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 sediment 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 ≈ 16,900 m³; R² > 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

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 1977; 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 twenty-first 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 a 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 twentieth 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 purposely 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 Vittal 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 programme 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 km²) 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 flumare, 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 was used as case studies (Fig. 1). The seven watersheds which cover about 900 km² 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.

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

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).

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:

\[
V_c = \frac{1}{6} \cdot h \cdot L \cdot (2B + B')
\]  

(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 1 × 1-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).

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:

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** | km² | m a.s.l | m a.s.l | % | IV | IV | IV | IV |
| Area | 132 | 38.4 | 55.5 | 11.5 | 415 | 61 | 160.1 |
| Mean altitude | 737 | 460 | 704 | 387 | 584 | 893 | 586 |
| Maximum altitude | 1420 | 1240 | 1770 | 800 | 1810 | 1610 | 1215 |
| Mean watershed slope | 22 | 27 | 26 | 30 | 15 | 29 | 23 |
| Stream order | IV | IV | IV | 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 |

(a) AL Allaro, AM Amusa, GA Gallico, MO Molaro, PE Petrace, SA Sant’Agata, TG Torbid 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, Torbid di Gioiosa)
(c) CD, check dams

Fig. 2 Sketch of the sediment wedge volume retained behind the check dams
(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, each torrent reach the number of check dams \( n \) can be determined by using the following formula:

\[
\begin{align*}
    n &= \frac{\Delta h_i}{h_{CDm}} \quad (2)
\end{align*}
\]

where \( \Delta h \) 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);

| Limits | Strengths |
|--------|-----------|
| 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 | Based on a simple formula, maintains a sufficient level of accuracy (Ramos-Diez et al. 2016) |
| In headwater areas and/or in mountain reaches, both check dams and sediment wedge dimensions can be obscured by vegetation cover | (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 |
| | (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 |

Fig. 3 Orthophoto showing the upstream sediment wedge (yellow) behind a check dam (black) – Sant’Agata watershed, Calabria, Italy
(c) considering a given channel reach, the total height of the check dam system \( (\Delta h) \) 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):

\[
\Delta h_i = (S_o - S_c) d
\]

(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):

\[
\frac{\Delta h_i}{h_{CDm}} = \frac{n}{\Delta h_i}
\]

\[
\Delta h_i = (S_o - S_c) d
\]

\[
S_c = 2/3 S_o
\]

\[
h_{CDm} = \frac{\Delta h_i}{n} = \frac{(3/2 S_c - S_c) d}{n}
\]

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, \( \Delta h_i \) = 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.
S_c = k \cdot S_o \quad (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 \( S_o = 3/2 \cdot S_c \), it is possible to express \( \Delta h_i \) 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 (\( h_{CDm} \)):

\[
h_{CDm} = \frac{\Delta h_i}{n} = \frac{\left( \frac{3}{2} S_c - S_c \right) d}{n} \quad (5)
\]

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 (\( L_{tot} \)):

\[
\sum_i \frac{h_{CDm_i} \cdot d_i}{L_{tot}} \quad (6)
\]

(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), most of which could be easily obtained by DTM.

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 dam 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).

### 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 southeast 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 Belmonte 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.

### 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).
The total $V_c$ calculated for each watershed using the Prism method varies between $394 \times 10^3$ m$^3$ (Amusa) and $1260 \times 10^3$ m$^3$ (Petrace; Table 4).

In the studied watersheds sediment wedge volumes trapped behind check dams range between $10^3$ and $30 \times 10^3$ m$^3$, with an average value per check dam of $5 \times 10^3$ 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 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 $1.14 \times 10^6$ 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, as well as combining the four morphometric parameters...
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).

### 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 $23 \times 10^3$ m$^3$ (Table 6) and an average difference between $V_c$ and $V_e$ of $24\%$.

![Methodological scheme for the preliminary estimation of a potential sediment volume retained by a check dam system at the watershed level](image)

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

### 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 h for fieldwork and 24000 km travelled) and about 230 h 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 Recking 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

| Watershed | AL | AM | GA | MO | PE | SA | TG | RMSE |
|-----------|----|----|----|----|----|----|----|------|
| 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% |

(*) percentage difference between $V_c$ and $V_e$

(a) AL Allaro, AM Amusa, GA Gallico, MO Molaro, PE Petrace, SA Sant’Agata, TG Torbido di Giososa
channel and watershed) easy to obtain by DTM; the number of check dams is normally known; conversely, detailed measurements of the structures (e.g. height, width) are time-consuming (and often difficult) field activity. In order to propose a simple method, a set of four morphometric parameters which take 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 $h_{CDm}$ (Eq. 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.

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 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 $20 \times 20$-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 Belmonte 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 are 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) 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.

![Fig. 8 Sediment storage capacity (Ssc) variation with different channel bed slopes (S_0' and S_0'')](image)

\[
h_1 = h_2 \\
\frac{S_0'}{S_0''} > 1 \\
\Rightarrow \quad L_1 < L_2 \\
\Rightarrow \quad \text{Ssc} CD_1 < \text{Ssc} CD_2
\]

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 | Belmonte Serrato et al. 2005 | Boix-Fayos et al. 2008 |
| Available literature data | Area km² | 27.3 | 30 | 53.5 |
| CD – | | 29 | 57 | 58 |
| Vc | 10³ m³ | 141.4 | 69.1 | 92.8 |
| 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 |
| Ve | 10³ m³ | 110.0 | 87.7 | 110.1 |
| Δ (*) % | -28.5 | +26.9 | +18.6 |

(*) percentage difference between Vc and Ve
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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Declarations

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

Conflict of Interest The authors declare no competing interests.

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