These authors mapped from aerial photographs the channel adjustments in the proximity of the studied check dams between 1955 and 2012 in the main reach of the same catchment, following the methods reported by Boix-Fayos et al. (2008) and Zema et al. (2014).

The land use of 2012 was estimated from the latest available orthophotos (in colour and with 0.5-m resolution), provided by the Calabria Region administration, while the bed level was measured by a topographic survey (with a total station). More details about the analysis of the land-use changes, local channel slope changes and channel morphology adjustments can be found in the cited paper of Fortugno et al. (2017).

Finally, the t-test was applied to evaluate the statistical significance of the differences (at p level < 0.05) in the factors and the *mCCI* values among the evaluated scenarios.

3. RESULTS

3.1. Changes in the individual factors of the *mCCI*

Both in 1955 and 2012, the *TC* factor was lower on the hillslopes ($TC \sim 10^{-5}$) than on the hydrographic network ($10^{-1} < TC < 1$). Compared to 1955, the mean *TC* is in general higher in both the scenarios related to the land use of 2012 (on average 1.19×10^{-3} for both against 7.82×10^{-4} in *LU1955/NO-CD* and 1.07×10^{-3} in *LU1955/CD*). The increase in the *TC* factor of channels is four to five orders of magnitude higher than on the hillslopes; moreover, the *TC* values increased in the channel banks from 1955 to 2012. However, the changes of *TC* at the catchment level (that is, comprising the hillslopes and the channels) between the monitoring dates are not reflected by its mean value (Figure 3 and Table 1).

Regarding the *GF* factor, as expected, the highest values were estimated in the torrent channels (on average 0.65 against 0.40 in the hillslopes) both in 1955 and 2012 (Table 1). This clearly confirmed that the terrain shape of channels is more concave compared to the other geomorphic units of the sub-catchment, and this enhances the sediment connectivity through the basin, which is caught by *GF*. Moreover, the scenarios of 1955 (*LU1955/NO-CD* and *LU1955/CD*) showed the same *GF* values. *GF* as used here showed an evolution from 1955 to 2012. We can point out:

- a noticeable reduction in scenario *LU2012/NO-CD* in the main channel (on the average by 8%), due to the longitudinal profile aggradation compared to 1955;
- a slight reduction in the hillslopes, because the changes in the transverse and longitudinal slope of the terrain were very low from 1955 to 2012.

The *TE* factor is strongly influenced by the presence of transverse structures in the channel. As response to the local adjustments induced by the check dams, the *TE* factor was instead different in the two scenarios of 1955. Therefore, the *TE* factor, which was between 0.1 and 1 in many cells (those located immediately upstream of the walls) for the scenario *LU1955/NO-CD*, after check dam installation, was instead equal to 1 in both scenarios *LU1955/CD* and *LU2012/CD*, since the wedges behind the check dams were totally and immediately filled with sediments (Figure 4).

The factor *FC* was always equal to 1, because all the channels in the studied sub-catchment were permanent ($P > 0.2 S$).

The factor *SP* follows the same spatial patterns as *TC*, due to the very similar mathematical structure.

The application of the t-test showed significant differences ($p < 0.05$) only for *TC* factor. It was significantly different between land-use scenarios (1955 vs. 2012) as well as the presence/absence of check dams. Conversely, no significant differences were found for *GF* and *SP* factors. The significance test was not applied for *TE* and *FC,* which assume categorical values (Table 1). The overall *mCCI* statistics do not show significant differences for the four scenarios except for minimum and maximum values between 1955 and 2012 scenarios (Table 2).

3.3. Changes in the mCCI

The comparison of the *mCCI* calculated for each cell of the Sant'Agata sub-catchment showed noticeable differences in sediment connectivity between 1955 and 2012. As the maps of Figure 5 clearly show, in 2012 the sediment connectivity decreases both in the main channel and in the hillslopes compared to 1955.

As combination of the five factors (*TC, TE, GF, FC* and *SP*), the mean *mCCI* decreased from 20.3 of the scenario *LU1955/NO-CD* (*ante operam*) to 19.8 of *LU1955/CD* (*post operam*), to 17.9 of *LU2012/CD* and *LU2012/NO-CD* corresponding to a change in sediment connectivity by -2.5 % (*LU1955/NO-CD* vs *LU1955/CD*), -9.4% (*LU1955/CD* vs *LU2012/CD*), and -11.8% (*LU1955/NO-CD* vs *LU2012/NO-CD*) (Table 2). This reduction is confirmed by the shift in frequency distributions of *mCCI* along with the four-time windows (Figure 6), which shows that the distribution of cell number along with a connectivity range always follows a normal law. In general, the distribution of sediment connectivity in 2012 and *LU1955/CD* is flattered compared to *LU1955/NO-CD*, therefore showing that not only the mean values but also the peaks in connectivity were strongly reduced. Compared to the *LU2012/CD* scenario, under the land use of 2012 and without check dams (scenario *LU2012/NO-CD*), negligible changes in the *mCCI* values were achieved.

4. DISCUSSIONS

To evaluate the changes in *mCCI* which the studied sub-catchment underwent since 1955 to present, a detailed analysis of all the factors is needed. The general decrease in the *TC* factor from 1955 to 2012 could be surprising, since it may contrast to expected response of the sub-catchment to the increase of the forest cover and, more in general, to the greening-up tendency of the drainage area (Fortugno et al., 2017).

However, a deeper analysis of the factors of *TC* shows:

(i) a reduction both in profile slope (*S*), due to the channel aggradation following the check dam installation, and in the precipitation erosivity (*R*), as evidenced in the previous paper of Fortugno et al. (2017);

(ii) a general increase in the cover factor (*C*).

The latter increase is higher than the product of the *R* and *S* factors, which led to the general increase of the *TC* factor, depending on the abandonment of areas devoted to agricultural activities in 1955 in spite of the afforestation of the upland areas of the sub-catchment. As a matter of fact, from 1955 to 2012 forests, shrublands and agricultural areas increased by 43%, 25% and 13%, respectively, while the not vegetated zones and pasture lands decreased by about 70% and 84%, respectively (Figure 7). Overall, from a soil conservation approach (linked to the vegetal cover), 45% of the catchment evolved from less soil protection to a higher soil protection, 16% experienced the reverse changes (that is, enhancing soil erosion), while 39% was not subjected to significant changes in land-use type; this general greening-up process of the studied sub-catchment made the soil of the studied sub-catchment less prone to runoff generation, also thanks to the lowering of the precipitation regime (annual depth and intensity), observed by Pérez Cutillas et al. (2018) in catchments of the semi-arid-environment and Fortugno et al. (2017) in the same catchment. These authors identified as factors of change in the sub-catchment (i) the slight decrease in the amount and erosivity of rainfall that could have induced a reduction of surface runoff; (ii) the reforestation and other land use changes, such as the spontaneous reforestation, vegetation encroachment in the channel and on the banks); and (iii) the installation of check dams, which induced local adjustments in the channel. Moreover, the more fragmented spatial pattern of land use in 2012 compared to 1955 could also have played an important role in decreasing water and sediment input from the hillslopes to the channel, since landscape fragmentation introduces a disconnectivity of water and sediments (Fortugno et al., 2017). Establishment of riparian vegetation in channel beds upstream of check dams is expected, since these structures reduce the profile slope and laminate the stream flow as well as induce more favourable edaphic conditions for vegetal species (Bombino et al., 2008; 2014; 2019).

The fact that the *TC* changes at the catchment level between 1955 and 2012 are not reflected by its mean value means that *mCCI* is not much sensitive in evaluating the local effects due to the presence of sediment traps (e.g., check-dams). For instance, the negligible increase of *TC* at the catchment level from the scenario of 1955 (without check dams) to 2012 (same land use, but with check dams) is due to the very low number of pixels of the hillslopes compared to the channel, which determines a very limited influence on the overall *TC* factor.

The highest values of the *GF* factor estimated in the torrent channels both in 1955 and 2012 clearly confirms that the terrain shape of channels is more concave compared to the other geomorphic units of the sub-catchment, and this enhances the sediment connectivity through the basin, which is caught by GF. Moreover, the scenarios of 1955 with and without check dams showed the same GF values. As noticed for the TC factor, this may be due to the limited influence of the few pixels in the channel on the GF of the entire sub-catchment compared to the large number in the hillslopes. At this point, despite the objectivity and facility to use a DEM basis for extracting the geomorphological factor, the field observations of the connections between the main channel and tributaries of the original index (Quiñonero et al., 2013) have the advantage to discriminate better the different geomorphological situations despite spatial scale. This problem is already pointed out by Heckmann et al. (2018) which states that (dis)connectivity operates at the landform scale and not at the raster cell scale. Sometimes, single raster cell bears not geomorphological significance and have difficulties to discriminate between different geomorphological features.

The presence of check dams in the channel influenced the *TE* factor and this is expected (Boix-Fayos et al., 2008; Bombino et al., 2009; Zema et al., 2014; 2018), because, between 1955 and 2012, the transverse structures determined local adjustments of the torrent bed, with channel aggradation immediately upstream of the 17 investigated check dams, and bed incisions downstream of each check dam. As response to these local adjustments, the TE factor was instead different in the two scenarios of 1955 since the construction of the check dams determines a barrier against the fluxes of water and sediments circulating in the sub-catchment (Harper et al., 2017). Therefore, the TE factor, which was between 0.1 and 1 in many cells (those located immediately upstream of the walls) for the scenario of 1955 without check dams, after check dam installation was instead equal to 1 in both scenarios of 1955 and 2012, since the wedges behind the check dams were totally and immediately filled with sediments. In other words, in the studied catchment there were no artificial reservoirs partially filled, which would retain sediments and this would give $TE \neq 0$. As a matter of fact, these check dams were presumably filled in the first few years after their building (on occasion of the first floods of medium-high magnitude, Viparelli and Maione, 1959), as previously reported by Zema et al. (2014) in a study on the same sub-catchment. In the Sant'Agata torrent, as happened in almost all *fiumaras* of Calabria and Sicily, check dams have already exhausted their sediment retention capacity and their trap efficiency became ineffective. These structures currently play a role of torrent bed stabilisation rather than a sediment collector and this influences the catchment sediment connectivity. It results that the main function of check-dams is the longitudinal slope correction rather than retaining sediments (Zema et al., 2014). Therefore, since this latter function was desired by catchment managers over time, the catchment management strategy was modified by the installation of further check dams (in general of lower size), which may be determined an excessive density of works. This led to money waste; moreover, in some catchments located close to the studied catchment and regulated by the same management strategy an increase of high flood events in urban areas was recorded, generated by the excessive reduction of the longitudinal slope (Surian et al., 2009).

As results of the combination of the changes in the *TC, TE* and *GF* factors, the *mCCI* reflected noticeable differences in sediment connectivity between 1955 and 2012. The decrease in the mean *mCCI* from the scenario of 1955 to the scenario of 2012 (both without check dams) is very important, because it highlights the benefits of areal interventions (usually cheaper, less environment-impactful, simpler in design, self-regulating) over lumped one, like check-dams installation, which, if not well designed can lead to money waste, unwanted side-effects and danger to people living nearby if a failure occurs.

The negligible changes in the *mCCI* values under the land use of 2012 and without check dams compared to a scenario with land use changes and control works may be again due to the limited number of pixels covering channels close to the check dams (that is, the sedimentation and scouring wedges in the proximity of the structures). This means that the main effect in sediment connectivity at the catchment scale is due to the changes in land uses over the hillslopes, which, under the two evaluated scenarios, is the same. Figure 8 shows that the reduction in sediment connectivity affected the afforested areas or the zones initially bare in 1955 and covered by agricultural crops or colonized by shrub vegetation in 2012. A relatively large area (with differences in *mCCI* over 1.8-2.0) suffered several landslides over time, revealing instability and a tendency to detachment and mobilization of sediments. Therefore, compared to 1955, these areas are characterised by steeper slopes and often by soil with not well-established vegetation, which increase sediment connectivity and thus *mCCI*.

5. CONCLUSIONS AND IMPLICATIONS

This study proposes a modified version of the *CCI* proposed by Quiñonero-Rubio et al. (2013), which improves and simplifies its calculation methodsThe *mCCI* is applied to a torrent of Southern Italy, in order to test the *mCCI*'s ability to interpret the sediment connectivity at the catchment scale in a water course with typical climatic and geomorphological conditions of ephemeral torrents. The case study has shown how and by what extent the natural (climate changes) and human impacts (land-use changes and check dam installation) have influenced the geomorphic processes driving sediment circulation in the studied basin throughout six decades. From 1955 to 2012, the application of the modified *CCI* to the studied sub-catchment estimated a general decrease of sediment connectivity. This was the combined effects of greening-up processes of the catchment (due to both natural afforestation and human-induced reforestation) and the installation of check dams, which have decreased the catchment potential to circulating sediments.

The lack of adequate information about the digital terrain model of 1955 limited the *mCCI* representativeness of the historical catchment morphology. In particular, if good terrain maps were available for the past scenarios, the influence of morphological data (e.g., profile slope, terrain curvature) would certainly have improved the evaluation of the sediment connectivity of the catchment. Moreover, the use of *mCCI* could be more appropriate when applied on different digital terrain models, but at comparable resolution. A high-resolution DEM should be used to overcome the *mCCI*’s inability to catch the impacts of check dam presence on the sediment connectivity of the catchment (mainly due to a limited number of pixels covering the channel areas under the direct effects of check dams). Moreover, the current and future availability of high-resolution terrain data (e.g., LIDAR) will give the possibility to use the *mCCI* for more precise evaluations of catchment sediment connectivity, also under future scenarios of climate change.

Overall, this study contributes to a wider and simpler applicability of the *CCI* to the semi-arid catchment. Thanks to the modifications brought by the *mCCI*, some factors of the original index are replaced by alternative methods, which are based on DEM or rely on summary hydrological evaluations. This reduces the need for field surveys, thus does not need geomorphological expertise, and allows the almost complete automation of the procedure, thanks to the large use of GIS tools. The *mCCI* seems to be more efficient in identifying and describing the hydrological and geomorphological features caught by the *CCI*. At the same time, compared to the *CCI*, the *mCCI* directly calculates the *CCI* factors using common GIS software, this possibility requires less direct surveys, whose reliability strictly depends on the ability and experience of the field operators.

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 an analytical tool to evaluate the influence of past or future changes in land use and climate by comparing scenarios of torrent connectivity.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, [P.D.], upon request.

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TABLES

Table 1 – Values of the modified Catchment Connectivity Index (*mCCI*) and their factors in the different scenarios adopted for application in the Sant'Agata torrent (Calabria, Italy).

Parameter	**Scenario**$^{(2)}$			
	Land use of 1955		*Land use of 2012*	
	Without check dams (*LU1955/NO-CD*)	*With check dams* (*LU1955/CD*)	*Without check dams* (*LU2012/NO-CD*)	*With check dams* (*LU2012/CD*)
TC	$7.82 \text{ x } 10^{-4 \text{ a}}$	$1.07 \text{ x } 10^{-3 \text{ b}}$	$1.19 \text{ x } 10^{-3 \text{ b}}$	$1.19 \text{ x } 10^{-3 \text{ b}}$
GF	$5.5979 \text{ x } 10^{-1 \text{ a}}$	$5.59641 \text{ x } 10^{-1 \text{ a}}$	$5.59641 \text{ x } 10^{-1 \text{ a}}$	$5.59641 \text{ x } 10^{-1 \text{ a}}$
TE$^{(1)}$	-	-	-	-
SP	$9.86405 \text{ x } 10^{-1 \text{ a}}$	$9.8688 \text{ x } 10^{-1 \text{ a}}$	$9.91 \text{ x } 10^{-1 \text{ a}}$	$9.91 \text{ x } 10^{-1 \text{ a}}$
FC$^{(1)}$	-	-	-	-
mCCI	**20.3**	**19.8**	**17.9**	**17.9**

Notes: (1) the TE and FC factors assume categorical values; (2) the lowercase letters indicate significant differences according to the t-test (at $p < 0.05$).

Table 2 - Univariate statistics of the modified Catchment Connectivity Index (*mCCI*) in the Sant'Agata torrent (Calabria, Italy).

Statistics	**Scenario**			**Difference (%)**		
	1955		*2012 (with or without check dams)* (*LU2012/CD* and *LU2012/NO-CD*)			
	Without check dams (*LU1955/NO-CD*)	*With check dams* (*LU1955/CD*)		2012 vs *LU1955/NO-CD*	2012 vs *LU1955/CD*	*LU1955/CD* vs *LU1955/NO-CD*
Minimum	0.6 ^{a}	0.5 ^{a}	1.1 ^{b}	83.3	120.0	-16.7
Maximum	63.4 ^{a}	34.5 ^{b}	36.1 ^{b}	-43.1	4.6	-45.6
Mean	20.3 ^{a}	19.8 ^{a}	17.9 ^{a}	-11.8	-9.6	-2.5
Standard deviation	3.8	3.8	3.6	-5.3	-5.3	0.0
Coefficient of variation (%)	18.6	19.3	19.9	7.0	3.1	3.8
1st quartile	18.3	17.7	16.1	-12.0	-9.0	-3.3
Median (2nd quartile)	20.6 ^{a}	20.1 ^{a}	18.2 ^{a}	-11.7	-9.5	-2.4
3rd quartile	22.6	22.1	20.0	-11.5	-9.5	-2.2
90th percentile	24.6	24.2	22.0	-10.6	-9.1	-1.6

Note: the lowercase letters indicate significant differences according to the t-test (at $p < 0.05$).

Figure captions

Figure 1 - Comparison of methods to calculate the *CCI* and *mCCI*.

Figure 2 - Location of the Sant'Agata catchment (Calabria, Southern Italy): (a) headwater and middle reaches, (b) check dams (*D*) under investigation and (c) sedimentary zone behind a check dam (marked by the yellow line)

Figure 3 - Maps of the *TC* factor of the *mCCI* in the Sant'Agata sub-catchment (Calabria, Southern Italy).

Figure 4 - Map of *TE* factor of the *mCCI* in the Sant'Agata sub-catchment (Calabria, Southern Italy).

Figure 5 - Map of the *mCCI* in the Sant'Agata sub-catchment (Calabria, Southern Italy).

Figure 6 - Frequency distribution of the *mCC*I in the Sant'Agata sub-catchment (Calabria, Southern Italy).

Figure 7 - Land-use changes in the Sant'Agata sub-catchment (Calabria, Southern Italy) between 1955 (left) and 2012 (right) (source: Fortugno et al., 2017 modified).

Figure 8 - Map of the difference in the *mCCI* (in binary logarithmic units) between 1955 and 2012 in the Sant'Agata sub-catchment (Calabria, Southern Italy).