Influence of site and check dam characteristics on sediment retention and structure conservation in a Mexican river

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Abstract
Previously, in a large river of Mexico regulated by more than 200 check dams, we demonstrated that vegetation cover and channel characteristics were the dominant factors on the structure conditions and capacity to store sediments. This study focuses on other categorical (i.e., check dam type and location, soil texture and land use) and numerical (i.e. water discharge, check dam dimensions) variables, to whom statistical analysis is applied, in order to assess their influence on sediment filling degree and conditions (functional or destroyed) of the check dams in the same river. ANOVA has shown that: (i) check dam type (gabion or stone) and location (headwater, middle or valley reaches), and soil texture significantly influence the sediment filling degree of structures; (ii) vegetation cover of the drained sub-watersheds, water discharge, channel width and check dam upstream depth significantly affect the structure conditions (functional or destroyed). PCA has provided two derivative variables, related to the geomorphological characteristics of channels and vegetation cover, to whom sediment retention behind check dams is related.

Keywords: soil erosion; vegetation cover; land use; soil characteristics; regulated river; water discharge.

1 Introduction

Check dams have been installed for controlling water flow and conserving soil in watersheds of many regions all over the world, as, for instance, in Italy, Ethiopia, Spain, China and USA (Abbasi et al., 2019). However, their desired impacts on river

hydrology, geomorphology and ecology are sometimes not achieved, due to reasons such as poor construction quality, improper location and inadequate design. From many examples worldwide, it appears that, after construction, the most important features that influence check dam function within the watershed system are sediment storage capacity and structural conditions (Nyssen et al., 2004; Lucas-Borja et al., 2018). However, there is limited information describing the influence of structure characteristics and site factors (such as river hydrology, channel and check dam geometry as well as land use and soils), on conditions of the check dams and their effectiveness for soil conservation at the watershed scale (Castillo et al., 2007) moreover, porous rock check dams are not deeply researched (Nichols and Polyakov, 2019). In a previous work, vegetation cover and channel characteristics have been shown to be dominant factors influencing the *post operam* conditions of check dams and their ability to store sediments in a large regulated river of Mexico (Lucas-Borja et al., 2018). A more comprehensive evaluation of the influence of other factors (for instance, site and check dam characteristics as well as channel hydrology) on functioning (in terms of sediment storage) and conditions (intact or destroyed) of check dams may be of help to watershed managers, in order to reduce check dam failure, accomplish the expected response, and increase the confidence in using check-dams as restoration tools at the watershed level. We hypothesize that check dam and channel dimensions, site features (e.g., soil and land use of the drained sub-watersheds), sediment filling degree behind the structures and hydrology may influence the structural conditions and functioning of the control works installed in the watershed.
To address these hypotheses, the ANalysis Of VAriance (ANOVA) and Principal Component Analyses (PCA) have been applied to the large dataset of check dam and site characteristics of the regulated watershed studied by Lucas-Borja et al. (2018). In more detail, ANOVA has separately evaluated the influence of some categorical and numerical variables (measuring as many site and check dam characteristics) on sediment filling degree and condition (functional or destroyed) of the check dams. PCA was used to link the derivative variables (principal components) to the numerical original variables, explaining check dam functioning.

2 Material and methods

2.1. The studied watershed

The watershed under investigation (Culiacan River, Mexico), which covers a total area of 10368 km^2, drains into the Sinaloa reservoir at an elevation of 128 m after running 25.3 kilometres from the headwater (Fig. 1). Topography ranges from mountains to lower lying hilly areas and plains. Average annual precipitation is 860 mm, mostly occurring in summer, and the mean annual temperature is 25 °C. The watershed is covered mainly by cropland (sorghum and corn) and protective forest. Soils can be classified as *Eutric regosols, Cromic vertisol* and *Haplic feozem.* In the watershed drainage network, approximately 270 small, temporary, stone check dams were recently built (2011-2015) across swales and drainage ditches. Many of these check dams are intact, but others have failed or damaged. The maximum height of the stone check dams is 3 metres; to increase their stability, the base of each check dams is embedded into the soil approximately at 1-meter depth. The structures were built as part of an "emergency" strategy to potentially control the channel grade and mitigate channel erosion; thus, it was expected that these control works would start functioning immediately after their installation, and this short-term monitoring activity can verify that they are functioning as anticipated.

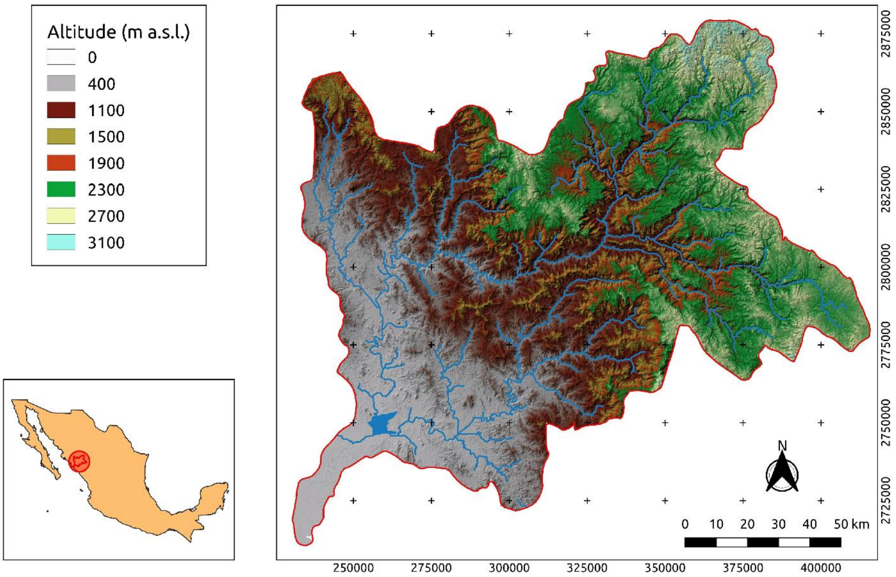

Fig. 1 Geographical location and map of Culiacan River (Mexico) with the location of the Sinaloa reservoir.

2.2. Data collection

The check dam dataset has been prepared using a combination of field surveys (measuring check dam and channel geometry) and remotely sensed data (for vegetation cover, land use and soil characteristics of the drained sub-watersheds) and digital terrain models (for the original and regulated channel profiles). A complete dataset was available for 206 out of the 273 check dams installed in the watersheds. Field data included both categorical and numerical variables. Categorical data for the check dams were *type* (gabion or stone), *condition* (functional or destroyed, related to check dam conservation), and *location* (headwater, middle or valley reaches). For each treated sub-watershed, *soil type and texture,* and *land use* were determined (Table 1).

The numerical variables were related to: *check dam dimensions* (width, and upstream and downstream height); *site features* (longitudinal slope and vegetation cover of the drained sub-watershed); *sediment retention* (initial capacity and filling degree); *channel geometry* (mean width and length) and *hydrology* (water discharge) associated with each check dam. In the absence of direct measures, water discharge in the active channel was estimated using Manning's equation based on channel dimensions and riverbed roughness. As regards check dam condition, each structure is classified as functional, if it is completely or partially filled with sediments, or destroyed, if it has completely collapsed and thus it is not functioning. With regards to the sediment stored behind each check dam, the initial storage capacity and filling degree of sediments - the latter considered as the ratio of actual sediment storage and the initial storage capacity - were estimated from the regulated and the original longitudinal profiles, and from check dam dimensions. It has been assumed that the deposited sediment volume behind a check dam has a prismatic shape with a trapezoidal section.

Table 1 Categorical data related to check dam and drained sub-watershed characteristics (Culiacan River, Mexico).

Check dam			Soil characteristics of the drained sub-watershed		
condition	**type**	**location**	**type**	**texture**	**land use**
Functional (189)	Gabion (106) Stone (82)	Headwater (44) Middle (31) Valley (113)	Haplic Feozem (46) Eutric Regosol (57) Cromic Vertisol (85)	Loamy-silty (93) Sandy-loamy (95)	Farming/grazing (13) Forest (175)
Destroyed (17)	Gabion (8) Stone (9)	Headwater (5) Middle (8) Valley (4)	Haplic Feozem (14) Eutric Regosol (3) Cromic Vertisol (0)	Loamy-silty (14) Sandy-loamy (3)	Farming/grazing (4) Forest (13)

Note: in brackets the number of check dams in each class is reported.

2.3. Statistical processing

ANOVA was used to evaluate the influence of: (i) the categorical variables (check dam type and location as well as soil type, texture and land use of the drained sub-watersheds) on sediment filling degree of functional check dams; (ii) the numerical variables (check dam dimensions, site features, sediment retention, channel geometry and hydrology) on check dam condition. The post hoc LSD (least square difference) test was used to explore statistical differences between the different levels of each studied variable. PCA was applied to the numerical variables, considered as explanatory, in order to elucidate their influence on sediment filling degree of the check dams (considered as response variable). PCA was carried out after standardisation and orthogonal transformation of the original variables. All statistical analyses were conducted using the R software version 3.2.4.

3. Results and Discussions

In the experimental watershed, the sediment filling degree of functional check dams is significantly influenced by the construction type and location (Table 2). The importance of the material and technique used for check dam construction in their integrity and functioning was stated also by other authors (i.e., Nyssen et al., 2014; Zhou et al., 2004).

Table 2 Results of the ANOVA used to evaluate the influence of categorical variables on sediment filling degree of functional check dams in the Culiacan River (Mexico).

Categorical (explanatory) variable	**Response variable (sediment filling degree of check dam)**	
	F value	Pr (> F)
Check dam+ type	47.90	0.0001***
Check dam+ location	15.59	0.0001***
Sub-watershed land use	1.08	0.2994
Sub-watershed soil type	1.63	0.3800
Sub-watershed soil texture	8.38	0.0043**

Note: *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; + Only functional check dams are considered.

The results of the LSD tests have demonstrated that the sediment filling degree is higher for check dams made of stone and located at the middle reaches compared to structures made of gabions and installed in middle and valley reaches, respectively (Table 3). The first evidence may be due to the higher porosity of gabions to water and sediments compared to stones, while the second evidence may be explained by the buffering effect of banks in some upper and valley reaches, which store sediment before entering in the river channel.

Table 3 Sediment filling degree (mean ± standard error) for each categorical variable of functional check dams in the Culiacan River (Mexico).

Check dam				
type		**location**		
Gabion	Stone	Headwater	Middle reach	Valley reach
54.6±2.5a	81.2±2.8b	54.2±3.3a	79.7±3.2b	62.5±3.8a

Sub-watershed						
soil type			**soil texture**		**land use**	
Haplic Feozem	Eutric Regosol	Cromic Vertisol	Loamy-silty	Sandy-loamy	Farming/ grazing	Forest
62.0±3.1a	45.0±8.4a	45.4±8.5a	64.5±2.7a	87.6±7.6b	59.6±6.7a	67.0±2.7a

Note: different lowercase letters indicate statistically significant differences ($p < 0.05$) according to the LSD test.

Vegetation cover, sediment filling degree, water discharge, channel width and check dam upstream depth are the factors that significantly influence check dam conditions

(Table 4). As a matter of fact, in those streams, where channels are narrower and vegetation cover is more developed, water discharge and sediment flows are lower; thus the dynamic actions on check dams decrease with higher structure stability (Lucas-Borja et al., 2018; Keesstra et al., 2018). Destroyed check dams are associated to a reduced functioning, since their sediment wedge has lower sediment filling degree and higher upstream depth compared to functional structures. The longitudinal slope and length of channels do not significantly affect the check dam condition (Table 4). This could be explained by the relatively relief of the watershed (with less than 150 m difference in elevation between the upper and the lower part of the watershed) and the very similar channel length between two consecutive check dams in many reaches.

Table 4 Results (mean ± standard error) of ANOVA to evaluate the influence of numerical variables on condition of check dams in the Culiacan River (Mexico).

Check dam condition	**Site features**		**Sediment retention**		**Hydrology**
	longitudinal slope (%)	vegetation cover (%)	initial capacity (m^3)	sediment filling degree (%)	water discharge (m^3/s)
Functional	7.12±0.48a	15.66±1.89a	67.23±5.72a	44.84±1.38a	15.68±3.59a
Destroyed	7.84±1.16a	46.47±7.82b	80.26±9.31a	0.08±0.02b	40.37±19.93b
	Channel geometry		**Check dam dimensions**		
	length (m)	width (m)	downstream depth (m)	upstream depth (m)	width (m)
Functional	15.47±0.73a	6.93±0.29a	1.10±0.09a	0.51±0.02a	6.53±0.23a
Destroyed	14.61±1.89a	8.54±0.75b	1.14±0.09a	0.63±0.05b	7.15±0.98a

Note: different lower case letters indicate statistically significant differences ($p < 0.05$) according to the LSD test.

PCA applied to the numerical factors (explanatory variables) and sediment filling degree of check dams (response variable) has provided two Principal Components (PCs), which together explain more than 70% of the variance of the original variables. Channel width (factor loading of 0.455) and length (0.378), as well as the initial capacity of sediment retention (0.355) and check dam downstream depth (0.432) are associated to PC1, while only the vegetation cover is associated to the PC2 (factor loading of -0.957) (Fig. 2). The remaining variables - longitudinal slope, check dam upstream depth and width, and water discharge - have lower influence on both PCs. Clearly and as expected (e.g., Zema et al., 2018; Lucas-Borja et al., 2018), the two selected PCs are separately related to different parameters, linked to geomorphological factors (PC1) and ecological features (PC2). These results are consistent with findings of other studies focusing the effects of check dams on river geomorphology and ecology (e.g., Bombino et al., 2019). Moreover, and unexpectedly (e.g, differently from findings of Zema et al., 2018), the hydraulic regime of the sub-watershed has not found to be an influencing factor on the sediment retention. This may be explained by the fact that the disruptive action exerted on the check dam during a flood can be mainly due to the sediment flow rather than the water discharge. No clusters of functional and destroyed check dams are evident from the analysis (Fig. 2).

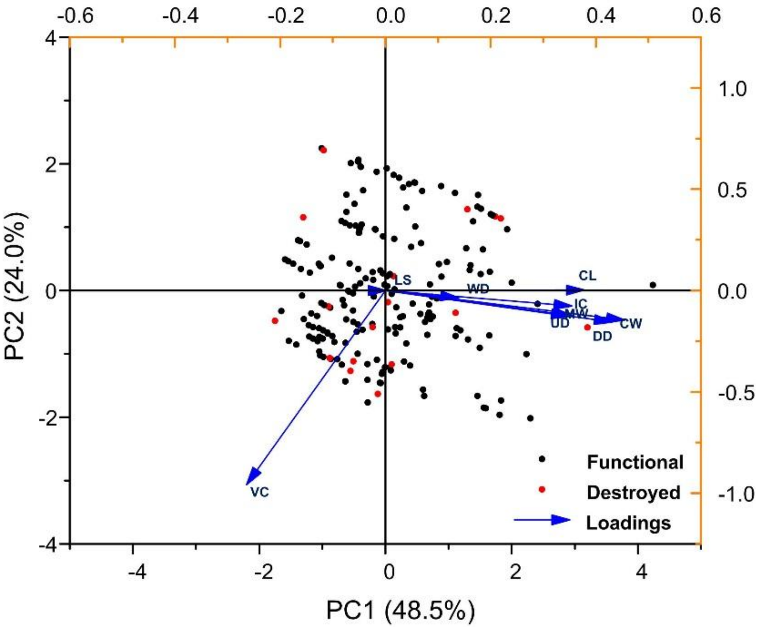

Fig. 2 Biplot of PCA applied to numerical factors (explanatory variables) and sediment filling degree (response variable) of check dams in the Culiacan watershed (Mexico). *(VC: Vegetation cover, LS: Longitudinal slope, CL: Channel length, CW: Channel width, IC: Initial sediment capacity, WD: Water discharge, UD: Upstream depth of check dam, DD: Downstream depth of check dam, MW: Mean width of check dam).*

4 Conclusions

This study has demonstrated that, among the hypothesized site and check dam characteristics of a large regulated watershed in Mexico, location (headwater, middle or valley reaches) and type (gabion or stone) of the structures as well as the soil texture significantly influence the sediment filling degree of check dams, while soil type and land use play a minor influence on sediment retention. The structural conditions (functional or destroyed) of the check dams are significantly influenced by the vegetation cover, water discharge and channel width, but not by the longitudinal slope and length of the channels where the structures are installed. PCA has provided two derivative variables, which are mainly related to channel dimensions and vegetation cover, respectively, thus demonstrating the influence of river features on sediment retention behind check dams. The output of these statistical models has allowed the identification of the dominant factors affecting both the structural condition of the check dams and their capacity to store sediment. Overall, the influence of check dam construction technique and location as well as vegetation cover and water discharge must be considered with care in developing the best strategies for soil conservation in watersheds regulated with check dams.

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