A METHOD FOR ESTIMATING STORED SEDIMENT VOLUMES BY CHECK DAM SYSTEMS AT THE WATERSHED LEVEL: EXAMPLE OF AN APPLICATION IN A MEDITERRANEAN ENVIRONMENT

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Abstract

Purpose. In this paper a quick, easy and accessible methodology to estimate the sediment volume trapped behind a fully filled check dam system is proposed. As it is well known, check dams play an important role in the sediments balance between watershed and coastline. However, on a large scale, especially in those contexts where a great number of structures was installed, detailed surveys and measurements of sediment storage capacity would be extremely time-consuming and costly in terms of both economic efforts and human resources. **Methods**. To this aim, the proposed method considers only four easy-to-obtain morphometric parameters to combine with the *number of check dams*. The method was calibrated on a sample of 912 check dams located in seven long-term studied watersheds and, therefore, validated in a sample of three regulated Spanish catchments with an independent dataset. **Results**. At watershed level, the comparison between the calculated and estimated values showed a good capability of the method in evaluating the sediment volume trapped by the 912 studied check dams (RMSE ≈ 16900 m^3; $R^2 > 0.9$). The validation revealed encouraging results with estimation errors below 25%. **Conclusion**. The use of this accessible and easily usable method could represent a supporting tool for planning, monitoring and assessment of the environmental effects of control works. Moreover, these results are useful to carry out actions aimed to mitigate natural hazard and environmental as well as socio-economic problems of the watershed-coast system (e.g. shoreline retreat and morphological instability of the urban and tourist areas).

Keywords: Mediterranean watersheds; check dams; sediment wedge; prism method; morphometric parameters

Statements and Declarations

All authors contributed equally to this work. Moreover, all authors read and approved the final manuscript.

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1. Introduction

Watershed management aims to regulate cascades and fluxes of sediments moving from some distributed sources to downstream areas (Montgomery and Buffington 1997; Dunne et al. 2003; Fryirs 2013; Dumitriu 2020). Consequently , addressing management efforts to preserve shorelines equilibrium in the proximity of river deltas (Komar 1998; Williams et al. 2018; Warrick 2020) is sensible particularly where urban and tourist settlements, as well as infrastructure, exist or are being planned. Control works of watershed drainage networks, and especially check dams, affect sediment fluxes and budgets (Conesa García 2004; Boix-Fayos et al. 2008; Díaz-Gutiérrez et al. 2019; Hu et al. 2019; Arabkhedri et al. 2021). Check dams produce upstream sediment storage along the stabilized river bed, reducing downstream sediment delivery (Rosskopf et al. 2018). Once installed, the structures induce short and long-time actions (Montgomery and Buffington 1997; Piton et al. 2017). In a short time (after structure installation) a sediment wedge begins to form behind the check dam and the silting upstream torrent bed starts to rise towards the top of the structure; this action takes a limited time, generally less than 30 years (Boix-Fayos et al. 2008; Quiñonero-Rubio et al. 2016). During the silting process, the transverse structures induce morphological and granulometric change in the river bed towards the ultimate bed slope (Lane 1955; Piton and Recking 2016), modifying the stream energy and, consequently, its lower sediment transport capacity, promoting local sediment deposition (Glassey 2010; Fryirs 2013; Church and Ferguson 2015).

Recent research has established that 85% of river deltas around the world shrank during the first decade of 21st century due to sediment capture by soil water conservation works (e.g., sediment check dams, Xu 2005; Wang et al. 2012; Zhao et al. 2017; Owens 2020).

In Italy a number of Authors recognized shoreline retreats as result of human interventions (Kondolf 1997; Martínez del Pozo and Anfuso 2008; Kuleli 2010; Acciarri et al. 2016). Studies conducted along the central and Southern Italian coast have shown unexpected off-site effects of check dams built since the second half of the 20th century (Coltori 1997; Boix-Fayos et al. 2007; Aiello et al. 2013), between the 1950s and 1990s. This occurred especially when check dams were installed in valley river beds (where the original slope is already quite limited, Rosskopf et al. 2018), regulating them with a number of check dams as if they were headwaters and mountain torrent reaches (Heede 1967, 1986; Piton and Recking 2016; Abbasi et al. 2019).

Therefore, the knowledge of sediment wedge volumes stored by check dams could usefully support sediment management at watershed-coast level, especially in those contexts where environmental problems and socio-economic aspects can be prevalent. Measuring campaigns of sediment volumes trapped by check dams have become of growing interest in recent years, and several tools have been purposedly developed (Boix-Fayos et al. 2008; Díaz et al. 2014); however, the complexity, the precision and the accuracy of these methodologies vary greatly as demonstrated by several applications (Nyssen et al. 2009; Bussi et al. 2014; Polyakov et al. 2014; Vanacker et al. 2014), particularly in the Mediterranean area (Castillo et al. 2007; Bellin et al. 2011; Sougnez et al. 2011; Romero-Díaz et al. 2012; Martín-Moreno et al. 2014; Quiñonero-Rubio et al. 2016), and pose problems of applicability on a large scale. For example, investigating a sample of 50 check dams, Ramos-Diez et al. (2016) calculated the volume of trapped sediments by each structure by using five different methods (Castillo et al. 2007; Romero-Díaz et al. 2007; Bellin et al. 2011; Sougnez et al. 2011; Díaz et al. 2014), demonstrating that the *Section Method*, which involves detailed and precise topographic surveys, is currently the most accurate (Díaz-Gutiérrez et al. 2019). Moreover, in order to gain better understanding of the efficiency of check dams on sediment retaining, Díaz et al. (2014) presented a methodology based on a topographical survey together with a calculation process matrix. However, when considering a single check dam, the results of these different methods are highly variable (Ramos-Diez et al. 2017). These methods are based on a simple hypothesis since they associate the wedge sediment volume behind the check dam with a solid of known geometry. According to the method approaches, their precision strongly depends on the accuracy of data collection which can be ensured only on small scales and for few check dams. On larger scales (e.g. wide river-basin district, sub-regional, regional) or in those environmental contexts where a huge number of check dams was installed (as it occurred in many watersheds of Calabria region, southern Italy), the extensive applicability of such estimation methods is generally limited, because they are time-consuming and expensive. Thus, the need for further investigations emerges for the development of large scale tools able to easily and roughly support the planning and programming of engineering control works. For example, the prior knowledge (even if summarily) of check dams effects in terms of both potential retention of sediment and shoreline dynamics could be drawn on throughout the process of structure design and placement phases (Bombino et al. 2006, 2007a, 2008; Mekonnen et al. 2015).

As it is well known, fluvial processes and mechanisms regulating sediment detachment and transport are peculiar of each watershed and depend on several factors expressing hydrological, geomorphological and climatic drivers. Literature reports many measurable morphometric parameters to describe hydrological (Strahler 1952; Chorley et al. 1984) and geomorphological processes of a given watershed (Chavare and Potdar 2014) as well as its attitude to produce sediment (Horton 1945; Leopold and Miller 1956; Montgomery and Dietrich 1989; Verstraeten and Poesen 2002; Herrero et al. 2017).

These parameters are indicative of the evolution of each watershed and are useful to identify geomorphological stages and relating problems. Furthermore, they provide management practice information for its regulation

(Strahler 1952; Chorley et al. 1984; Srinivasa Vittala et al. 2004; Sharma and Sarma 2013) and, consequently, for identifying requirements, design criteria and storage capacity of check dams.

The combination of a method, among those available, which requires lower data demand (e.g. in terms of field measurements) with a set of accessible morphometric parameters (e.g. easy to extract at the watershed level), could potentially lead to a practicable methodology to get acceptable and quick estimation for a large number of check dams. Therefore, starting from an available huge database in Calabria, Italy, this work aims to explore the development of an accessible methodology for estimation of the potential sediment wedge volume trapped by check dam systems (considered fully filled).

2. Materials and methods

2.1. The study area and check dams data collection

A program of torrent regulation works in Calabria, aimed at mitigating hydro-geomorphological hazards, was implemented by the Italian Government in the second half of the twentieth century, moving from particularly extreme and catastrophic events that occurred in the region (Medici 1954; Sorriso-Valvo et al. 1995; Antronico et al. 1998; Sabato and Tropeano 2004; Petrucci and Pasqua 2012, 2013; Aceto et al. 2016). Through *Italian Special Laws,* hundreds of kilometres of embankments, about 150,000 hectares of reforestation and 10,000 check dams were built over approximately 60 years between 1955 and 2012, according to an integrated approach at the watershed level (Petrucci and Polemio 2007; D'Ippolito et al. 2013).

The most intensely regulated watersheds (with over five check dams per km^2) are located in the southernmost part of the region (in the area of the Strait between Calabria and Sicily), and in some Ionian sides. They peculiar torrents named *fiumare*, falling down from the Aspromonte massif and the mountain side of the Serre ridge. Among these, a sample of seven watersheds named Allaro, Amusa, Gallico, Molaro, Petrace, Sant'Agata and Torbido di Gioiosa, were used as case studies (Fig. 1). The seven watersheds which cover about 900 km^2, have a torrential hydrological regime typically influenced by the Mediterranean semi-arid climate and show hydraulic control works along 75% of their stream network, with one check dam per square kilometre on average and up to six check dams per square kilometre (Molaro; Bombino et al. 2006, 2007b). Other morphological and climatic characteristics of the chosen watershed are shown in Table 1.

Fig. 1 Localization of the seven sample watersheds in the southernmost part of Calabria region, Italy

Within the selected watersheds, long-term observations, data collection and *ex-post* analysis regarding the effects of the check dam system as well as both the riparian ecosystem and the channel geo-morphology were carried out for over 20 years (Bombino et al. 2006, 2009, 2019). In particular, all check dams were initially mapped and inventoried by consulting and analysing maps, orthophotos and cartographies, video documents shot from helicopter flights, GIS software and Digital Terrain Model (DTM); whenever available, plans and projects implemented over the past decades by several institutions were viewed. Thereafter, this information was verified by detailed field surveys, and the following main geometric characteristics, both of structures and sediment wedges, were measured and collected according to the sketch showed in Fig. 2:

- height (h) and width (B) of check dam (the surveyed check dams were found to be fully filled; therefore, the actual capacity of the work coincides with the maximum one);
- maximum sediment wedge length (L), as the distance, measured along the thalweg, between the structure and the river bed transversal section resulting (by visual inspection) in a slope change (as determined by contact between the check dams silting and the upstream “undisturbed” reach);
- upstream width (B’) of the sediment wedge measured at the slope change site as explained before.

The conservation status of each check dam (e.g. possible structure damage such as spillway wearing-away, foundations failures and body cracking) was surveyed as well as the type and size of the spillway in order to evaluate its hydraulic capacity and efficiency (the latter ones are not taken into consideration in the present study).

The data on 912 check dams (each one positioned through X-Y coordinates in according to the WGS84 reference system) were integrated in a purposedly created geo-database (A.FO.R. 1998; Bombino et al. 2009).

Fig. 2 Sketch of the sediment wedge volume retained behind the check dams

For each watershed Table 1 reports the main characteristics of the check dam systems and some morphometric information (e.g., length, difference in elevation, drainage area).

Table 1 Main morphometric and climatic characteristics of the studied watersheds, main properties of the check dam systems and sediment wedges characteristics in the selected watersheds

2.2. Survey of the sediment wedge volume trapped by each check dam

Measurements of both the geometric characteristics of the 912 check dams and the corresponding sediment wedge were used for the quantification of the retained sediment volumes (calculated volume, V_c). To this purpose, the Prism Method (Castillo et al. 2007) was selected among available geometric models, according to the strengths/limits shown in Table 2. The Prism Method considers the V_c of a triangular prism (Fig. 2). The V_c was thus calculated using the following equation:

$$V_C = \frac{1}{6} \cdot h \cdot L \cdot (2B + B') \tag{1}$$

where h and B are respectively the height and the width of the check dams, L and B' are the length and the upstream width of the sediment wedge, as above.

Field surveys were integrated with LIDAR data (with 1x1 m resolution) and orthophotos (with 0.5 m planimetric resolution) analysis for measuring the sediment wedge length (Fig. 3), when it was not detectable in the field (Verstraeten and Poesen 2002).

Table 2 Limits and strengths related to the application of the Prism Method to calculate the sediment wedge volume retained by the check dams installed in the selected watershed

Fig. 3 Orthophoto showing the upstream sediment wedge (yellow) behind a check dam (black) – Sant'Agata watershed, Calabria, Italy

2.3. Search for the relations at watershed level between the calculated volumes retained by the check dam system and the morphometric parameters

In order to search a linkage between V_c and morphometric parameters, the following work hypotheses, at the watershed level, were adopted:

a) the required number of check dams derives from hydro-geomorphological processes of any watershed;

b) all else equal, in general, the number of check dams depends on the channel length per unit area; specifically, for each torrent reach the number of check dams (*n*) can be determined by using the following formula:

$$n = \frac{\Delta h_i}{h_{CDm}} \tag{2}$$

where Δh is the overall height difference to be filled with a number of check dams, *i* is meant as the i^{th} torrent reach, and h_{CDm} is the average effective height of the check dam (excluding the foundation depth);

c) considering a given channel reach, the total height of the check dam system (Δh) is determined by the difference between the original (*S_o*) and the equilibrium slope (*S_c*) with respect to the horizontal distance (*d*) between the first (downstream) and the last (upstream) structure in the channel (Fig. 4a):

$$\Delta h_i = (S_o - S_c)\, d \tag{3}$$

d) the design storage capacity of a check dam system installed in a given torrent reach depends on both the total height of the structures and the channels morphology (slope, width, shape, etc.);

e) all else equal, if the check dam system is composed of structures having the same height, its total storage capacity will be lower where the channel slope is higher;

f) the check dam system determines the current S_c of the hydrographic network;

g) S_c can be expressed as a function of S_o through the following equation, as reported by several Authors (Woolhiser and Lenz 1965; Della Lucia and Fattorelli 1981; Ferro 2002):

$$S_c = k\, S_o \tag{4}$$

where S_c is the (current) compensation mean slope (*post-operam*), S_o is the original slope (*ante-operam*) and *k* is a coefficient which varies from 0.55 to 0.77, to which a value of about 0.66 can be attributed (Piton and Recking 2014). Being $S_o = 3/2\ S_c$, it is possible to express Δh_i as a function of S_c only; to this point, it is reasonable to use the following formula to determine the average value of the height of the check dams (h_{CDm}):

$$h_{CDm} = \frac{\Delta h_i}{n} = \frac{\left(\frac{3}{2}Sc - Sc\right) d}{n} \tag{5}$$

Extending these hypotheses to the entire hydrographic network (Fig. 4b), we can assume the mean value of the check dams height for each reach (5) to be the average value weighted (using *d* as weights, i.e. the horizontal distance between the first (downstream) and the last (upstream) structure in the channel) over the total length of the hydrographic network (L_{tot});

$$\frac{\sum_i h_{CDm,i} \cdot d_i}{L_{tot}} \tag{6}$$

h) following the previous assumptions, the height of the check dams could be overlooked and the storage capacity of the structures system (and consequently the retained volume once fully filled) could be estimated by linking the number of check dams with some morphometric parameters (e.g., mean slope of hydrographic network, drainage density, etc.), most of which could be easily obtained by DTM.

Fig. 4 Sketch of a check dam system considered both at the torrent reach (a) and at the watershed (b) level: n = number of required check dams, Δh_i = overall height difference to be filled with a number of check dams,

h_{CDm} = average effective height of check dam (excluding the foundation depth), S_o = original slope of the channel, S_c = (current) equilibrium slope, d = horizontal length between the first and the last check dam in the channel, n_{tot} = total number of torrent reaches, L_{tot} = total length of the hydrographic network

A set of 15 morphometric parameters (in addition to the number of check dams – hereinafter CD) regarding linear and areal characteristics of the watershed was initially chosen (Table 3). These parameters are easy to acquire and are among the most common in the literature: they provide information on the evolutionary stage of the watershed and its ability to produce sediment. These data can be obtained by using traditional (topographic maps), advanced (e.g., remote sensing) methods, or from DTM, commonly used as a tool for the automated extraction of several elements in geoprocessing activities. The linkage between the 15 morphometric parameters, CD and the surveyed sediment volumes retained by the check dam system (V_c) was explored at the watershed level, and processed by using a Lasso Model (Least Absolute Shrinkage and Selection Operator; Tibshirani 1996). Specifically, the model called Lasso Cross-Validation (LassoCV), developed in Python™ using a scikit-learn implementation (Pedregosa et al. 2011), was used. This is a linear model, widely used in several scientific fields including Earth Sciences (Wang et al. 2006; Tibshirani 2011; Hammami et al. 2012; Bardsley et al. 2015; Camilo et al. 2017), which in addition to its simplicity of application has numerous advantages: in fact it (*i*) estimates sparse coefficients, (*ii*) identifies solutions with as few non-zero coefficients as possible, (*iii*) reduces the number of features upon which the solution is dependent. Since the parameters have different scales and units of measurement, they were standardized by subtracting the mean and dividing by their standard deviation. The obtained values represented an important input by the model designed to estimate the most accurate value of the potential sediment volumes retained by the check dams system (V_e, closer to V_c); their *feature importance* was assessed by using the Permutation Importance (Fisher et al. 2019). Finally, to evaluate the predictive reliability of the model, surveyed and estimated values were compared by applying RMSE (Wallach and Goffinet 1989).

Table 3 Set of morphometric parameters (to combine with the check dam number) and related range of values initially selected for the seven watersheds

2.4 Validation of the proposed methodology in three regulated Mediterranean watersheds

The proposed method was validated by using an independent data set covering three regulated watersheds, located in south-east Spain whose characteristics (in terms of morphometry, number of check dams and their storage capacity) are similar to those of the watersheds studied in this work (Table 5). As in the case of the calibration, the four morphological parameters were obtained through a DTM processed by means of GIS software while the number of check dams was extrapolated from the work of Serrato et al. (2005), Castillo et al. (2007) and Boix-Fayos et al. (2008).

The working steps undertaken in this work are shown in Fig. 5. The initial phase regards the data analysis followed by the calculation of the sediment wedge volumes, the selection of the morphometric parameters and the application of the model. Finally, the data validation was applied for confirming the reliability of the methodology.

Fig. 5 Methodological scheme for the preliminary estimation of a potential sediment volume retained by a check dam system at the watershed level

3. Results

3.1 Measurement of the sediment volumes trapped behind check dam system

The available data shows that at watershed level the number of check dams varies between 41 (Amusa) and 264 (Gallico); the average width and height of the 912 detected check dams are about 53 m and 2 m respectively (Table 1). The average length of the sediment wedge varies from 80 m (Gallico) to 122 m (Sant'Agata); the sediment wedges' thalweg has an average slope of 7.6% (with a 2.7% variation coefficient). Total V_c calculated for each watershed using the *Prism Method* varies between 394 x 10^3 m^3 (Amusa) and 1260 x 10^3 m^3 (Petrace; Table 4).

In the studied watersheds sediment wedge volumes trapped behind check dams range between 10^3 and 30 x 10^3 m^3, with an average value per check dam of 5 x 10^3 m^3. The relevant literature review has shown a wide variability of sediment volumes retained by check dams: (i) in Spain, in some watersheds similar to the ones this paper focuses on, in terms of climate conditions, Ramos-Diez et al. (2017) and Díaz-Gutiérrez et al. (2019) found average values of sediment wedge volumes from 38 m^3 to 74 m^3 (it should be remembered that Calabrian watersheds are characterized by intense geomorphological processes and sediment transport (Sabato and Tropeano 2004; Sorriso-Valvo and Terranova 2006), and check dams are larger on average and fully filled within 4-5 years after their construction); (ii) in other geographical, geomorphological and climatic conditions, very different from the studied watersheds' ones, much higher values of up to 1.14 x 10^6 m^3 were observed (China, Zhao et al. 2017).

3.2 Relationship between sediment stored volume behind check dam system, the morphometric parameters and the number of check dams

The application of the Lasso Model made it possible to restrict the initial 15 morphometric parameters to those four with the higher explanation potential, to combine with the *number of check dams* (CD), and namely *drainage density* (hereinafter DD), *mean slope* (MS) and *length* (NL) *of the hydrographic network*, *percentage of watershed area with slope* > *75%* (P75) (Fig. 6).

By comparing the calculated (V_c) and estimated (V_e) sediment volumes, ~~the combination of~~ as well as combining the four morphometric parameters and CD, we obtained the most satisfying result (Fig. 7) with a determination coefficient $R^2 > 0.9$. The difference between V_c and V_e varies from -3.9% to 3.3% (Table 5).

Fig. 6 Normalized representation of the feature importance of the parameters indicated by the model

Table 4 Comparison between V_c and V_e

Fig. 7 Comparison between V_c and V_e based on the combination between the four morphometric parameters and the number of check dams, for the seven selected watersheds

3.3 Method validation

The validation of the proposed methodology, by using the four selected morphometric parameters values (DD, MS, NL, P75) as independent dataset together with the CD number of the three Spanish watersheds, highlighted realistic estimates of the sediment volume at the watershed level.

Moreover, the comparison between the calculated (V_c) and the estimated storage capacity (V_e) showed a good reliable prediction of the proposed model, with the RMSE value of 23 x 10^3 m^3 (Table 6) and an average difference between V_c and V_e of 24%.

Table 5 Main available features and morphometric parameters values (to combine with the check dam number, CD) of the three regulated watersheds used for the validation

4. Discussion

Detailed measurements of both the geometric characteristics of the 912 (fully filled) check dams within the seven selected watersheds and the corresponding sediment wedge enabled the quantification of the retained sediment volumes behind the structures and, consequently, the creation of a huge data collection. These activities required about 80 field surveys (960 hours for fieldwork and 24000 km travelled) and about 230 hours to create, process and update the geo-database.

The geomorphic evolution of any watershed, the number of check dams and their geometric characteristics are basic to evaluate the design sediment storage capacity of the structures (Piton and Racking, 2016). Geomorphic evolution of the watershed can be explicated by linear, areal and relief features (e.g. drainage density, the main slope of both main channel and watershed, etc.) easy to obtain by DTM; the number of check dams is normally known; conversely, detailed measurements of the structures (e.g. height, width, etc.) are time-consuming (and often difficult) field activity. In order to propose a simple method, a set of four morphometric parameters which takes into account the above-mentioned factors was selected. Among these, the drainage density, which expresses the nature and magnitude of fluvial processes, is indicative of channel geometry and capacity in response of natural (e.g. frequency of peak discharge and climate, sediment source, vegetation cover) or human (e.g. channel regulation) changes (Gregory 1976). Drainage density, more specifically, contains approximately the channel geometric variability from upstream to downstream, on which the average width of the check dam system depends.

The current mean slope (S_c) of the hydrographic network, as a result of channels regulation, is related to the original slope (S_o), according to the formula (4): this relationship, observed by several Authors through many experimental works over the world (Woolhiser and Lenz 1965; Ferro 2002), allowed us to consider only S_c when calculating the average height of the check dam system h_{CDm} (Equation 5, Fig. 4a). The developed method shows a good approximation in estimating the potential volume of retained sediment and takes into account the above simplification.

The role of the slope is crucial: in fact, for example, in the case of check dams with the same height installed on torrent reaches with different slopes, the reach with the higher slope shows a shorter sediment wedge, and, consequently, also the sediment storage capacity will be reduced (Ramos-Diez et al. 2017; Diaz-Gutierrez et al. 2019) as showed in Fig. 8.

Fig. 8 Sediment storage capacity (Ssc) variation with different channel bed slopes (S_o' and S_o''); h_1 = h_2 = average check dam height; L_1 and L_2 = sediment wedge length

In fact, the four morphometric parameters to combine with the *number of check dams* (CD) (which is detectable through the analysis of orthophotos or digital maps) and namely *drainage density* (DD)*, mean slope* (MS) *and length* (NL) *of hydrographic network and percentage of watershed area with slope > 75%* (P75), allow~~s~~ us to neglect the detection of more challenging measurements on check dams (e.g.~~,~~ height and width). Moreover, all four morphometric features are easily detectable by GIS processing a DTM (with 20 x 20 m resolution). The good results of the calibration obtained in the studied watersheds, validated with an independent dataset covering three intensively arranged Spanish watersheds (for which data on the number of check dams and their sediment storage capacity were available, as reported by Serrato et al. (2005), Castillo et al. (2007) and Boix-Fayos et al. (2008)), made it possible to extend the investigation within the Mediterranean area, contributing to a widespread application of the proposed methodology in an environmental context widely regulated by check dams. The processing of the DTM by using software GIS allowed extrapolating the four morphometric parameters easily and, therefore, estimating the sediments volumes.

Since in the validation watersheds the greatest number of check dams is mainly distributed along the main stream unlike our case studies, in order to evaluate the effectiveness of the method, a parallel test was carried out on the Gallico watershed, where the check dams (compared with the other analysed catchments) mainly regulate the main stream. The test revealed an error having the same order of magnitude ~~of~~ as the estimation error obtained for the validation watersheds.

At the watershed level, the method reveals that the sediment wedge volumes retained by the check dam system is positively correlated with CD (obviously), DD, MS and NL. On the contrary a negative correlation was observed with P75 (percentage of watershed area with slope > 75%): this parameter, as already explained, takes into account that in channels with a very steep slope sediment wedges are small resulting in~~,~~ much lower than the average value in the rest of the watershed.

As the developed method requires few and easily detectable data input, a rough large-scale (e.g., watershed, regional, etc.) estimation of sediment wedge volume retained (or which will be retain) by check dam systems, appears possible and reliable. However, two major limitations come to the fore: the proposed method, cannot be applied (i) without knowing the total number of check dams within the catchment and (ii) in poorly regulated watersheds.

The first limit can occur when the design documents are no longer available, and it is therefore necessary to integrate the analysis of digital images (which often do not allow the identification of the works due to, for example, vegetation cover) with field surveys which are time-consuming and expensive. Regarding the second limit, inaccurate results are obtained in watersheds with a small number of check dams, as demonstrated by our tests in two poorly regulated watershed (Alessi and Turrina, located in the middle part of Calabria region) where unacceptable errors were recorded (percentage difference of estimated volumes, V_e, greater than 60%).

5. Conclusions

Based on a huge database collected through studies, investigation and field surveys on check dam effects over 20 years in Calabria, Italy, the carried out work allowed us to develop a methodology for the estimation of maximum potential sediment volume stored by check dam systems. In particular, working on a sample of seven watersheds with 912 check dams, the reference value of stored sediment volumes was obtained through the *Prism Method* applied to the available measures of geometric characteristics both of silted structures and the corresponding sediment wedge.

The developed method, validated on three Spanish watersheds, considers the relationship between the sediment volume stored by check dam systems and the selected parameters of easily obtainable: DD (drainage density), MS and NL (the mean slope and the length of the hydrographic network, respectively), P75 (percentage of watershed area with slope > 75%) to combine with CD (number of check dams).

The use of this methodology could represent an accessible and valid as well as practical tool for supporting the largest number of actors, especially when it is necessary to estimate an approximate value of sediment volumes retained, or likely to be retained, by check dam systems. During planning, programming and design phases of engineering control works it could be useful to carry out a preliminary estimation of the effects of check dams in terms of both reduction of sediment production at the watershed outlet and shoreline equilibrium. Therefore, the developed methodology could support both watershed management and restoration projects, providing indications for (i) decision-makers and stakeholders, (ii) optimizing the design and the localization of control works and (iii) minimizing the socio-economic and environmental impacts of these structures as well as (iv) implementing actions to mitigate natural hazard in both watershed and coastal areas.

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Tables

Table 1 Main morphometric and climatic characteristics of the studied watersheds, main properties of check dam systems and sediment wedges characteristics in the selected watersheds

Watershed (a)			AL	AM	GA	MO	PE	SA	TG
Morphometric and climatic characteristics									
Area		km^2	132	38.4	55.5	11.5	415	61	160.1
Mean altitude		m a.s.l.	737	460	704	387	584	893	586
Maximum altitude		m a.s.l.	1420	1240	1770	800	1810	1610	1215
Mean watershed slope		%	22	27	26	30	15	29	23
Stream order			IV	IV	IV	V	V	IV	V
Length of main stream		km	17.4	12.3	21	9.3	38.7	23.6	20.3
Mean annual rainfall depth (b)		mm	1827	964	1608	597	1503	1327	896
Mean annual air temperature (b)		°C	12.9	17.9	10.7	17.3	16.7	11.2	19.5
Main properties of check dam systems and sediment wedges characteristics									
Check dams	**Number**	-	48	41	264	103	134	130	192
	Density	no. CD km^{-2} (c)	0.36	1.07	4.76	8.96	0.32	2.13	1.2
Sediment wedges	**Average width**	m	50.3	69.3	46.2	64.6	46.3	39.1	56.1
	Average height	m	1.7	1.9	2.0	1.8	2.0	2.1	2.2
	Average length	m	107.6	99.6	79.7	82.4	116.6	122.2	109.3
	Average slope	m m^{-1}	0.093	0.086	0.085	0.099	0.056	0.091	0.023

Note: (a) AL, Allaro; AM, Amusa; GA, Gallico; MO, Molaro; PE, Petrace; SA, Sant'Agata; TG, Torbido di Gioiosa; (b) detected at the weather stations in: Fabrizia (948 m a.s.l, for Allaro), Caulonia (10 m a.s.l, Amusa), Gambarie (1200 m a.s.l, Gallico), Reggio Calabria (330 m a.s.l, Molaro), S. Cristina d'Aspromonte (510 m a.s.l, Petrace), Cardeto (670 m a.s.l, S. Agata) and Gioiosa Ionica (125 m a.s.l, Torbido di Gioiosa); (c) CD, check dams

Table 2 Limits and strengths related to the application of the Prism Method to calculate the sediment wedge volume retained by the check dams installed in the selected watershed

Limits	**Strengths**
-	Based on a simple formula, maintains a sufficient level of accuracy (Ramos-Diez et al. 2016)
The transversal variability of "wedge shape" between mountain (V-shaped) and valley (U-shaped, shallow/wide) reaches is not taken into account because we assume the upper and lower width of check dams are the same	(i) The chosen geometric method is suitable to balance out the transversal variability of "wedge shape" within the watershed when a large number of check dams are considered (ii) The Prism method allows assessing the planimetric wedge shapes in both mountain and valley reaches thanks to B' dimension

In headwater areas and/or in mountain reaches, both check dams and sediment wedge dimensions can be obscured by vegetation cover	(i) B, B’ and L can be also detected from orthophotos (planimetric resolution of 0.5 m) or maps (ii) High resolution LIDAR data, could help in B, B’ and L measurement

Table 3 Set of morphometric parameters (to combine with the check dam number) and related range of values initially selected for the seven watersheds

Parameter	Unit	Range of values	Drivers
Number of check dams	-	37 - 103	
Drainage density	km^{-1}	0.7 – 6.7	It is the result of interacting factors controlling the surface runoff and influences the output of water and sediment from the drainage watershed. It is affected by climate and vegetation, soil and rock properties, relief and landscape evolution processes. Watershed hydrology changes significantly in response to the changes in the drainage density. It controls the watershed travel time (Carlston 1963; Ozdemir and Bird 2009; Chorley 2021).
Mean elevation	m a.s.l.	460 – 893	Watershed relief parameters contributes in understanding the geomorphic processes and landform characteristics. Erosion rates and processes by fluvial, hillslope generally increase with increasing slope (Montgomery et al. 2000).
Watershed mean slope	$m\ m^{-1}$	0.1 - 0.3	
Percentage of flat terrain	%	9 - 41	
Percentage of watershed area with slope > 75%	%	0.1 – 1.5	
Percentage of watershed below 200 m a.s.l	%	9 - 29	
Percentage of watershed between 400-1000 m a.s.l	%	36 – 51	
Drainage frequency	km^{-2}	0.3 – 2.2	Drainage frequency depends on the lithology and reflects the texture of the drainage network infiltration capacity, vegetation cover, relief nature and amount of rainfall. It indicates the various stages of landscape evolution. The higher stream order is associated with greater discharge and indicates lesser permeability and infiltration (Hajam et al. 2013).
Horton number	-	4 – 5	
Integral of the ipsographic curve	-	0.3 – 0.5	Related to the disequilibrium in the balance of erosive and tectonic forces. Differences in the shape of the curve and the hypsometric integral value are related to the degree of disequilibria in the balance of erosive and tectonic forces (Weissel et al. 1994).
Length of hydrographic network	km	70 – 428	Related to the surface flow discharge and erosional stage of the watershed (Sreedevi et al. 2009).
Max watershed length	km	7.5 - 30.7	Indicate flood formation tendency, erosion and transport capability of sediment load (Strahler 1964; Verstappen 1983, 1995; Ghosh and Chhibber 1984; Morisawa 1985; Nag 1998; Srinivasa Vittala et al. 2004).
Shape factor	-	0.1 – 0.5	
Watershed area	km^2	569 - 130	
Watershed perimeter	km	10 - 76	

Table 4 Comparison between V_c and V_e

	Watershed (a)							RMSE
	AL	AM	GA	MO	PE	SA	TG	

CD	-	48	41	264	103	134	130	192	**10^3 m^3**
V_c	10^3 m^3	430.5	394.7	986.6	682.2	1260.8	983.6	496.7	
V_e	10^3 m^3	444.6	393.1	1008.5	675.0	1236.1	1000.5	477.3	16.9
$\Delta^{(*)}$	%	3.3%	-0.4%	2.2%	-1.1%	-2.0%	1.7%	-3.9%	

$^{(a)}$ AL, Allaro; AM, Amusa; GA, Gallico; MO, Molaro; PE, Petrace; SA, Sant'Agata; TG, Torbido di Gioiosa; $^{(*)}$ percentage difference between V_c and V_e

Table 5 Main available features and morphometric parameters values (to combine with the check dam number, CD) of the three regulated watersheds used for the validation

	Watershed		El Carcavo	Quipar (sub-catchment)	Rogativa
	Authors / Source		Castillo et al. 2007	Serrato et al. 2005	Boix-Fayos et al. 2008
Available literature data	**Area**	km^2	27.3	30	53.5
	CD	-	29	57	58
	V_c	10^3 m^3	141.4	69.1	92.8
Morphometric parameters (determined by using GIS software)	**DD**	km^{-1}	0.47	0.47	0.88
	MS	m m^{-1}	0.43	7.88	0.23
	NL	km	13.9	14.1	41
	P75	%	0.025	0	0.07
	V_e	10^3 m^3	110.0	87.7	110.1
	$\Delta^{(*)}$	%	-28.5	+26.9	+18.6

Note: $^{(*)}$ percentage difference between V_c and V_e

Figure captions

Fig. 1 Localization of the seven sample watersheds in the southern part of Calabria region, Italy

Fig. 2 Sketch of the sediment wedge volume retained behind the check dams

Fig. 3 Orthophoto showing the upstream sediment wedge (yellow) behind a check dam (black) – Sant'Agata watershed, Calabria, Italy

Fig. 4 Sketch of a check dam system considered both at the torrent reach (a) and at the watershed (b) level: n = number of required check dams, Δh_i = overall height difference to be filled with a number of check dams, h_{CDm} = average effective height of check dam (excluding the foundation depth), S_o = original slope of the channel, S_c = (current) equilibrium slope, d = horizontal length between the first and the last check dam in the channel, n_{tot} = total number of torrent reaches, L_{tot} = total length of the hydrographic network

Fig. 5 Methodological scheme for the preliminary estimation of a potential sediment volume retained by a check dam system at the watershed level

Fig. 6 Normalized representation of the feature importance of the parameters indicated by the model

Fig. 7 Comparison between V_c and V_e based on the combination between the four morphometric parameters and the number of check dams, for the seven selected watersheds

Fig. 8 Sediment storage capacity (Ssc) variation with different channel bed slopes (S_o' and S_o''); h_1 = h_2 = average check dam height; L_1 and L_2 = sediment wedge length

Figures

A METHOD FOR ESTIMATING STORED SEDIMENT VOLUMES BY CHECK DAM SYSTEMS AT THE WATERSHED LEVEL: EXAMPLE OF AN APPLICATION IN A MEDITERRANEAN ENVIRONMENT

Journal of Soils and Sediments

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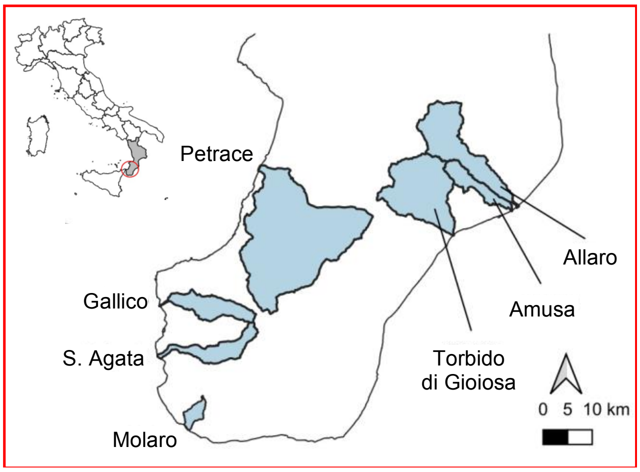


Fig. 1 Localization of the seven sample watersheds in the southern part of Calabria region, Italy

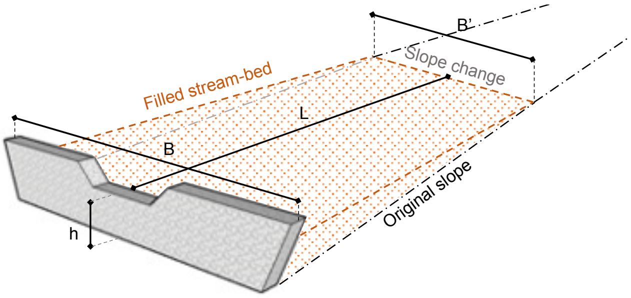
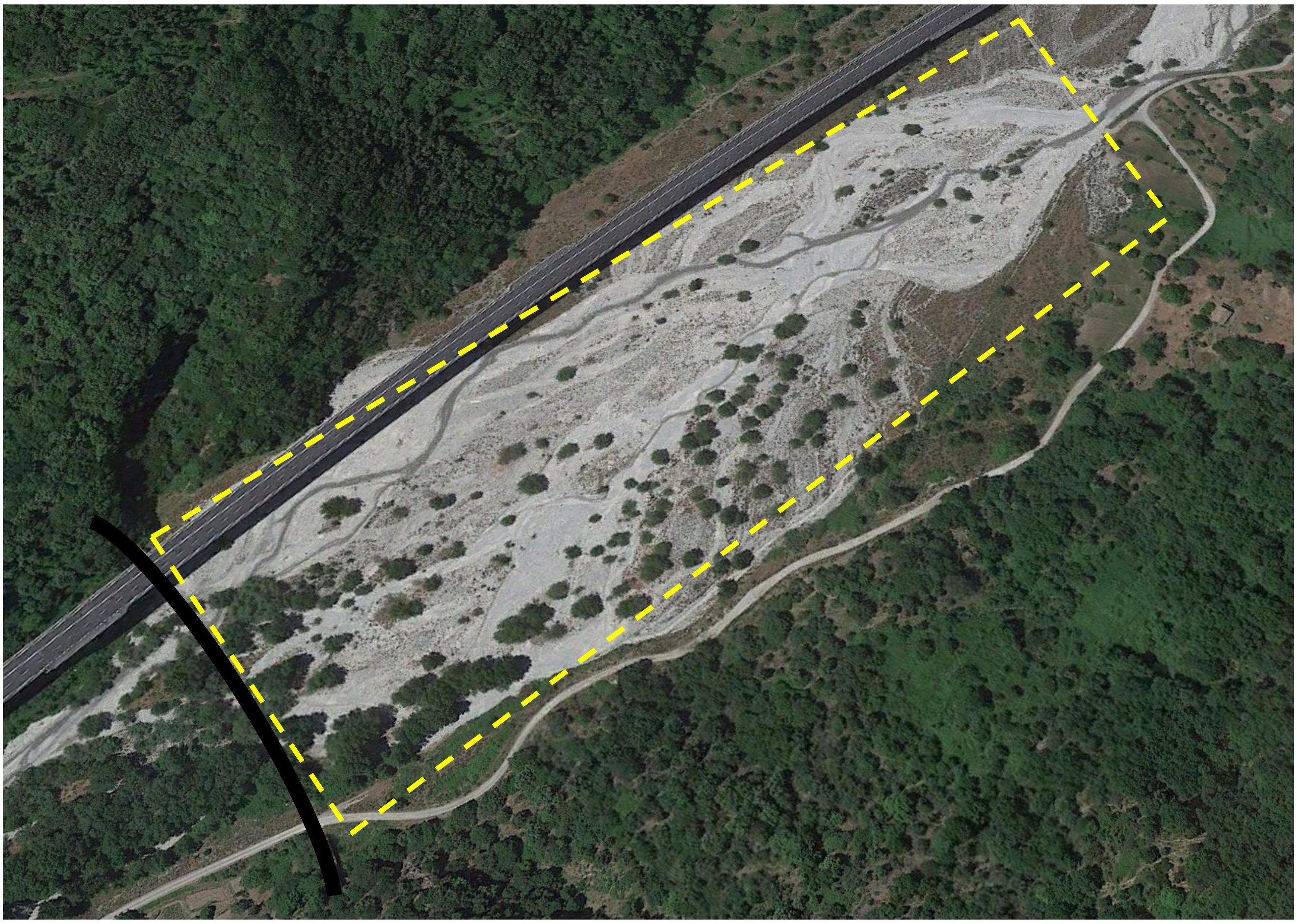


Fig. 2 Sketch of the sediment wedge volume retained behind the check dams



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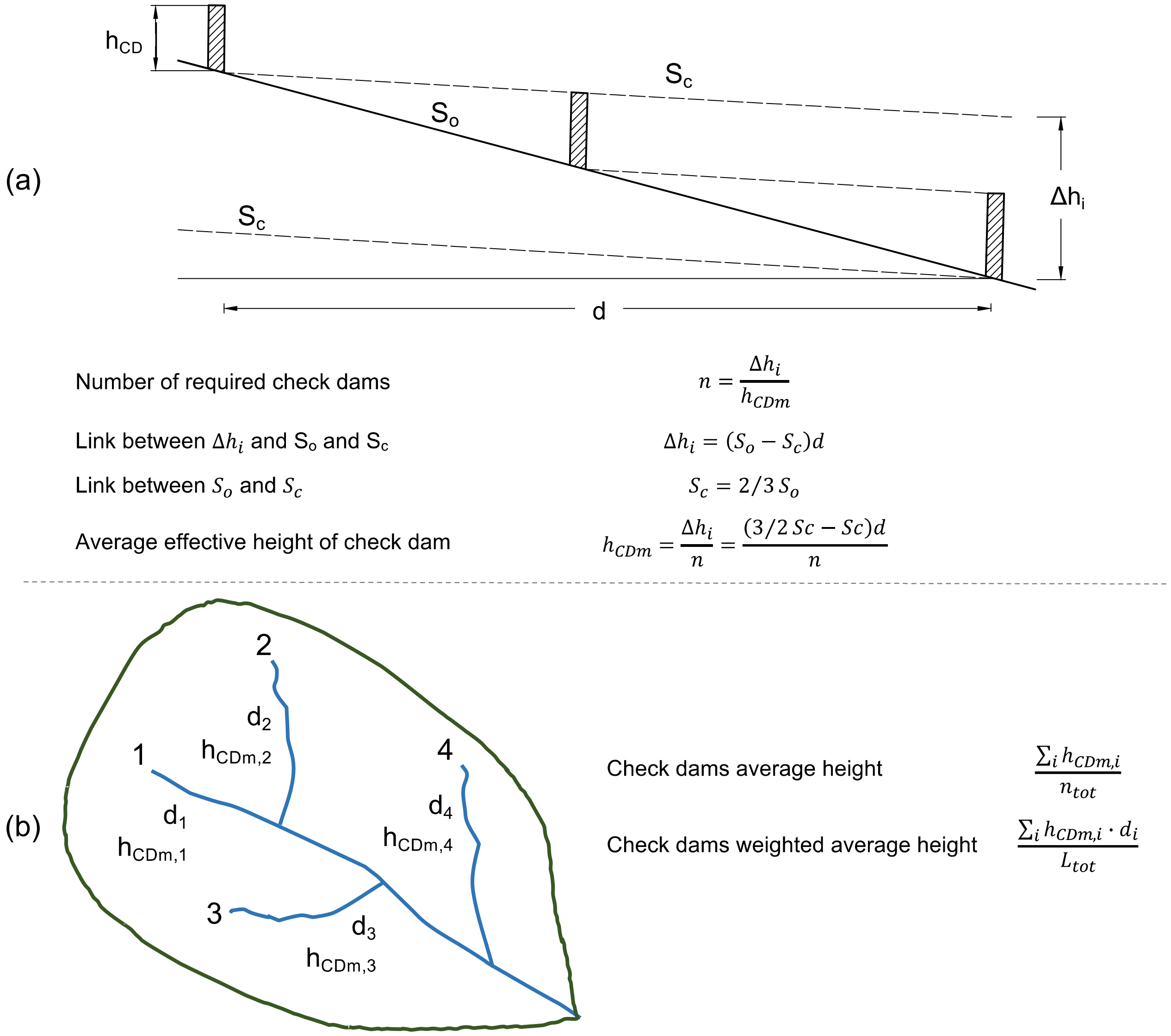

Number of required check dams $n = \frac{\Delta h_i}{h_{CDm}}$

Link between Δh_i and S_o and S_c $\Delta h_i = (S_o - S_c)d$

Link between S_o and S_c $S_c = 2/3\, S_o$

Average effective height of check dam $h_{CDm} = \frac{\Delta h_i}{n} = \frac{(3/2\, Sc - Sc)d}{n}$

Check dams average height $\frac{\sum_i h_{CDm,i}}{n_{tot}}$

Check dams weighted average height $\frac{\sum_i h_{CDm,i} \cdot d_i}{L_{tot}}$

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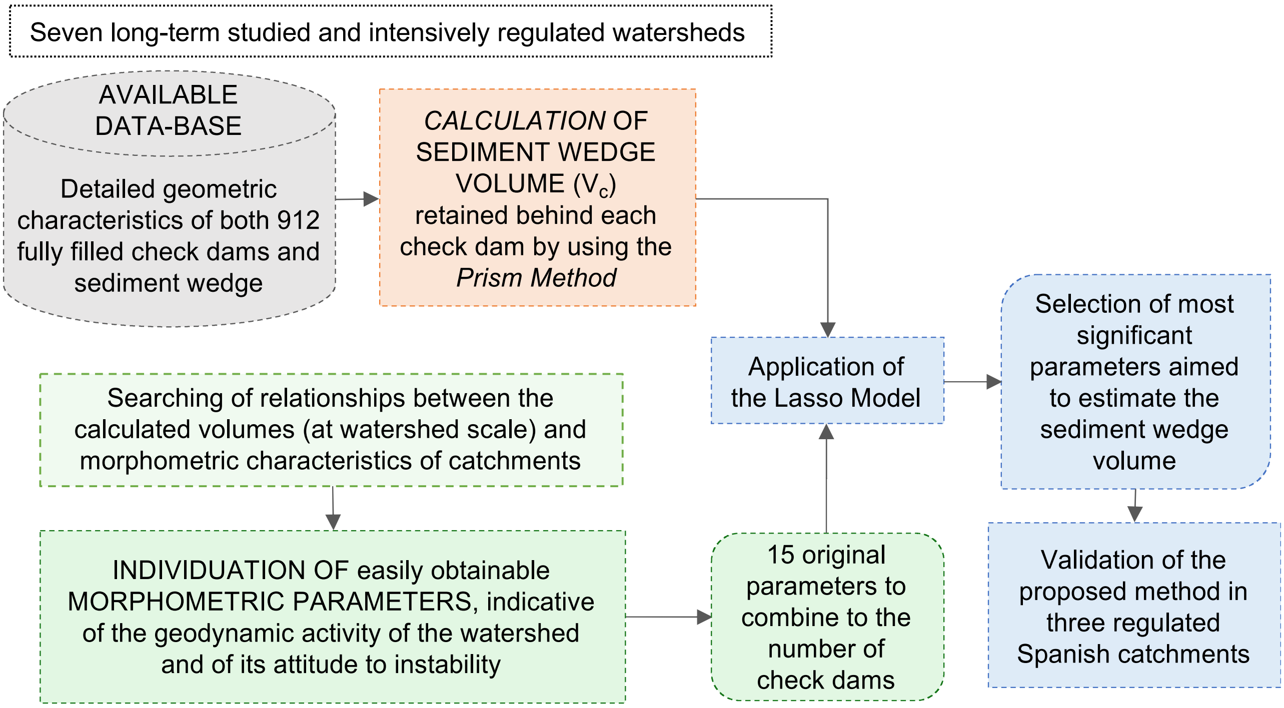
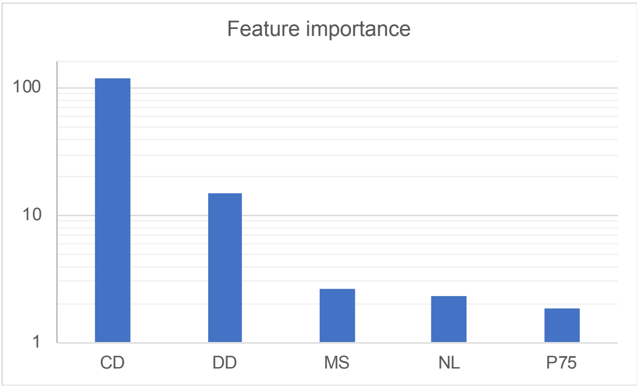


Fig. 5 Methodological scheme for the preliminary estimation of potential sediment volume retained by check dam system at watershed level



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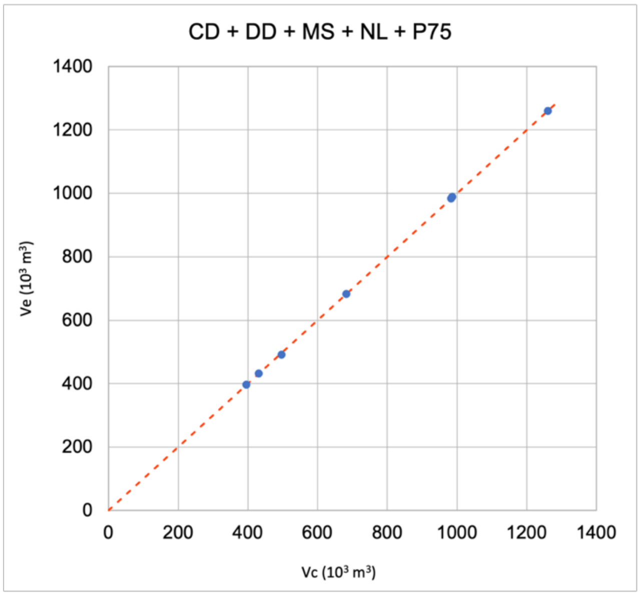

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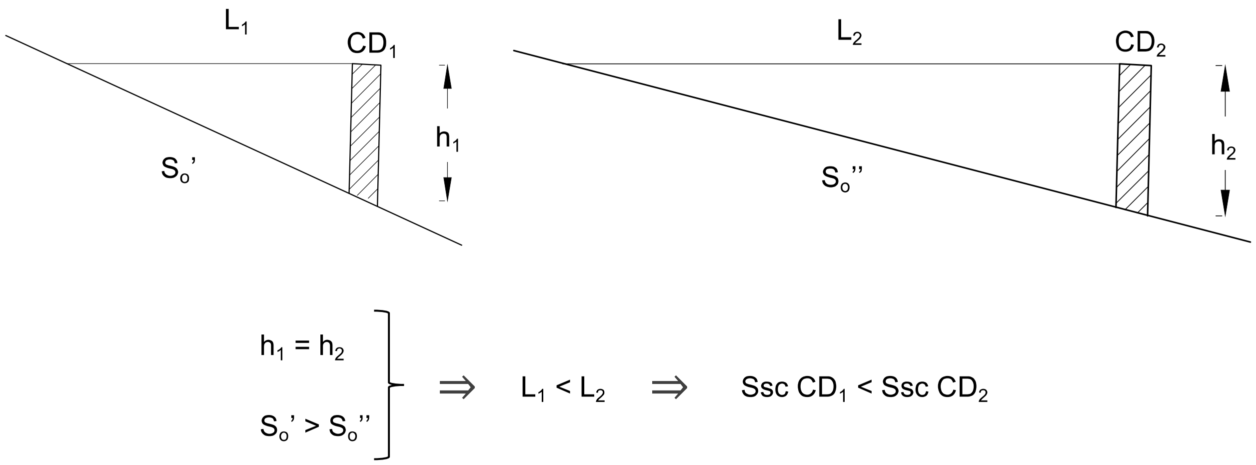

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