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Title: Exploring the influence of vegetation cover, sediment storage capacity and channel dimensions on stone check dam conditions and effectiveness in a large regulated river in México

Article Type: Research Paper

Keywords: Vegetation cover; watershed management; check dam failure; sediment wedge; soil erosion.

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Abstract: Check dams are widely used for soil conservation at the watershed scale. When structurally sound, these engineering control works retain sediment as planned. However, there is limited information describing the influence of site characteristics on post-construction condition including structural stability and sediment retention capacity. More specifically, the effects of channel morphology, check dam geometry and vegetation characteristics as potentially influencing factors on sediment retention capacity at the watershed level are poorly understood. Thus, an investigation applying field and remotely sensed measurements, multi-regression models, redundancy and sensitivity analysis, and correlation analysis was conducted in a Mexican watershed where the characteristics of 273 check dams were evaluated 3-5 years after construction. Vegetation cover and dimensions of the channel were found to be the most important factors influencing check dam fate. Taller structures experienced the greatest failure risk, in contrast to lower and wider structures and associated vegetation cover that retained long and wide sediment wedges, which helped to stabilise the check dams. The potential sediment storage capacity of the check dams mainly depends on the downstream height of the structure, but also on the vegetation cover near the structure walls; check dams constructed across a range of channel dimensions are able to effectively store sediment. Overall, this study provides a quantitative evaluation of the dominant factors influencing the post-construction conditions of check dams and their ability to store sediment, and thus provides land managers insights into the best strategies for soil conservation at the watershed scale using check dams.

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Dear Prof. Vymazal,

We would like to thank You for giving us the possibility to revise our manuscript. We have appreciated very much the work of the referees since it helps to improve our paper. All their requests have been duly considered and included in the text. We would be very grateful if You could reconsider the revised MS for publication on Your valued journal. You will find in the resubmission a file containing the revision notes replying to each of the referees' comments; moreover, all changes made to the MS are evidenced in red characters. Finally, we have also uploaded a MS clean version.

Kind regards.

Dr. Manuel Esteban Lucas-Borja

Corresponding author

AUTHORS' REPLY TO THE EDITOR

Dear Prof. Vymazal,

We would like to thank You for giving us the possibility to revise our manuscript. We have appreciated very much the work of the referees since it helps to improve our paper. All their requests have been duly considered and included in the text. We would be very grateful if You could reconsider the revised MS for publication on Your valued journal. You will find in the resubmission the revision notes replying to each of the referees' comments; moreover, all changes made to the MS are evidenced in red characters.

AUTHORS' REPLY TO COMMENTS OF THE REFEREES

Dear Sir/Madam, thanks a lot for Your revision work that we have considered very useful to improve our MS. In the following table you will find our replies to all Your comments. However, we refer You to the resubmitted manuscript file For the actual revisions.

<i>Referee's comment</i>	<i>Authors' reply</i>
<i>Referee n. 2</i>	
<p>It is a very interesting paper about construction of check dams in a river basin in México. This kind of structures are necessary although the bad construction or the bad design in its dimension can be problems in terms of damages downstream. This is because interesting. The authors did a very good inventory of all the dams, a total of 273 so the work it is very specific and with a large number of individuals to have good conclusions. The introduction as well the discussion is very well documented, with a large number of references what makes the topic of a world interest. The methodology is very adjusted to have profit of all the efforts and also the data treatment. The results are so very clear and achieve the objectives.</p>	<p>Thank You very much for Your opinion. We are glad that the paper is considered interesting and scientifically sound by You.</p>
<p>I have just said minor revision because the graphical abstract is a repeat of figures and pictures of the paper. So I do not know if it is necessary in this way, It do not provides new information.</p>	<p>We have removed the graphical abstract (not compulsory according to the editorial rules) and left only the highlights (which seem to be more exhaustive than the GA).</p>
<i>Referee n. 3</i>	
<p>The manuscript deals with a relevant topic, which should be of interest to the journal's readership. It presents an interesting data set concerning check dams and linked processes. However some changes are necessary before the publication.</p>	<p>Thanks a lot for Your opinion about the paper. Of course, Your suggestions, which we find very relevant and constructive, have been embedded in the revised MS version.</p>
<p>First, there are several sentences that are</p>	<p>All the sentences used in the other papers have</p>

<p>similar to the sentences used in other works by same authors (abstract included). This should be avoided otherwise the paper could be not so original.</p>	<p>been rephrased to improve the MS originality. Some of them, when considered unnecessary, have been removed to shorten Discussions (as suggested by you, see below).</p>
<p>In the introduction section, I don't quite see the explanation about the "significant contribution" of this work. Here the authors can work more.</p>	<p>Thanks for the suggestion, that allows us to better stress the usefulness of our paper. In the Conclusions section we have added a related explanation.</p>
<p>The authors report a several works about "long terms effects of check dams" and just few works assess short terms effects, so I'm not entirely convinced that the paper can analyze the effects of check dams built only 3-5 years ago (the period isn't enough).</p>	<p>This is an interesting observation. Here we detail our considerations about the evaluation of the check dam effects.</p> <p>These control works are usually designed to control sediment dynamics, which mainly depend on climatic and geomorphological characteristics of the torrent as well as those of check dams.</p> <p>The main goal of our study was just the assessment of the short-term effects of the check dam installation, since in the Culiacan watershed these structures are in general small (not higher than 3 metres), temporary and made of stone (see line 164 of the new MS). These structures are built by watershed managers adopting an "emergency" strategy (that is, to retain sediments generated by channel erosion in occasion of heavy rainstorms) rather to protect riverine territories after high floods. Thus it is expected that these control works start functioning immediately after their installation.</p> <p>In the previous works to whom you refer (mainly those assessing the check dam effects on vegetation) we have carried out long term investigations, since growth and establishment of riparian vegetation requires many years and often decades (particularly the tree species), while sediment storage dynamics and morphological effects on the channel (linked to the sediment transfer along the watershed) have been found much more rapid to act, in spite of the large check dam size. For instance, the retention capacity of many check dams more than 6-8 metres high and made of concrete or stone-concrete in Calabria was practically depleted few years since check dam installation and the channel reached a steady-state layout and profile (e.g. Zema et al., 2014). This geomorphological effects of check dams is what is happened also in the Culiacan watershed, where, as mentioned above, the check dams are of limited height and presumably the sediment dynamics is quite rapid, being regulated by</p>

	<p>moderate and frequent precipitation events rather than floods with high magnitude and low frequency, as in Calabria.</p>
<p>The paper should be improved with information about rainfall trends, land use changes and local channel slope changes, longitudinal channel profiles showing check dam and gradient changes on watershed (as reported in Polyakov et al., 2014 and Nichols et al., 2016).</p>	<p>We have added:</p> <ul style="list-style-type: none"> - a chart (see the new Figure 2) reporting the monthly precipitation and temperature recorded during the monitoring period (2011-2015); - a new Figure (n. 5) reporting a sample of four reaches with the layout as well as the original and regulated longitudinal profiles of the channel with the staggered check dams (unfortunately, given the scattered position of the 273 check dams it is impossible to do the same for all the check dams); this allows also to show the channel gradient changes following the structure installation. <p>Given the shortness of the monitoring period, no land use changes have been recorded compared to the situation reported in the MS).</p>
<p>It is not clear as the authors calculate ASS (line 270) without data about local channel slope.</p>	<p>Here we clarify better (beyond the information reported at lines 187-193 and 202-212 of the MS previously submitted, clearly not sufficient and maybe misunderstanding) that during the topographic surveys the channel height was measured upstream and downstream of the check dam at a longitudinal step of 5-10 metres between two consecutive structure. Given the original profile slope (estimated from the last available digital terrain models created before the check dam construction or, when available, from the check dam designs, see lines 200-207) and after reconstructing the regulated channel profile from the topographic surveys, we have estimated the volume of the sediment wedge behind each check dam, which was assumed to be the actual stored sediment (thus the variable "ASS").</p> <p>We have added slight more information in the revised MS (lines 200-207).</p>
<p>Other statistical indexes could be necessary to explain the relation between sediment, channel shape and vegetation cover.</p>	<p>Thanks for the suggestion. Accordingly, we have performed a correlation analysis between the variables reported in Table 1, to explain existing correlations between the analysed variables.</p>
<p>An enlargement of the map (figure 1) with check dams location is necessary.</p>	<p>We have added the location of the check dams in the new Figure 5.</p>
<p>Reading the sentences between 526-536 seems that check dams are not able to trap sediments....It is not ...</p>	<p>Right observation. These sentences (particularly those at lines 529-535 of the previous MS) are misleading and lead to the same conclusion made by the reviewer. Of course, we have modified them, explaining better our thoughts.</p>

Discussion section is too long, some sentences can be avoid.

We have shortened the Discussion section, removing the unnecessary/redundant sentences.

1 **Exploring the influence of vegetation cover, sediment storage capacity and channel**
2 **dimensions on stone check dam conditions and effectiveness in a large regulated**
3 **river in México**

4

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25

26 **ABSTRACT**

27

28 Check dams are widely used for soil conservation at the watershed scale. When
29 structurally sound, these engineering control works retain sediment as planned.
30 However, there is limited information describing the influence of site characteristics on
31 post-construction condition including structural stability and sediment retention
32 capacity. More specifically, ~~the interactions of watershed morphological and ecological~~
33 ~~characteristics, and check dam geometry influencing potential sediment retention~~
34 ~~capacity~~ **the effects of channel morphology, check dam geometry and vegetation**

35 characteristics as potentially influencing factors on sediment retention capacity at the
36 watershed level are poorly understood. Thus, an investigation applying field and
37 remotely sensed measurements, multi-regression models, ~~and~~ redundancy and
38 sensitivity analysis, and correlation analysis was conducted in a Mexican watershed of
39 Mexico, where the characteristics of 273 check dams were evaluated 3-5 years after
40 construction. Vegetation cover and dimensions of the channel were found to be the most
41 important factors influencing check dam fate. Taller structures experienced the greatest
42 failure risk, in contrast to lower and wider structures and associated vegetation cover
43 that retained long and wide sediment wedges, which helped to stabilise the check dams.
44 The potential sediment storage capacity of the check dams mainly depends on the
45 downstream height of the structure, but also on the vegetation cover near the structure
46 walls; check dams constructed across a range of channel dimensions are able to
47 effectively store sediment. Overall, this study provides a quantitative evaluation of the
48 dominant factors influencing the post-construction conditions of check dams and their
49 ability to store sediment, and thus provides land managers insights into the best
50 strategies for soil conservation at the watershed scale using check dams.

51

52 **Keywords:** Vegetation cover; watershed management; check dam failure; sediment
53 wedge; soil erosion.

54

55

56 1. Introduction

57

58 Check dams are made of various materials, including concrete blocks, loose stones,
59 rocks in gabion baskets, or wood, and they can be identified as a small barriers built
60 across a drainage channel to control runoff and sediment transport, and enhance
61 sedimentation (Nyssen et al., 2004). These stream control works are widely used around
62 the world, often as one component of watershed scale efforts to control runoff, erosion,
63 and sediment transfers (Mekonnen et al., 2015a; 2015b; Quiñonero et al., 2016). ~~For~~
64 ~~example, Bombino et al. (2007) observed that in some river basins of southern Calabria~~
65 ~~(Italy) 75% of the stream network is affected by control works with up to 6 check dams~~
66 ~~per km², many of which were constructed in combination with complimentary~~
67 ~~engineering works.~~ They often have been installed throughout drainage networks
68 covering extensive regions. For instance in torrents of Calabria (Southern Italy), where

69 up to 6 check-dams per km² (Bombino et al., 2007) were installed, more than 75% of
70 the hydrographic network has been treated. Guyassa et al. (2017) report extensive
71 installation of check dams during the last three decades in gullies of the Highlands of
72 Northern Ethiopia as soil and water conservation practices. In ephemeral channels of
73 southeast Spain, check dams were used to stabilize hillslopes by inducing deposition
74 and forming flat sediment wedges that reduce runoff slopes (Conesa Garcia and Garcia
75 Lorenzo, 2010). In addition to their use in soil conservation, check dams have been
76 constructed in gullies to retain sediment and form farmland in Loess Plateau in China
77 (Xu et al., 2004).

~~78 The installation of check dams is usually aimed at slowing water and sediment~~
~~79 movements along stream channels (e.g. Heede, 1978; Nyssen et al., 2004). After their~~
~~80 installation in the river system, check dam structures can have important effects on both~~
~~81 channel morphology and vegetation, which in aggregate can be important effects on~~
~~82 stream systems because of their sediment retention capacity. The effects of check dams~~
~~83 on many different aspects such as channel morphology, vegetation recovery or soil~~
~~84 properties have been documented by international literature~~ Check dams, which are
85 usually build to control water and sediment fluxes along stream channels (e.g. Heede,
86 1978; Nyssen et al., 2004) also exert important effects on channel morphology, bed
87 sediment and vegetation (Conesa Garcia and Garcia Lorenzo, 2010; Xu et al., 2004;
88 Boix-Fayos et al. 2007; Zema et al., 2014; 2018). In the Mediterranean environment of
89 southern Italy, Bombino et al. (2009) showed the positive effects of check dams on
90 headwater mountain channels affecting both physical adjustments and the extent and
91 development of riparian vegetation. Boix-Fayos et al. (2007) evaluated the effects of
92 check dams on river channel morphology in Spain and found that after 30 years, most of
93 the check dams lost much of their trap efficiency, and erosion of the alluvial deposits
94 upstream of check dam had begun. Xu et al. (2012) performed a series of calculations to
95 quantify the effects of conservation managements in terms of retaining soil, water, and
96 especially nutrients 50 years after implementation in a representative catchment on the
97 Loess Plateau (China). This research resulted in recommendations of preferred
98 conservation practice in the area. An evaluation of check dams constructed in two small
99 semi-arid watersheds in the south-western United States revealed that check dam
100 failures were minimal, however loss of sediment retention capacity was rapid, within
101 seven years, due to high sediment loads (Polyakov et al., 2014; Nichols et al., 2016).
102 Nyssen et al. (2004) reported that soils influenced the rate of check dam failures with

103 higher rates in areas with smectite-rich soils that are prone to swelling. However,
104 although check dams are widely used as a watershed management tool, **often in**
105 **combination with complimentary engineering works**, for enhancing watershed and
106 grade stabilization and their impacts have been investigated in various ecosystems,
107 information describing and quantifying the watershed factors affecting check dam
108 stability and efficacy is limited. ~~These factors are of different nature (human, physical,~~
109 ~~biological) and strictly linked (e.g. soil and vegetation, channel slope, width and depth).~~
110 ~~The influence of each of the above mentioned factors is difficult to identify and more~~
111 ~~research is needed.~~

112 From the previous examples, it appears that after ~~the check dams~~ construction, one of
113 the most important features influencing the effectiveness of check dams on the
114 watershed system is their sediment storage capacity. Storage capacity is directly related
115 to structural condition, but the efficacy of check dams is also related to biotic and
116 abiotic factors, such as channel geometry, land use, soil type, and vegetation cover. In
117 particular, **the** scientific literature has evidenced the basic role of ~~this latter watershed~~
118 ~~factor~~ **vegetative cover** for an ecologically sound regulation activity of rivers (e.g.
119 Gurnell and Petts, 2002; 2006; Allmendinger e al., 2005; Corenblit et al., 2007). In our
120 study, we hypothesised that, vegetation cover percentage and type may significantly
121 influence sediment transfer and channel deposition, which in turn affects check dams
122 stability and failure. We expect that lower vegetation cover will result in higher
123 sediment transfers and thus the likelihood of stone check dam failure will increase.
124 Therefore, in view of an integrated management of regulated watersheds, there is ~~the a~~
125 need to investigate which of the factors mentioned above are the most influencing on
126 both the condition of check dam structures and their ability to store sediment with
127 particular stress on the role of the vegetation cover. This information is important to
128 maximize the likelihood of successful conservation works. Failure to account for high
129 intensity rainstorms, upstream areas with highly erodible soils, absence of vegetation
130 cover in the watershed, inadequate channel dimensions for a check dams installation or
131 steeped channels may generate high quantities of sediment transfer and drawing
132 attention to the risks posed by these structures as they fill with sediment and deteriorate
133 (Wang et al. 2009). Check dams failure and **the** sudden or gradual erosion of ~~these~~
134 ~~sediment deposits~~ **previously deposited sediment** ~~and the amount of material entrained~~
135 ~~may be huge~~ **can reintroduce large quantities of sediment for subsequent transport**
136 (Brooks and Lawrence 1999).

137 To address these issues, a large regulated watershed in Mexico is presented as a case
138 study. Here, more than 250 check dams, recently built to slow runoff and retain
139 sediment, are intact, but many other structures have failed. A large dataset describing
140 the condition and functioning of the check dams was compiled and reported by Cruz
141 Hernandez et al. (2014). This dataset is combined with remotely sensed data to interpret
142 possible cause-effect relationships between sub-watershed characteristics and the
143 structural condition and functioning (in terms of sediment storage capacity) of the check
144 dams. Specifically, a combination of analytical techniques (stepwise regression,
145 redundancy analysis, ~~and~~ increase-rate-analysis **and correlation analysis**) to the check
146 dam dataset collected in the watershed. The subsequent interpretation identifies and
147 quantifies the most influential watershed factors (channel dimensions, vegetation cover,
148 characteristics of the check dams and others) affecting both the structural condition and
149 functioning of check dams; finally, the role of the vegetation is focussed as a co-factor
150 ~~synergic~~ **synergetic** with the actions of check dams towards ~~an~~ ecologically sound
151 regulation of the studied river.

152

153 **2. Materials and methods**

154

155 **2.1 Study area**

156

157 This study was conducted in the Culiacan watershed in the state of Sinaloa, north-
158 western Mexico (latitude 24.867346°N, longitude -107.181013°W) (Figure 1). The
159 watershed, which covers 10368 km², drains into the Sinaloa reservoir at an elevation of
160 128 m after running 25.3 kilometres from the headwater. Topography ranges from
161 mountains to lower lying hilly areas and plains. Average annual precipitation is 860
162 mm, mostly occurring, together with the resulting surface runoff, during July, August
163 and September; winters are generally milder and in this season rainfall is less intense.
164 Mean annual temperatures are in the range 24-26 °C. **Figure 2 reports the annual trends**
165 **of precipitation and mean temperature measured at the Culiacàn meteorological station**
166 **during the period 1995-2015.**

167 Main land uses are cropland (sorghum and corn), covering 44.2% of the total watershed
168 area, protective forest and grazing, 46.7% and 0.3% of the area, respectively. Typical
169 vegetation consists of medium-statured tropical forest (including semi-evergreen forest,
170 sub-deciduous forests, and riparian forests), Pinus-Quercus forest, spiny forest; gallery

171 forest (includes “selva mediana ribereña”), tropical dry forest (Pérez-García et al.,
172 2012). Geology is representative of Jurassic to Quaternary periods, while, according to
173 FAO (1988), soils of the study area can be classified as *Eutric regosols* and *haplic*
174 *Feozem*. The drainage patterns of the watershed are controlled by the low relief and
175 surface runoff resulting in a trellis pattern that has produced numerous ephemeral
176 channels. Artificial cut-offs or bank protection were not constructed to reduce lateral
177 migration.

178 In this watershed, small, temporary, stone check dams were constructed across swales
179 and drainage ditches (Figure 3 and 4). These structures were built to reduce flow
180 velocity and thereby potentially control the channel grade and mitigate channel erosion.
181 The maximum height of the stone check dams is 3 metres; to increase their stability, the
182 base of each check dams is embedded into the soil approximately at 1-meter depth. The
183 check dams were constructed to achieve complete cover of the channel and to assure
184 that the middle of the dam is lower than the edges. ~~Disrupting floods with large return~~
185 ~~interval have been not recorded~~ No large magnitude, low frequency floods were
186 recorded during the period of study (2011-2015). Figure 5 shows a general map and the
187 original/regulated longitudinal profile of of four reaches containing the staggered check
188 dams, allowing the identification of the channel gradient changes following the
189 structure installation.

190

191 2.2. Survey methods

192

193 The studied stone check dams ~~have been~~ were regularly evaluated from 2011 to 2015 to
194 assess for their effectiveness and impact on in their functioning (as channel adjustments,
195 sediment storage, and vegetation dynamics). The structures were built as part of an
196 "emergency" strategy aiming to retain water and sediment fluxes generated by
197 rainstorms on upstream areas with highly erodible soils; thus it is expected that these
198 control works start functioning immediately after their installation and a short-term
199 monitoring activity can assure these requirements.

200 This study was carried out by using a combination of fieldwork and analysis of
201 remotely sensed data. Field surveys were made by Cruz Hernandez et al. (2014) to
202 analyse the operating condition of each check dam. During these surveys, structure
203 dimensions and both upstream and downstream channel morphology were quantified
204 through measurements (Figure 4 6) using standard topographic surveying equipment

205 and laser technology (measurements up to 75 m, accuracy ± 3 mm). Field data included
206 both categorical and continuous variables. Categorical data for the stone check dams
207 were *type* (gabion and stone check dams); *year of construction* (from 2011 to 2015,
208 drawn from check dam design or construction reports available at managing
209 authorities); *current operational condition* ("functional", i.e. operating as designed,
210 "filled", by sediment or "broken", that is, completely collapsed and thus not
211 functioning); *location* (low, between 59 and 104 m a.s.l., middle, 107 - 153 m, or upper
212 watershed, 154 - 200 m); *structure* (gabions or unembedded stones). The continuous
213 variables surveyed include *check dam location* (X, Y UTM coordinates); *check dam*
214 *dimensions* (length, width and downstream height, in metres, see also Figure 4 6);
215 *longitudinal slope of the channel* (% , measured as the difference between the heights of
216 the channel and check dam divided by the channel length); *potential storage capacity*
217 (m^3); *actual sediment storage* (m^3); *ratio actual sediment storage/potential storage*
218 *capacity* (%) (see below); *channel dimensions* associated with each check dam (m).
219 During topographic surveys, the channel elevation was measured upstream of each
220 check dam at a longitudinal step of 5-10 metres, in order to define the longitudinal
221 profile of the regulated channel. The original channel profile was estimated from the
222 last available digital terrain models created before the check dam construction
223 (resolution of 1x1 metres, years 2010-11) or, when available, from the check dam
224 designs. The two reconstructed longitudinal profiles allowed reconstructing the
225 sediment wedge dimensions and estimating the local slope behind each check dam
226 (Figures 5 and 6).
227 From the current (regulated) and the original longitudinal profiles close to the check
228 dams as well as from check dam dimensions, ~~the~~ the potential storage capacity and actual
229 sediment storage were estimated ~~from field measurements of check dam dimensions and~~
230 ~~current channel profile~~, assuming that the deposited sediment volume behind a check
231 dam has a prismatic shape with a trapezoidal section (Castillo et al., 2007; Ramos-Diez
232 et al., 2016a; 2016b; 2017a). ~~The original channel profile was estimated from the last~~
233 ~~available digital terrain models created before the check dam construction (resolution of~~
234 ~~1x1 metres, years 2010-11) or, when available, from the check dam designs.~~ The
235 surveyed channel dimensions include *upstream/downstream depth* (measured at the
236 check dam location); *length*; *average width* (measured every 5 metres starting
237 immediately upstream of the check dam until the check dam located immediately
238 upstream or, for the first structure, the watershed perimeter).

239 Remotely sensed data was used to quantify watershed characteristics such as vegetation
240 cover and soils. More in detail, *vegetation cover* of the sub-watershed (% of area,
241 estimated by maps produced by remotely sensed data); *soil type* and *land use* (forest or
242 crop, analysed separately for each of the sub-watershed in which the main basin was
243 discretised) for *each reach/sub-watershed* was derived from GIS analyses and satellite
244 images (Landsat 8 source data at 30-m resolution and Rapideye images at 5-m
245 resolution). Watershed morphometric information was delineated from DEM (at 1-m
246 resolution) which was firstly georeferenced and then processed by a GIS software. This
247 processing allowed identifying the hydrographic network and 273 sub-
248 watersheds/reaches (each one containing a check dam); more specifically, each check
249 dam was associated to a reach and considered its outlet: this latter drains a sub-
250 watershed (part of the entire watershed) conveying water to the reach. Check dams were
251 located on the watershed map according to their geographical coordinates drawn from
252 satellite images (where the structures were visible) or from the topographic survey.

253

254 **2.3. Analytical methods**

255

256 The collected data were processed by a combination of ~~three~~ four analytical techniques:
257 (i) linear correlation analysis; ~~(i)~~ (ii) stepwise regression analysis; ~~(ii)~~ (iii) redundancy
258 analysis (RDA); ~~(iii)~~ (iv) increase-rate-analysis (IRA). Firstly, in order to identify
259 possible mathematical structures among vegetation cover, sediment storage capacity
260 and channel dimensions and to determine the related correlation coefficients, the
261 Spearman correlation matrix was computed based on the current values of the variables
262 surveyed for the sampled check dams. Preliminarily, the indicators were standardised by
263 converting data to zero mean and unit variance.

264 Then, ~~S~~ stepwise regression analysis was used to build an optimized mathematical
265 model ~~between~~ relating the *response (dependent) variable* (in our case the current
266 operational condition of check dams) ~~and to the~~ explanatory (independent) factors (the
267 remaining categorical and continuous variables). Stepwise regression is a type of
268 multiple linear regression which can choose the best-fitted combination of explanatory
269 variables for response variable predication with forward-adding and backward-deleting
270 variables. The stepping procedure begins as an initial model definition with a stepped
271 forward addition of a variable to the previous model. The critical F value is then used to
272 check the eligibility of the added variable. With a new variable added, the previous

273 variables in the model may lose their predictive ability. Thus, stepping criteria are used
274 to check the significance of all the included variables. Based on this situation, the
275 significant variables could be confirmed. While, if the variable is insignificant, then the
276 backward method is used to delete it. Forward adding and backward deleting are
277 repeated until no variable is added or removed. The stepping procedure is eliminated
278 when the optimized model is constructed. The stepping criteria were used to check the
279 significance (at $p = 0.05$) of all the included variables. The procedure was stopped when
280 the optimized model was built and the maximum r^2 between *response variable* and
281 explanatory factors was achieved.

282 RDA was used with the main focus on the relationships between the check dam
283 conditions (functional, filled or broken) and those factors influencing it (selected by
284 stepwise regression). The check dam conditions were response variables in this analyses,
285 whereas the explanatory variables selected according to the stepwise regression belongs
286 to the three categories (check dams characteristics, check dam volume and channel
287 dimensions): therefore, the explanatory variables included the selected significant
288 variables that could represented each categories. In order to explore the factors affecting
289 check dam conditions comprehensively, the raw data were **standardized** before the RDA
290 analyses, and the significance of the variables was tested with Monte Carlo simulations.
291 All the above ~~analyze~~ **analyses** were performed with R software version 3.2.0 (R Core
292 Team 2013), with the main aim of a quantitative expression of the explanatory factors
293 on check dam conditions.

294 A revised IRA (Xu et al., 2015) was used to evaluate the variation in the ratio of the
295 actual sediment storage (henceforth, ASS) to the potential storage capacity (PSC) of
296 check dams, with respect to changes in the significant explanatory variables (considered
297 as causal factors). This ratio (that is, ASS/PSC) is equal to the sediment filling degree
298 (SFD, in %) of a check dam. Specifically, ASS is the volume (m^3) of the actual
299 sediment wedge behind a check dam, while PSC is the volume (m^3) that the sediment
300 wedge would have, if the check dam was entirely filled with sediments. Therefore, a
301 filled check dam shows a SFD equal to 100% ($ASS = PSC$), for an empty structure SFD
302 $= 0$, while a functional structure has a SFD between 0 and 100% ($0 < ASS < PSC$). In
303 the first case, the check dam is not able to retain more sediment in the future, being its
304 capacity completely depleted.

305 In order to carry out a sensitivity analysis, all dams were ordered according to the
306 amount of potential storage capacity from the largest to the smallest. The difference in

307 SFD between two successively ordered check dams (i and $i-1$), RP_i (%), was calculated
 308 as follows:

309

$$310 \quad RP_i = \frac{2(SFD_i - SFD_{i-1})}{SFD_i + SFD_{i-1}} \quad [1]$$

311

312 where P_i is the SFD (%) of the i -th check dam.

313 As reported in details by Xu et al. (2015), the Absolute Sensitivity Parameter (S), S_j ,

314 towards an explanatory variable t is calculated by its mean growth rate:

315

$$316 \quad S_j = \overline{(RP_{i,j} / Rt_{i,j})}_{i=1,N} \quad [2]$$

317

318 being j the j -th explanatory variable, N the total number of check dams and:

319

$$320 \quad Rt_i = \frac{2(t_i - t_{i-1})}{t_i + t_{i-1}} \quad [3]$$

321

322 Rt_i is the increase rate calculated for two successively ordered check dams (i and $i-1$),

323 where t is the value of the explanatory variable. Finally, the Relative Sensitivity

324 Parameter (s) of the j -th explanatory variable t_j , s_j , which can be used to qualitatively

325 evaluate the effect of the explanatory variable t on s was calculated as follows:

326

$$327 \quad s_j = \frac{S_j}{\min(S_j)_{j=1,M}} \quad [4]$$

328

329 where M is the total number of the explanatory variables.

330 In our study, we calculated the Absolute and Relative Sensitivity Parameters of SFD

331 (henceforth, S_{SFD} and s_{SFD}); as explanatory variables of S_{SFD} and s_{SFD} , vegetation cover,

332 longitudinal slope, channel depths (measured immediately from the downstream and the

333 upstream of a check dam) as well as length and width of the channel (equal to that of

334 the check dam) were considered.

335

336

337 **3. Results**

338

339 The results show that the potential storage capacity of the studied stone check dams
340 ranged from ~~493.9~~ to 0.5 to 493.5 m³, with a mean value of 51.5 m³. The actual volume
341 of sediment stored upstream of the check dams ranged from ~~237.6~~ to 0.2 to 237.6 m³
342 with a mean value of 26.7 m³. The average width of the upstream sediment wedge was
343 6.5 m, ranging from ~~22.5 m~~ to 2.4 to 22.5 m. The mean downstream depth of the stone
344 check dams was 1.1 m, ranging from ~~1.9~~ to 0.1 to 1.9 m. Finally, the length of the
345 sediment wedge stored upstream ranged from ~~39.1~~ m to 3.9 to 39.1 m, with a mean
346 value of 13.8 m.

347 Of the 273 analysed check dams, 116 (43%) are operating as designed and thus
348 currently regulate water and sediment flows inside the watershed. They are classified as
349 *functional*. Seventy-four of the check dams (27%) show a compromised structure (that
350 is, they have lost their functionality, because they have collapsed) and they are
351 classified as *broken*; and 83 (30%) are classified as *filled*, showing thus a totally full
352 upstream wedge, and presumably the equilibrium channel slope has been reached. On
353 average, the functional check dams were filled to 45% of their storage capacity, and
354 thus have the capacity to retain additional sediment (Table 1).

355 The average longitudinal channel slope among all evaluated check dams was quite
356 similar (ranging from 6.53-7.68%). In general, channel profiles were steepest upstream
357 of filled check dams (7.68%) and shallower upstream of functional (6.66%) and broken
358 (6.53%) structures. The impact of sub-watershed vegetation cover in the immediate
359 vicinity of the investigated control works was clear. In sub-watersheds where the
360 vegetation cover is high (45-53%), fewer check dams were broken in comparison to
361 those check dams in sub-watersheds where vegetation cover was low (13%) (Table
362 1). ~~Concerning channel dimensions influenced by the presence of the surveyed check
363 dams, the data can be observed in Table 1.~~

364 Results of the stepwise regression showed that six of the ~~considered~~ categorical and
365 continuous independent variables were significant in explaining the variability in check
366 dam condition ($p < 0.05$) (Table 2), and there was a strong association between these
367 selected variables and soil conditions ($r^2 = 0.96$). The six significant variables were
368 grouped into three categories: (i) check dam site characteristic, consisting only of
369 vegetation cover; (ii) sediment volume characteristics behind check dams, including
370 potential storage capacity and actual sediment storage; and (iii) channel dimension
371 characteristics, taking into account channel length as well as upstream depth and width

372 of the channel. Check dam condition was positively correlated with vegetation cover,
373 potential storage capacity, actual sediment storage, length and average width of the
374 sediment wedge; more specifically, check dam condition (explained by sediment
375 retention capacity) was positively correlated with vegetation cover. In contrast, a
376 negative relationship was found between check dam condition and depth of the
377 upstream channel.

378 The analysis of the Spearman matrix indicated high correlations (> 0.73) among pairs of
379 site, check dam and channel dimension variables. In more detail, the potential storage
380 capacity of the check dams was associated to the channel upstream depth ($r = 0.86$) and
381 the structure sediment storage ($r = 0.83$), with these latter variables also strictly linked
382 each other ($r = 0.73$). Also the channel downstream depth was strongly correlated ($r =$
383 0.98) to the mean channel width. Lower correlation levels (but always significant at $p <$
384 0.05) were detected among other variables, such as vegetation cover and sediment
385 filling degree ($r = 0.48$), potential storage capacity of the check dams and all channel
386 dimensions ($r > 0.47$), as well as couples of variables related to channel dimensions ($r >$
387 0.44) (Table 3).

388 RDA using the explanatory variables of the three categories (vegetation cover, sediment
389 storage volume, and channel characteristics) as influencing factors and check dam
390 condition as the response variable, quantitatively showed that vegetation cover and
391 channel dimensions explain 32.5 and 33.2% of the variability in check dam condition
392 respectively. In contrast, although sediment storage characteristics also showed
393 significantly influences on check dam conditions, the explanatory percentage was only
394 4.01%, thus much lower than the vegetation cover and channel dimensions.

395 The results of the sensitivity ~~analysis—performed by IRA—~~ of the channel dimensions
396 (average channel width, channel length, downstream and upstream depth), longitudinal
397 slope, and vegetation cover on sediment potential store capacity **performed by IRA** are
398 reported in Table 4=3. The larger the sensitivity of an explanatory variable, the more
399 prominently this variable influences the sediment retention capacity. Channel depth
400 downstream of the check dam was found to be the most important influential variable as
401 it is the most sensitivity parameter (136.7). The relative sensitivity of channel depth
402 upstream of the check dam and vegetation cover are comparable to each other, although
403 these variables are less important than the channel depth downstream of the check dam
404 (38.1 and 20.7, respectively). Finally, the relative sensitivity of longitudinal slope,
405 length and average width of the channel are very low and negative.

406

407 4. Discussion

408

409 Check dams can be an effective tool for mitigating degradation provided that they are
410 maintained after construction. Check dam failure, which may be due to many factors,
411 can cause scour problems and release sediment into flow downstream. This is the case
412 of more than a half of the 273 stone check dams installed in the Culiacan watershed,
413 which were not operating as designed just 3-5 years after their construction, due to both
414 ~~siltation~~ **sedimentation** and structural failure. As a matter of fact, among the structures
415 analysed in this case study, 27% of stone check dams were damaged by water and
416 sediment during runoff, while for 30% of the structures the sediment storage capacity
417 was practically depleted. In the first case, it is evident that the collapsed check dams are
418 not functioning as designed. In the second case, it is true that the check dams no longer
419 accumulate the solid material transported by runoff; however, these structures do
420 contribute to bed stabilisation (due to the longitudinal slope reduction) and flood
421 attenuation (because of the wider channel section).

422 **The investigation** ~~A deeper investigation on the relationships between check dam site~~
423 ~~characteristics, sediment storage capacity and channel dimensions on one hand and the~~
424 ~~current operation conditions of the studied check dams on the other hand~~ revealed that
425 longitudinal channel slope behind the surveyed check dams is not noticeably different
426 among filled, functional and broken structures (~~Table 1 and Figure 2 and 3~~). In general
427 we might expect to see variations in slope because where intact structures act as a
428 barrier against runoff and, when flow velocity is reduced, sediment accumulates behind
429 the check dam thus aggrading locally its profile (Bombino et al., 2008). This
430 unexpected result could be explained by the fact that in our check dams aggradation is
431 localized and proximate to the structure and channel measurements ~~were not made~~ **just**
432 **limited to points** immediately behind a check dam where most of the sediment
433 accumulates, but were deliberately made at a distance upstream of the check dams.‡
434 ‡This choice was adopted because we wanted to check whether the stabilising effects of
435 a check dam on channel profile is localised or extends upstream of the structure, that is,
436 far from its direct influence (as instead, revealed by Bombino et al., 2008, however in
437 other environmental contexts). Evidently, the profile survey highlights the overall
438 stability of channel slope, independent of check dam conditions.

439 Furthermore, higher vegetation cover is found in sub-watershed with functional and
440 filled check dams (~~Table 1~~), thus confirming the positive effects of check dams on
441 vegetation development behind the structures, documented in other environments (e.g.
442 Boix-Fayos et al., 2007; Bombino et al., 2006; 2009; 2013). Vegetation helps channel
443 stabilisation: in-channel vegetation reduce water velocity and soil detachment, and in
444 vegetated hillslopes water and sediment supply to the channel decrease (Keesstra et al.,
445 2108). ~~This investigation confirms outcomes of the above mentioned studies, who~~
446 ~~demonstrated that, where good edaphic conditions are observed for filled and functional~~
447 ~~check dams (resulting in a larger presence of vegetation), as in this study, the~~
448 ~~consequent higher cover and height of vegetation reduces stream velocity and~~
449 ~~consolidates plant roots channel bed. This reduces hydrodynamic water and soil forces~~
450 ~~on check dams, which improves stability of the structures. In other words, as vegetation~~
451 ~~cover increased, the check dams were less likely to have failed.~~

452 From this investigation it is clear that the potential storage capacity of functional check
453 dams is higher (by over 100%, ~~Table 1~~) than filled structures, and the functional
454 structures are located downstream of longer channels (supplying water and sediment)
455 compared to filled check dams (~~Table 1~~); conversely, the channel profile upstream of
456 the filled check dams is steeper compared to functional structures. This finding (that is,
457 longer channels upstream of functional check dams) partially contrasts with the results
458 of research conducted by Li et al. (2007), who stated that check dams with a longer or
459 steeper up-gully have a low capacity to retain soil, because soil from the upper reaches
460 is not easily deposited by larger and more rapid flood events. In our study, the
461 vegetation cover associated with both filled and functional check dams (whose values
462 are very similar) likely limits soil particle detachment and transport thereby reducing
463 the volume of sediment available for deposition: for functional check dams this leads to
464 a not already depleted sediment storage capacity; filled check dams, also showing a well
465 developed vegetation cover, stores an actual sediment volume similar to functional
466 check dams, but their potential storage capacity has not depleted (~~Table 1~~).

467 Broken check dams (~~Figure 2~~) retained the capacity to store accumulated sediment
468 (although lower by about 70% than functional check dams). In particular, sediment was
469 stored behind non-broken side walls. The actual sediment storage is similar for
470 functional and filled check-dams, in spite of the higher length of the channel upstream
471 of the latter (~~Table 1~~). On average, the ratio of actual to potential sediment storage of
472 functional check dams (SFD) is close to 50% (~~Table 1~~), which should increase with

473 time assuming the check dams continue to function. ~~Based on the data investigated from~~
474 ~~the check dams in the hilly and gully region of In~~ the Loess Plateau, Jiao et al (2003)
475 concluded that the ratio of the soil retained by a check dam to the total transported from
476 the upper reaches ranged from 23.3% to 52.9%, and the ratio had a positive relationship
477 with check dam height and a negative relationship with the sub-watershed area above of
478 the check dam. ~~A similar conclusion was also drawn by Fang et al. (1998), who~~
479 ~~analyzed the data of 864 check dams observed in the Wudinghe watershed and north-~~
480 ~~west of Shanxi (Northern China).~~

481 The analysis of channel dimension characteristics grouped according to the current
482 operating condition of check dams (~~Table 1~~) shows better developed sediment wedges
483 (higher upstream depth, width and length) for functional check dams compared to filled
484 structures. As expected, larger structures stored greater volumes of sediments and
485 nevertheless the sediment storage capacity of these structures has not been fully
486 depleted. It is interesting to notice that downstream of broken check dams the channel
487 depth is higher compared to the other check dam conditions; evidently, in spite of the
488 lower upstream depth, the local scouring on the downstream side of broken structure is
489 high, due to the erosive power of the water stream. This phenomenon was observed
490 extensively for the broken check dams (more than 80%) through the presence of
491 destroyed stones (~~Figure 2~~) at the sides of the channel that caused a decrease in cross
492 section area, ~~thus increasing stream velocity and erosive power, resulting in erosion of~~
493 ~~the channel bed (Peyras et al. 1992; Conesa García and García Lorenzo, 2010; Conesa~~
494 ~~García et al., 2007; Lenzi et al., 2003).~~

495 The construction of multi-regression models between the check dam conditions and
496 factors (linked to site location, sediment storage and channel dimension characteristics)
497 highlights that only six of the potentially influencing variables considered have a
498 significant impact on check dam conditions. Moreover, of these six causal factors,
499 vegetation cover and channel dimensions were found to be the most influential ones
500 (see results of redundancy analysis, explaining more than 65% of the variability of the
501 check dam conditions). Overall, channel dimension was the most important factor
502 determining check dam condition, followed by vegetation cover.

503 The negative correlation between check dam condition and upstream channel depth
504 leads one to think that taller structures are most likely to be exposed to failure risk,
505 because of the soil bank strains behind check dams of non-embedded building material.
506 Conversely, sediment wedges behind check dams with lower height, but with overall

507 larger widths lengths appear to be more stable, given comparable retained sediment
508 volumes. Finally, the actual sediment storage appears to be the most influential variable
509 on check dam conditions.

510 It has been highlighted in the literature (e.g. Conesa García and Garcia Lorenzo, 2010;
511 Ramos-Diez et al., 2017b) that a large number of factors influence sediment storage
512 capacity behind check dams. This study showed that, within the Culiacan watershed,
513 sediment retention of check dams is related to both the downstream and upstream
514 depths of the structure and thus the height of the check dam is important. This result is
515 expected because the structures with greater height are associated with two predominant
516 processes: (i) local scouring downstream of the check dam, which increases and thus
517 mobilises more sediment to be transported downstream ~~with structure height (equal to~~
518 ~~downstream depth)~~; (ii) aggradation of channel bed upstream of check dam, forming
519 long and wide sediment wedges, in which large volumes of sediment are stored during
520 flooding events; ~~the extent of these sediment wedges (and thus their potential or actual~~
521 ~~sediment storage) is higher in reaches confined downstream by higher check dams.~~
522 However, in our study, the sensitivity analysis has highlighted that the magnitude of the
523 second process is noticeably lower than scouring action downstream, as shown by the
524 values of S_{SFD} (136.7 for downstream depth against 38.1 for upstream height of the
525 check dam, ~~Table 3~~). Moreover, the performed analysis confirms the importance of
526 vegetation cover on reducing sediment loads and thus extending the life of check dams
527 by retaining potential storage capacity. As a matter of fact, in areas with low vegetation
528 cover (both in the channel and in the hillslopes) the channel bed surface remains
529 exposed to stream erosion, which mobilises sediments along the reach (as reported
530 above). Finally, the other factors analysed (channel profile slope, length and width)
531 were ~~not~~ found to affect **by a much lesser extent** potential storage capacity, **except for**
532 **channel depth measured upstream of check dams (thus confirming the influence of**
533 **sediment storage)**. This also implies that a smaller increase in the above conditions will
534 result in a smaller decrease of the potential storage capacity.

535 Although the lack of influence of channel profile slope on potential storage capacity
536 may be explained by its low variability mentioned above, the substantial independence
537 of potential storage capacity on channel length and width is less expected. From a
538 deeper analysis of morphological data of the individual check dams, we noticed that for
539 the majority of the structures channel length and width do not follow a corresponding
540 trend; in other words, often-wider check dams are not associated to longer reaches,

541 which leads to a substantial balance between these explanatory variables. The results of
542 our study are in contrast with findings of Zema et al. (2014), **who found that the ability**
543 **to retain sediment and channel local scouring downstream is linked to the local profile**
544 **slope and width of reaches regulated by check dams.** ~~who found that~~
545 ~~scouring/sedimentation dynamics depend mainly on the channel slope and width in~~
546 ~~proximity to the check dams;~~ **H**owever, it should be noted that in the Zema et al.
547 (2014) study, structure spacing, geomorphic conditions, and hydrologic regime were
548 different ~~that than~~ our study ~~and these characteristics were thought to influence the~~
549 ~~general scouring and sedimentation dynamics.~~

550 This research confirms that it is necessary to apply an integrated approach to solve the
551 problems of watershed soil conservation, since the factors governing the related
552 processes - in particular ~~when the river is~~ **in streams** regulated by check dams - are
553 numerous and of different origin. The use of check dams can be definitely useful when
554 the sediment source is located close to or in the channel (e.g. in-channel sediment
555 supply, channel incision, bank erosion, armour layer removal, etc.). However, **where**
556 installation of check dams alone can not mitigate watershed soil degradation
557 **(particularly in hillslopes with bare soil),** ~~because often the source of the sediments is~~
558 ~~located on the hillslopes, and~~ it is necessary to reduce sediments at the sources,
559 preferably by enhancing the establishment of a structured and extended vegetation
560 cover; as a matter of fact, the study has demonstrated that vegetation cover can be a
561 prerequisite for good conditions and functioning of check dams. **Overall, soil**
562 **conservation and flood risk mitigation at watershed scale must be addressed by a**
563 **rational and integrated combination of in-channel (such as check dams) and extensive**
564 **(for instance, afforestation and terracing) actions.**

565

566 **5. Conclusions**

567

568 A quantitative analysis to understand the relation between sub-watershed characteristics
569 (vegetation cover, sediment storage capacity and channel dimensions) and check dam
570 conditions and effectiveness was carried out in a large ~~river of~~ **Mexican watershed in**
571 ~~Mexico.~~ In this regulated watershed 273 stone control structures were recently built; the
572 factors mostly influencing their functioning and conservation - with particular regard to
573 vegetation cover - were surveyed and ~~processed~~ **analysed using** by a combination of
574 ~~three~~ **four** analytical techniques. This study showed that the ~~collapsed~~ **failure of** check

575 dams was associated with low vegetation cover; conversely, with a well developed
576 vegetation cover the majority of check dams were functional or filled, in both cases not
577 broken. Multi-regression models showed that, under the specific environmental
578 conditions, vegetation cover and channel dimensions explain together more than 65% of
579 the variability of the check dam conditions. Overall, channel dimension is the most
580 important factor determining check dam condition, but a basic role is played also by
581 vegetation cover, since this ecological factor is important for potential storage capacity.
582 Taller structures are most likely to be exposed to failure risk, while check dams with
583 lower height, but with well-developed sediment wedges and large vegetation cover, are
584 more stable. A sensitivity analysis showed strong dependence of potential sediment
585 storage capacity of the check dams - and therefore of their ability to retain sediment
586 circulating in the watershed - on downstream depth of the structure. However, also
587 upstream height of check dams and vegetation cover of the drained sub-watershed are
588 factors with a considerable influence on sediment retention processes acting behind the
589 stone structures.

590 Overall, this study has provided a quantitative identification of the most important
591 factors affecting the structural condition of check dams and their ability to store
592 sediment, highlighting ~~on which factors~~ (channel characteristics, dimensions of check
593 dams and vegetation cover **as dominant factors**). ~~land managers~~ **One** must pay ~~more~~
594 attention to **these factors** ~~identify~~ **in developing** the best strategies for soil conservation
595 at the watershed scale; the role of vegetation is clear and it definitely helps for a
596 ecologically sound management and functioning of watersheds. **These findings suggest**
597 **that managers: (i) consider with caution the installation of control works (such as stone**
598 **or rock check dams) in sub-watershed with low vegetation cover and highly erodible**
599 **soils, since here the high sediment transfer rates may increase the structure failure**
600 **likelihood; (ii) adopt a larger number of small structures rather than controlling the**
601 **evolution of the channel longitudinal profile by large-sized check dams, since taller**
602 **structures are most likely to be exposed to failure risk, thus losing much of their**
603 **functioning.**

604

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606

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613

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806 Table 1 - Site characteristics, sediment storage and channel dimensions for 273 check dams surveyed in the Culiacan watershed (Mexico).

807

808

Check dam condition (number)	Site characteristics		Check dams Sediment storage			Channel dimensions			
	Longitudinal slope (%)	Vegetation cover (%)	Potential storage capacity (m ³)	Actual sediment storage (m ³)	Sediment Filling Degree* (%)	Length (m)	Downstream** depth (m)	Upstream** depth (m)	Average width of the sediment wedge (m)
<i>Functional</i> (116)	6.66±0.57	45±2	77.54±7.44	35.78±4.04,	45±0.01	15.47±0.73	1.14±0.02	0.51±0.02	6.93±0.29
<i>Filled</i> (83)	7.68±0.76	53±3	37.64	37.64	100	11.15±0.85	0.99±0.03	0.36±0.02	5.49±0.28
<i>Broken</i> (74)	6.53±0.60	13±3	25.47±8.67	-	-	14.62±0.97	1.24±0.05	0.15±0.04	8.54±0.56

809 * ratio of actual sediment storage to potential storage capacity; ** measured immediately close to the check dams.

810

811 Table 2 - Best-fit combination of explanatory variables for check dam conditions as
812 response variable using stepwise regression analysis applied to check dam data in
813 Culiacan watershed (Mexico).

814

Explanatory variables	Estimate	Std. Error	F-value	Pr(> t)
Vegetation cover	0.070	0.030	30.34	<0.001
Potential storage capacity	0.001	0.000	2.06	0.04
Actual sediment storage	1.760	0.030	3.19	0.002
Channel length	0.010	0.010	66.14	<0.001
Upstream channel depth	-1.110	0.060	-19.84	<0.001
Average channel width	0.070	0.010	10.49	<0.001

815

816 Table 3 - Spearman's correlation matrix among variables measured close to 273 check dams in Culiacan watershed (Mexico).

817

Variable		Site characteristics		Check dams			Channel dimensions			
		Longitudinal slope	Vegetation cover	Potential storage capacity	Actual sediment storage	Sediment Filling Degree	Length	Downstream depth	Upstream depth	Average width of the sediment wedge
Site characteristics	Longitudinal slope	1	-0.024	0.025	-0.039	0.027	-0.020	-0.041	-0.037	-0.050
	Vegetation cover		1	0.209	0.343	0.484	-0.199	-0.138	0.264	-0.170
Check dams	Potential storage capacity			1	0.826	0.281	0.512	0.552	0.860	0.468
	Actual sediment storage				1	0.586	0.359	0.375	0.734	0.301
	Sediment Filling Degree					1	-0.200	-0.157	0.380	-0.193
Channel dimensions	Length						1	0.534	0.231	0.530
	Downstream depth							1	0.442	0.977
	Upstream depth								1	0.378
	Average width of the sediment wedge									1

818 Table 4.3 - Sensitivity analysis of site characteristics and channel dimensions
 819 (explanatory variables, ordered by SFD) on sediment retention of check dams in the
 820 Culiacan watershed (Mexico).

821

Parameter	Explanatory variables					
	<i>Downstream depth</i>	<i>Upstream depth</i>	<i>Vegetation cover</i>	<i>Longitudinal slope</i>	<i>Channel length</i>	<i>Average channel width</i>
<i>Absolute Sensitivity (S_{SFD})</i>	1.0056	0.2802	0.1525	-0.0377	-0.0107	-0.0074
<i>Relative Sensitivity (S_{SFD})</i>	136.7	38.1	20.7	-5.1	-1.5	-1.0

822

823 **Figure captions**

824

825 Figure 1. Geographic location of the stone check dams investigated in the Culiacan
826 watershed (Mexico).

827

828 **Figure 2 - Annual trends (mean \pm std. dev.) of precipitation and mean temperature**
829 **measured at the meteorological station of Culiacan in the period 1995-2015.**

830

831 Figure ~~3~~². Stone check dam failure (broken) **in the** (Culiacan watershed) (Mexico).

832

833 Figure ~~4~~³. A working gabion check dam **in the** (Culiacan watershed) (Mexico).

834

835 **Figure 5. Map (a) as well as longitudinal original and regulated profiles (b) of four**
836 **check dam staggered series in the Culiacan watershed (Mexico).**

837

838 Figure ~~6~~⁴. Annotated schematic showing side and oblique views of a typical stone
839 check dam in the Culiacan watershed (Mexico).

1 **Exploring the influence of vegetation cover, sediment storage capacity and channel**
2 **dimensions on stone check dam conditions and effectiveness in a large regulated**
3 **river in México**

4

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25

26 **ABSTRACT**

27

28 Check dams are widely used for soil conservation at the watershed scale. When
29 structurally sound, these engineering control works retain sediment as planned.
30 However, there is limited information describing the influence of site characteristics on
31 post-construction condition including structural stability and sediment retention
32 capacity. More specifically, the effects of channel morphology, check dam geometry
33 and vegetation characteristics as potentially influencing factors on sediment retention
34 capacity at the watershed level are poorly understood. Thus, an investigation applying

35 field and remotely sensed measurements, multi-regression models, redundancy and
36 sensitivity analysis, and correlation analysis was conducted in a Mexican watershed
37 where the characteristics of 273 check dams were evaluated 3-5 years after construction.
38 Vegetation cover and dimensions of the channel were found to be the most important
39 factors influencing check dam fate. Taller structures experienced the greatest failure
40 risk, in contrast to lower and wider structures and associated vegetation cover that
41 retained long and wide sediment wedges, which helped to stabilise the check dams. The
42 potential sediment storage capacity of the check dams mainly depends on the
43 downstream height of the structure, but also on the vegetation cover near the structure
44 walls; check dams constructed across a range of channel dimensions are able to
45 effectively store sediment. Overall, this study provides a quantitative evaluation of the
46 dominant factors influencing the post-construction conditions of check dams and their
47 ability to store sediment, and thus provides land managers insights into the best
48 strategies for soil conservation at the watershed scale using check dams.

49

50 **Keywords:** Vegetation cover; watershed management; check dam failure; sediment
51 wedge; soil erosion.

52

53

54 **1. Introduction**

55

56 Check dams are made of various materials, including concrete blocks, loose stones,
57 rocks in gabion baskets, or wood, and they can be identified as a small barriers built
58 across a drainage channel to control runoff and sediment transport, and enhance
59 sedimentation (Nyssen et al., 2004). These stream control works are widely used around
60 the world, often as one component of watershed scale efforts to control runoff, erosion,
61 and sediment transfers (Mekonnen et al., 2015a; 2015b; Quiñonero et al., 2016). They
62 often have been installed throughout drainage networks covering extensive regions. For
63 instance in torrents of Calabria (Southern Italy), where up to 6 check-dams per km²
64 (Bombino et al., 2007) were installed, more than 75% of the hydrographic network has
65 been treated. Guyassa et al. (2017) report extensive installation of check dams during
66 the last three decades in gullies of the Highlands of Northern Ethiopia as soil and water
67 conservation practices. In ephemeral channels of southeast Spain, check dams were
68 used to stabilize hillslopes by inducing deposition and forming flat sediment wedges

69 that reduce runoff slopes (Conesa Garcia and Garcia Lorenzo, 2010). In addition to their
70 use in soil conservation, check dams have been constructed in gullies to retain sediment
71 and form farmland in Loess Plateau in China (Xu et al., 2004).

72 Check dams, which are usually build to control water and sediment fluxes along stream
73 channels (e.g. Heede, 1978; Nyssen et al., 2004) also exert important effects on channel
74 morphology, bed sediment and vegetation (Conesa Garcia and Garcia Lorenzo, 2010;
75 Xu et al., 2004; Boix-Fayos et al. 2007; Zema et al., 2014; 2018). In the Mediterranean
76 environment of southern Italy, Bombino et al. (2009) showed the positive effects of
77 check dams on headwater mountain channels affecting both physical adjustments and
78 the extent and development of riparian vegetation. Boix-Fayos et al. (2007) evaluated
79 the effects of check dams on river channel morphology in Spain and found that after 30
80 years, most of the check dams lost much of their trap efficiency, and erosion of the
81 alluvial deposits upstream of check dam had begun. Xu et al. (2012) performed a series
82 of calculations to quantify the effects of conservation managements in terms of
83 retaining soil, water, and especially nutrients 50 years after implementation in a
84 representative catchment on the Loess Plateau (China). This research resulted in
85 recommendations of preferred conservation practice in the area. An evaluation of check
86 dams constructed in two small semi-arid watersheds in the south-western United States
87 revealed that check dam failures were minimal, however loss of sediment retention
88 capacity was rapid, within seven years, due to high sediment loads (Polyakov et al.,
89 2014; Nichols et al., 2016). Nyssen et al. (2004) reported that soils influenced the rate of
90 check dam failures with higher rates in areas with smectite-rich soils that are prone to
91 swelling. However, although check dams are widely used as a watershed management
92 tool, often in combination with complimentary engineering works, for enhancing
93 watershed and grade stabilization and their impacts have been investigated in various
94 ecosystems, information describing and quantifying the watershed factors affecting
95 check dam stability and efficacy is limited.

96 From the previous examples, it appears that after construction, one of the most
97 important features influencing the effectiveness of check dams on the watershed system
98 is their sediment storage capacity. Storage capacity is directly related to structural
99 condition, but the efficacy of check dams is also related to biotic and abiotic factors,
100 such as channel geometry, land use, soil type, and vegetation cover. In particular, the
101 scientific literature has evidenced the basic role of vegetative cover for an ecologically
102 sound regulation activity of rivers (e.g. Gurnell and Petts, 2002; 2006; Allmendinger e

103 al., 2005; Corenblit et al., 2007). In our study, we hypothesised that, vegetation cover
104 percentage and type may significantly influence sediment transfer and channel
105 deposition, which in turn affects check dam stability and failure. We expect that lower
106 vegetation cover will result in higher sediment transfers and thus the likelihood of stone
107 check dam failure will increase. Therefore, in view of an integrated management of
108 regulated watersheds, there is a need to investigate which of the factors mentioned
109 above are the most influencing on both the condition of check dam structures and their
110 ability to store sediment with particular stress on the role of the vegetation cover. This
111 information is important to maximize the likelihood of successful conservation works.
112 Failure to account for high intensity rainstorms, upstream areas with highly erodible
113 soils, absence of vegetation cover in the watershed, inadequate channel dimensions for a
114 check dams installation or steeped channels may generate high quantities of sediment
115 transfer and drawing attention to the risks posed by these structures as they fill with
116 sediment and deteriorate (Wang et al. 2009). Check dams failure and the sudden or
117 gradual erosion of previously deposited sediment can reintroduce large quantities of
118 sediment for subsequent transport (Brooks and Lawrence 1999).

119 To address these issues, a large regulated watershed in Mexico is presented as a case
120 study. Here, more than 250 check dams, recently built to slow runoff and retain
121 sediment, are intact, but many other structures have failed. A large dataset describing
122 the condition and functioning of the check dams was compiled and reported by Cruz
123 Hernandez et al. (2014). This dataset is combined with remotely sensed data to interpret
124 possible cause-effect relationships between sub-watershed characteristics and the
125 structural condition and functioning (in terms of sediment storage capacity) of the check
126 dams. Specifically, a combination of analytical techniques (stepwise regression,
127 redundancy analysis, increase-rate-analysis and correlation analysis) to the check dam
128 dataset collected in the watershed. The subsequent interpretation identifies and
129 quantifies the most influential watershed factors (channel dimensions, vegetation cover,
130 characteristics of the check dams and others) affecting both the structural condition and
131 functioning of check dams; finally, the role of the vegetation is focussed as a co-factor
132 synergetic with the actions of check dams towards ecologically sound regulation of the
133 studied river.

134
135

136 2. Materials and methods

137

138 2.1 Study area

139

140 This study was conducted in the Culiacan watershed in the state of Sinaloa, north-
141 western Mexico (latitude 24.867346°N, longitude -107.181013°W) (Figure 1). The
142 watershed, which covers 10368 km², drains into the Sinaloa reservoir at an elevation of
143 128 m after running 25.3 kilometres from the headwater. Topography ranges from
144 mountains to lower lying hilly areas and plains. Average annual precipitation is 860
145 mm, mostly occurring, together with the resulting surface runoff, during July, August
146 and September; winters are generally milder and in this season rainfall is less intense.
147 Mean annual temperatures are in the range 24-26 °C. Figure 2 reports the annual trends
148 of precipitation and mean temperature measured at the Culiacan meteorological station
149 during the period 1995-2015.

150 Main land uses are cropland (sorghum and corn), covering 44.2% of the total watershed
151 area, protective forest and grazing, 46.7% and 0.3% of the area, respectively. Typical
152 vegetation consists of medium-statured tropical forest (including semi-evergreen forest,
153 sub-deciduous forests, and riparian forests), Pinus-Quercus forest, spiny forest; gallery
154 forest (includes “selva mediana ribereña”), tropical dry forest (Pérez-García et al.,
155 2012). Geology is representative of Jurassic to Quaternary periods, while, according to
156 FAO (1988), soils of the study area can be classified as *Eutric regosols* and *haplic*
157 *Feozem*. The drainage patterns of the watershed are controlled by the low relief and
158 surface runoff resulting in a trellis pattern that has produced numerous ephemeral
159 channels. Artificial cut-offs or bank protection were not constructed to reduce lateral
160 migration.

161 In this watershed, small, temporary, stone check dams were constructed across swales
162 and drainage ditches (Figure 3 and 4). These structures were built to reduce flow
163 velocity and thereby potentially control the channel grade and mitigate channel erosion.
164 The maximum height of the stone check dams is 3 metres; to increase their stability, the
165 base of each check dam is embedded into the soil approximately at 1-meter depth. The
166 check dams were constructed to achieve complete cover of the channel and to assure
167 that the middle of the dam is lower than the edges. No large magnitude, low frequency
168 floods were recorded during the period of study (2011-2015). Figure 5 shows a general
169 map and the original/regulated longitudinal profile of four reaches containing the

170 staggered check dams, allowing the identification of the channel gradient changes
171 following the structure installation.

172

173 **2.2. Survey methods**

174

175 The studied stone check dams were regularly evaluated from 2011 to 2015 to assess
176 their effectiveness and impact on channel adjustments, sediment storage, and vegetation
177 dynamics. The structures were built as part of an "emergency" strategy aiming to retain
178 water and sediment fluxes generated by rainstorms on upstream areas with highly
179 erodible soils; thus it is expected that these control works start functioning immediately
180 after their installation and a short-term monitoring activity can assure these
181 requirements.

182 This study was carried out by using a combination of fieldwork and analysis of
183 remotely sensed data. Field surveys were made by Cruz Hernandez et al. (2014) to
184 analyse the operating condition of each check dam. During these surveys, structure
185 dimensions and both upstream and downstream channel morphology were quantified
186 through measurements (Figure 6) using standard topographic surveying equipment and
187 laser technology (measurements up to 75 m, accuracy ± 3 mm). Field data included both
188 categorical and continuous variables. Categorical data for the stone check dams were
189 *type* (gabion and stone check dams); *year of construction* (from 2011 to 2015, drawn
190 from check dam design or construction reports available at managing authorities);
191 *current operational condition* ("functional", i.e. operating as designed, "filled", by
192 sediment or "broken", that is, completely collapsed and thus not functioning); *location*
193 (low, between 59 and 104 m a.s.l., middle, 107 - 153 m, or upper watershed, 154 - 200
194 m); *structure* (gabions or unembedded stones). The continuous variables surveyed
195 include *check dam location* (X, Y UTM coordinates); *check dam dimensions* (length,
196 width and downstream height, in metres, see also Figure 6); *longitudinal slope of the*
197 *channel* (% , measured as the difference between the heights of the channel and check
198 dam divided by the channel length); *potential storage capacity* (m^3); *actual sediment*
199 *storage* (m^3); *ratio actual sediment storage/potential storage capacity* (%) (see below);
200 *channel dimensions* associated with each check dam (m). During topographic surveys,
201 the channel elevation was measured upstream of each check dam at a longitudinal step
202 of 5-10 metres, in order to define the longitudinal profile of the regulated channel. The
203 original channel profile was estimated from the last available digital terrain models

204 created before the check dam construction (resolution of 1x1 metres, years 2010-11) or,
205 when available, from the check dam designs. The two reconstructed longitudinal
206 profiles allowed reconstructing the sediment wedge dimensions and estimating the local
207 slope behind each check dam (Figures 5 and 6).

208 From the current (regulated) and the original longitudinal profiles close to the check
209 dams as well as from check dam dimensions, the potential storage capacity and actual
210 sediment storage were estimated assuming that the deposited sediment volume behind a
211 check dam has a prismatic shape with a trapezoidal section (Castillo et al., 2007;
212 Ramos-Diez et al., 2016a; 2016b; 2017a). The surveyed channel dimensions include
213 *upstream/downstream depth* (measured at the check dam location); *length*; *average*
214 *width* (measured every 5 metres starting immediately upstream of the check dam until
215 the check dam located immediately upstream or, for the first structure, the watershed
216 perimeter).

217 Remotely sensed data was used to quantify watershed characteristics such as vegetation
218 cover and soils. More in detail, *vegetation cover* of the sub-watershed (% of area,
219 estimated by maps produced by remotely sensed data); *soil type* and *land use* (forest or
220 crop, analysed separately for each of the sub-watershed in which the main basin was
221 discretised) for *each reach/sub-watershed* was derived from GIS analyses and satellite
222 images (Landsat 8 source data at 30-m resolution and Rapideye images at 5-m
223 resolution). Watershed morphometric information was delineated from DEM (at 1-m
224 resolution) which was firstly georeferenced and then processed by a GIS software. This
225 processing allowed identifying the hydrographic network and 273 sub-
226 watersheds/reaches (each one containing a check dam); more specifically, each check
227 dam was associated to a reach and considered its outlet: this latter drains a sub-
228 watershed (part of the entire watershed) conveying water to the reach. Check dams were
229 located on the watershed map according to their geographical coordinates drawn from
230 satellite images (where the structures were visible) or from the topographic survey.

231

232 **2.3. Analytical methods**

233

234 The collected data were processed by a combination of four analytical techniques: (i)
235 linear correlation analysis; (ii) stepwise regression analysis; (iii) redundancy analysis
236 (RDA); (iv) increase-rate-analysis (IRA). Firstly, in order to identify possible
237 mathematical structures among vegetation cover, sediment storage capacity and channel

238 dimensions and to determine the related correlation coefficients, the Spearman
239 correlation matrix was computed based on the current values of the variables surveyed
240 for the sampled check dams. Preliminarily, the indicators were standardised by
241 converting data to zero mean and unit variance.

242 Then, stepwise regression analysis was used to build an optimized mathematical model
243 relating the *response (dependent) variable* (in our case the current operational condition
244 of check dams) to the explanatory (independent) factors (the remaining categorical and
245 continuous variables). Stepwise regression is a type of multiple linear regression which
246 can choose the best-fitted combination of explanatory variables for response variable
247 predication with forward-adding and backward-deleting variables. The stepping
248 procedure begins as an initial model definition with a stepped forward addition of a
249 variable to the previous model. The critical F value is then used to check the eligibility
250 of the added variable. With a new variable added, the previous variables in the model
251 may lose their predictive ability. Thus, stepping criteria are used to check the
252 significance of all the included variables. Based on this situation, the significant
253 variables could be confirmed. While, if the variable is insignificant, then the backward
254 method is used to delete it. Forward adding and backward deleting are repeated until no
255 variable is added or removed. The stepping procedure is eliminated when the optimized
256 model is constructed. The stepping criteria were used to check the significance (at $p =$
257 0.05) of all the included variables. The procedure was stopped when the optimized
258 model was built and the maximum r^2 between *response variable* and explanatory factors
259 was achieved.

260 RDA was used with the main focus on the relationships between the check dam
261 conditions (functional, filled or broken) and those factors influencing it (selected by
262 stepwise regression). The check dam conditions were response variables in this analyses,
263 whereas the explanatory variables selected according to the stepwise regression belongs
264 to the three categories (check dams characteristics, check dam volume and channel
265 dimensions): therefore, the explanatory variables included the selected significant
266 variables that could represented each categories. In order to explore the factors affecting
267 check dam conditions comprehensively, the raw data were standardized before the RDA
268 analyses, and the significance of the variables was tested with Monte Carlo simulations.
269 All the above analyses were performed with R software version 3.2.0 (R Core Team
270 2013), with the main aim of a quantitative expression of the explanatory factors on
271 check dam conditions.

272 A revised IRA (Xu et al., 2015) was used to evaluate the variation in the ratio of the
 273 actual sediment storage (henceforth, ASS) to the potential storage capacity (PSC) of
 274 check dams, with respect to changes in the significant explanatory variables (considered
 275 as causal factors). This ratio (that is, ASS/PSC) is equal to the sediment filling degree
 276 (SFD, in %) of a check dam. Specifically, ASS is the volume (m³) of the actual
 277 sediment wedge behind a check dam, while PSC is the volume (m³) that the sediment
 278 wedge would have, if the check dam was entirely filled with sediments. Therefore, a
 279 filled check dam shows a SFD equal to 100% (ASS = PSC), for an empty structure SFD
 280 = 0, while a functional structure has a SFD between 0 and 100% (0 < ASS < PSC). In
 281 the first case, the check dam is not able to retain more sediment in the future, being its
 282 capacity completely depleted.

283 In order to carry out a sensitivity analysis, all dams were ordered according to the
 284 amount of potential storage capacity from the largest to the smallest. The difference in
 285 SFD between two successively ordered check dams (*i* and *i-1*), RP_i (%), was calculated
 286 as follows:

287

$$288 \quad RP_i = \frac{2(SFD_i - SFD_{i-1})}{SFD_i + SFD_{i-1}} \quad [1]$$

289

290 where P_i is the SFD (%) of the *i*-th check dam.

291 As reported in details by Xu et al. (2015), the Absolute Sensitivity Parameter (S), S_j ,
 292 towards an explanatory variable *t* is calculated by its mean growth rate:

293

$$294 \quad S_j = \overline{(RP_{i,j} / Rt_{i,j})}_{i=1,N} \quad [2]$$

295

296 being *j* the *j*-th explanatory variable, N the total number of check dams and:

297

$$298 \quad Rt_i = \frac{2(t_i - t_{i-1})}{t_i + t_{i-1}} \quad [3]$$

299

300 Rt_i is the increase rate calculated for two successively ordered check dams (*i* and *i-1*),
 301 where *t* is the value of the explanatory variable. Finally, the Relative Sensitivity

302 Parameter (s) of the j -th explanatory variable t_j , s_j , which can be used to qualitatively
303 evaluate the effect of the explanatory variable t on s was calculated as follows:

304

$$305 \quad s_j = \frac{S_j}{\min(S_j)_{j=1,M}} \quad [4]$$

306

307 where M is the total number of the explanatory variables.

308 In our study, we calculated the Absolute and Relative Sensitivity Parameters of SFD
309 (henceforth, S_{SFD} and s_{SFD}); as explanatory variables of S_{SFD} and s_{SFD} , vegetation cover,
310 longitudinal slope, channel depths (measured immediately from the downstream and the
311 upstream of a check dam) as well as length and width of the channel (equal to that of
312 the check dam) were considered.

313

314 **3. Results**

315

316 The results show that the potential storage capacity of the studied stone check dams
317 ranged from 0.5 to 493.5 m³, with a mean value of 51.5 m³. The actual volume of
318 sediment stored upstream of the check dams ranged from 0.2 to 237.6 m³ with a mean
319 value of 26.7 m³. The average width of the upstream sediment wedge was 6.5 m,
320 ranging from 2.4 to 22.5 m. The mean downstream depth of the stone check dams was
321 1.1 m, ranging to 0.1 to 1.9 m. Finally, the length of the sediment wedge stored
322 upstream ranged from 3.9 to 39.1 m, with a mean value of 13.8 m.

323 Of the 273 analysed check dams, 116 (43%) are operating as designed and thus
324 currently regulate water and sediment flows inside the watershed. They are classified as
325 *functional*. Seventy-four of the check dams (27%) show a compromised structure (that
326 is, they have lost their functionality, because they have collapsed) and they are
327 classified as *broken*; and 83 (30%) are classified as *filled*, showing thus a totally full
328 upstream wedge, and presumably the equilibrium channel slope has been reached. On
329 average, the functional check dams were filled to 45% of their storage capacity, and
330 thus have the capacity to retain additional sediment (Table 1).

331 The average longitudinal channel slope among all evaluated check dams was quite
332 similar (ranging from 6.53-7.68%). In general, channel profiles were steepest upstream
333 of filled check dams (7.68%) and shallower upstream of functional (6.66%) and broken
334 (6.53%) structures. The impact of sub-watershed vegetation cover in the immediate

335 vicinity of the investigated control works was clear. In sub-watersheds where the
336 vegetation cover is high (45-53%), fewer check dams were broken in comparison to
337 those check dams in sub-watersheds where vegetation cover was low (13%) (Table 1).

338 Results of the stepwise regression showed that six of the categorical and continuous
339 independent variables were significant in explaining the variability in check dam
340 condition ($p < 0.05$) (Table 2), and there was a strong association between these
341 selected variables and soil conditions ($r^2 = 0.96$). The six significant variables were
342 grouped into three categories: (i) check dam site characteristic, consisting only of
343 vegetation cover; (ii) sediment volume characteristics behind check dams, including
344 potential storage capacity and actual sediment storage; and (iii) channel dimension
345 characteristics, taking into account channel length as well as upstream depth and width
346 of the channel. Check dam condition was positively correlated with vegetation cover,
347 potential storage capacity, actual sediment storage, length and average width of the
348 sediment wedge; more specifically, check dam condition (explained by sediment
349 retention capacity) was positively correlated with vegetation cover. In contrast, a
350 negative relationship was found between check dam condition and depth of the
351 upstream channel.

352 The analysis of the Spearman matrix indicated high correlations (> 0.73) among pairs of
353 site, check dam and channel dimension variables. In more detail, the potential storage
354 capacity of the check dams was associated to the channel upstream depth ($r = 0.86$) and
355 the structure sediment storage ($r = 0.83$), with these latter variables also strictly linked
356 each other ($r = 0.73$). Also the channel downstream depth was strongly correlated ($r =$
357 0.98) to the mean channel width. Lower correlation levels (but always significant at $p <$
358 0.05) were detected among other variables, such as vegetation cover and sediment
359 filling degree ($r = 0.48$), potential storage capacity of the check dams and all channel
360 dimensions ($r > 0.47$), as well as couples of variables related to channel dimensions ($r >$
361 0.44) (Table 3).

362 RDA using the explanatory variables of the three categories (vegetation cover, sediment
363 storage volume, and channel characteristics) as influencing factors and check dam
364 condition as the response variable, quantitatively showed that vegetation cover and
365 channel dimensions explain 32.5 and 33.2% of the variability in check dam condition
366 respectively. In contrast, although sediment storage characteristics also showed
367 significantly influences on check dam conditions, the explanatory percentage was only
368 4.01%, thus much lower than the vegetation cover and channel dimensions.

369 The results of the sensitivity of the channel dimensions (average channel width, channel
370 length, downstream and upstream depth), longitudinal slope, and vegetation cover on
371 sediment potential store capacity performed by IRA are reported in Table 4. The larger
372 the sensitivity of an explanatory variable, the more prominently this variable influences
373 the sediment retention capacity. Channel depth downstream of the check dam was found
374 to be the most important influential variable as it is the most sensitivity parameter
375 (136.7). The relative sensitivity of channel depth upstream of the check dam and
376 vegetation cover are comparable to each other, although these variables are less
377 important than the channel depth downstream of the check dam (38.1 and 20.7,
378 respectively). Finally, the relative sensitivity of longitudinal slope, length and average
379 width of the channel are very low and negative.

380

381 **4. Discussion**

382

383 Check dams can be an effective tool for mitigating degradation provided that they are
384 maintained after construction. Check dam failure, which may be due to many factors,
385 can cause scour problems and release sediment into flow downstream. This is the case
386 of more than a half of the 273 stone check dams installed in the Culiacan watershed,
387 which were not operating as designed just 3-5 years after their construction, due to both
388 sedimentation and structural failure. As a matter of fact, among the structures analysed
389 in this case study, 27% of stone check dams were damaged by water and sediment
390 during runoff, while for 30% of the structures the sediment storage capacity was
391 practically depleted. In the first case, it is evident that the collapsed check dams are not
392 functioning as designed. In the second case, it is true that the check dams no longer
393 accumulate the solid material transported by runoff; however, these structures do
394 contribute to bed stabilisation (due to the longitudinal slope reduction) and flood
395 attenuation (because of the wider channel section).

396 The investigation revealed that longitudinal channel slope behind the surveyed check
397 dams is not noticeably different among filled, functional and broken structures. In
398 general we might expect to see variations in slope because where intact structures act as
399 a barrier against runoff and, when flow velocity is reduced, sediment accumulates
400 behind the check dam thus aggrading locally its profile (Bombino et al., 2008). This
401 unexpected result could be explained by the fact that in our check dams aggradation is
402 localized and proximate to the structure and channel measurements just limited to points

403 immediately behind a check dam where most of the sediment accumulates, but were
404 deliberately made at a distance upstream of the check dams. This choice was adopted
405 because we wanted to check whether the stabilising effects of a check dam on channel
406 profile is localised or extends upstream of the structure, that is, far from its direct
407 influence (as instead, revealed by Bombino et al., 2008, however in other environmental
408 contexts). Evidently, the profile survey highlights the overall stability of channel slope,
409 independent of check dam conditions.

410 Furthermore, higher vegetation cover is found in sub-watershed with functional and
411 filled check dams, thus confirming the positive effects of check dams on vegetation
412 development behind the structures, documented in other environments (e.g. Boix-Fayos
413 et al., 2007; Bombino et al., 2006; 2009; 2013). Vegetation helps channel stabilisation:
414 in-channel vegetation reduce water velocity and soil detachment, and in vegetated
415 hillslopes water and sediment supply to the channel decrease (Keesstra et al., 2108).

416 From this investigation it is clear that the potential storage capacity of functional check
417 dams is higher (by over 100%) than filled structures, and the functional structures are
418 located downstream of longer channels (supplying water and sediment) compared to
419 filled check dams; conversely, the channel profile upstream of the filled check dams is
420 steeper compared to functional structures. This finding (that is, longer channels
421 upstream of functional check dams) partially contrasts with the results of research
422 conducted by Li et al. (2007), who stated that check dams with a longer or steeper up-
423 gully have a low capacity to retain soil, because soil from the upper reaches is not easily
424 deposited by larger and more rapid flood events. In our study, the vegetation cover
425 associated with both filled and functional check dams (whose values are very similar)
426 likely limits soil particle detachment and transport thereby reducing the volume of
427 sediment available for deposition: for functional check dams this leads to a not already
428 depleted sediment storage capacity; filled check dams, also showing a well developed
429 vegetation cover, stores an actual sediment volume similar to functional check dams,
430 but their potential storage capacity has not depleted.

431 Broken check dams retained the capacity to store accumulated sediment (although lower
432 by about 70% than functional check dams). In particular, sediment was stored behind
433 non-broken side walls. The actual sediment storage is similar for functional and filled
434 check-dams, in spite of the higher length of the channel upstream of the latter. On
435 average, the ratio of actual to potential sediment storage of functional check dams (SFD)
436 is close to 50%, which should increase with time assuming the check dams continue to

437 function. In the Loess Plateau, Jiao et al (2003) concluded that the ratio of the soil
438 retained by a check dam to the total transported from the upper reaches ranged from
439 23.3% to 52.9%, and the ratio had a positive relationship with check dam height and a
440 negative relationship with the sub-watershed area above of the check dam.

441 The analysis of channel dimension characteristics grouped according to the current
442 operating condition of check dams shows better developed sediment wedges (higher
443 upstream depth, width and length) for functional check dams compared to filled
444 structures. As expected, larger structures stored greater volumes of sediments and
445 nevertheless the sediment storage capacity of these structures has not been fully
446 depleted. It is interesting to notice that downstream of broken check dams the channel
447 depth is higher compared to the other check dam conditions; evidently, in spite of the
448 lower upstream depth, the local scouring on the downstream side of broken structure is
449 high, due to the erosive power of the water stream. This phenomenon was observed
450 extensively for the broken check dams (more than 80%) through the presence of
451 destroyed stones at the sides of the channel that caused a decrease in cross section area.

452 The construction of multi-regression models between the check dam conditions and
453 factors (linked to site location, sediment storage and channel dimension characteristics)
454 highlights that only six of the potentially influencing variables considered have a
455 significant impact on check dam conditions. Moreover, of these six causal factors,
456 vegetation cover and channel dimensions were found to be the most influential ones
457 (see results of redundancy analysis, explaining more than 65% of the variability of the
458 check dam conditions). Overall, channel dimension was the most important factor
459 determining check dam condition, followed by vegetation cover.

460 The negative correlation between check dam condition and upstream channel depth
461 leads one to think that taller structures are most likely to be exposed to failure risk,
462 because of the soil bank strains behind check dams of non-embedded building material.
463 Conversely, sediment wedges behind check dams with lower height, but with overall
464 larger widths lengths appear to be more stable, given comparable retained sediment
465 volumes. Finally, the actual sediment storage appears to be the most influential variable
466 on check dam conditions.

467 It has been highlighted in the literature (e.g. Conesa Garcìa and Garcia Lorenzo, 2010;
468 Ramos-Diez et al., 2017b) that a large number of factors influence sediment storage
469 capacity behind check dams. This study showed that, within the Culiacan watershed,
470 sediment retention of check dams is related to both the downstream and upstream

471 depths of the structure and thus the height of the check dam is important. This result is
472 expected because the structures with greater height are associated with two predominant
473 processes: (i) local scouring downstream of the check dam, which increases and thus
474 mobilises more sediment to be transported downstream; (ii) aggradation of channel bed
475 upstream of check dam, forming long and wide sediment wedges, in which large
476 volumes of sediment are stored during flooding events. However, in our study, the
477 sensitivity analysis has highlighted that the magnitude of the second process is
478 noticeably lower than scouring action downstream, as shown by the values of S_{SFD}
479 (136.7 for downstream depth against 38.1 for upstream height of the check dam).
480 Moreover, the performed analysis confirms the importance of vegetation cover on
481 reducing sediment loads and thus extending the life of check dams by retaining potential
482 storage capacity. As a matter of fact, in areas with low vegetation cover (both in the
483 channel and in the hillslopes) the channel bed surface remains exposed to stream
484 erosion, which mobilises sediments along the reach (as reported above). Finally, the
485 other factors analysed (channel profile slope, length and width) were found to affect by
486 a much lesser extent potential storage capacity, except for channel depth measured
487 upstream of check dams (thus confirming the influence of sediment storage). This also
488 implies that a smaller increase in the above conditions will result in a smaller decrease
489 of the potential storage capacity.

490 Although the lack of influence of channel profile slope on potential storage capacity
491 may be explained by its low variability mentioned above, the substantial independence
492 of potential storage capacity on channel length and width is less expected. From a
493 deeper analysis of morphological data of the individual check dams, we noticed that for
494 the majority of the structures channel length and width do not follow a corresponding
495 trend; in other words, often-wider check dams are not associated to longer reaches,
496 which leads to a substantial balance between these explanatory variables. The results of
497 our study are in contrast with findings of Zema et al. (2014), who found that the ability
498 to retain sediment and channel local scouring downstream is linked. However, it should
499 be noted that in the Zema et al. (2014) study, structure spacing, geomorphic conditions,
500 and hydrologic regime were different than our study.

501 This research confirms that it is necessary to apply an integrated approach to solve the
502 problems of watershed soil conservation, since the factors governing the related
503 processes - in particular in streams regulated by check dams - are numerous and of
504 different origin. The use of check dams can be definitely useful when the sediment

505 source is located close to or in the channel (e.g. in-channel sediment supply, channel
506 incision, bank erosion, armour layer removal, etc.). However, where installation of
507 check dams alone can not mitigate watershed soil degradation (particularly in hillslopes
508 with bare soil), it is necessary to reduce sediments at the sources, preferably by
509 enhancing the establishment of a structured and extended vegetation cover; as a matter
510 of fact, the study has demonstrated that vegetation cover can be a prerequisite for good
511 conditions and functioning of check dams. Overall, soil conservation and flood risk
512 mitigation at watershed scale must be addressed by a rational and integrated
513 combination of in-channel (such as check dams) and extensive (for instance,
514 afforestation and terracing) actions.

515

516 **5. Conclusions**

517

518 A quantitative analysis to understand the relation between sub-watershed characteristics
519 (vegetation cover, sediment storage capacity and channel dimensions) and check dam
520 conditions and effectiveness was carried out in a large Mexican watershed. In this
521 regulated watershed 273 stone control structures were recently built; the factors mostly
522 influencing their functioning and conservation - with particular regard to vegetation
523 cover - were surveyed and analysed using a combination of four analytical techniques.
524 This study showed that the failure of check dams was associated with low vegetation
525 cover; conversely, with a well developed vegetation cover the majority of check dams
526 were functional or filled, in both cases not broken. Multi-regression models showed
527 that, under the specific environmental conditions, vegetation cover and channel
528 dimensions explain together more than 65% of the variability of the check dam
529 conditions. Overall, channel dimension is the most important factor determining check
530 dam condition, but a basic role is played also by vegetation cover, since this ecological
531 factor is important for potential storage capacity. Taller structures are most likely to be
532 exposed to failure risk, while check dams with lower height, but with well-developed
533 sediment wedges and large vegetation cover, are more stable. A sensitivity analysis
534 showed strong dependence of potential sediment storage capacity of the check dams -
535 and therefore of their ability to retain sediment circulating in the watershed - on
536 downstream depth of the structure. However, also upstream height of check dams and
537 vegetation cover of the drained sub-watershed are factors with a considerable influence
538 on sediment retention processes acting behind the stone structures.

539 Overall, this study has provided a quantitative identification of the most important
540 factors affecting the structural condition of check dams and their ability to store
541 sediment, highlighting channel characteristics, dimensions of check dams and
542 vegetation cover as dominant factors. One must pay attention to these factors in
543 developing the best strategies for soil conservation at the watershed scale; the role of
544 vegetation is clear and it definitely helps for a ecologically sound management and
545 functioning of watersheds. These findings suggest that managers: (i) consider with
546 caution the installation of control works (such as stone or rock check dams) in sub-
547 watershed with low vegetation cover and highly erodible soils, since here the high
548 sediment transfer rates may increase the structure failure likelihood; (ii) adopt a larger
549 number of small structures rather than controlling the evolution of the channel
550 longitudinal profile by large-sized check dams, since taller structures are most likely to
551 be exposed to failure risk, thus losing much of their functioning.

552

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554

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561

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740 performance of check-dams in mitigation of soil erosion in Jiangjia stream, China.
741 Environ. Geol. 58, 897–911.

742 Table 1 - Site characteristics, sediment storage and channel dimensions for 273 check dams surveyed in the Culiacan watershed (Mexico).

743

744

Check dam condition (number)	Site characteristics		Check dams			Channel dimensions			Average width of the sediment wedge (m)
	Longitudinal slope (%)	Vegetation cover (%)	Potential storage capacity (m ³)	Actual sediment storage (m ³)	Sediment Filling Degree* (%)	Length (m)	Downstream** depth (m)	Upstream** depth (m)	
<i>Functional</i> (116)	6.66±0.57	45±2	77.54±7.44	35.78±4.04,	45±0.01	15.47±0.73	1.14±0.02	0.51±0.02	6.93±0.29
<i>Filled</i> (83)	7.68±0.76	53±3	37.64	37.64	100	11.15±0.85	0.99±0.03	0.36±0.02	5.49±0.28
<i>Broken</i> (74)	6.53±0.60	13±3	25.47±8.67	-	-	14.62±0.97	1.24±0.05	0.15±0.04	8.54±0.56

745 * ratio of actual sediment storage to potential storage capacity; ** measured immediately close to the check dams.

746

747 Table 2 - Best-fit combination of explanatory variables for check dam conditions as
 748 response variable using stepwise regression analysis applied to check dam data in
 749 Culiacan watershed (Mexico).

750

Explanatory variables	Estimate	Std. Error	F-value	Pr(> t)
Vegetation cover	0.070	0.030	30.34	<0.001
Potential storage capacity	0.001	0.000	2.06	0.04
Actual sediment storage	1.760	0.030	3.19	0.002
Channel length	0.010	0.010	66.14	<0.001
Upstream channel depth	-1.110	0.060	-19.84	<0.001
Average channel width	0.070	0.010	10.49	<0.001

751

752 Table 3 - Spearman's correlation matrix among variables measured close to 273 check dams in Culiacan watershed (Mexico).

753

Variable		Site characteristics		Check dams			Channel dimensions			
		<i>Longitudinal slope</i>	<i>Vegetation cover</i>	<i>Potential storage capacity</i>	<i>Actual sediment storage</i>	<i>Sediment Filling Degree</i>	<i>Length</i>	<i>Downstream depth</i>	<i>Upstream depth</i>	<i>Average width of the sediment wedge</i>
Site characteristics	<i>Longitudinal slope</i>	1	-0.024	0.025	-0.039	0.027	-0.020	-0.041	-0.037	-0.050
	<i>Vegetation cover</i>		1	0.209	0.343	0.484	-0.199	-0.138	0.264	-0.170
Check dams	<i>Potential storage capacity</i>			1	0.826	0.281	0.512	0.552	0.860	0.468
	<i>Actual sediment storage</i>				1	0.586	0.359	0.375	0.734	0.301
	<i>Sediment Filling Degree</i>					1	-0.200	-0.157	0.380	-0.193
Channel dimensions	<i>Length</i>						1	0.534	0.231	0.530
	<i>Downstream depth</i>							1	0.442	0.977
	<i>Upstream depth</i>								1	0.378
	<i>Average width of the sediment wedge</i>									1

754 Table 4 - Sensitivity analysis of site characteristics and channel dimensions
 755 (explanatory variables, ordered by SFD) on sediment retention of check dams in the
 756 Culiacan watershed (Mexico).

757

Parameter	Explanatory variables					
	<i>Downstream depth</i>	<i>Upstream depth</i>	<i>Vegetation cover</i>	<i>Longitudinal slope</i>	<i>Channel length</i>	<i>Average channel width</i>
<i>Absolute Sensitivity (S_{SFD})</i>	1.0056	0.2802	0.1525	-0.0377	-0.0107	-0.0074
<i>Relative Sensitivity (S_{SFD})</i>	136.7	38.1	20.7	-5.1	-1.5	-1.0

758

759 **Figure captions**

760

761 Figure 1. Geographic location of the stone check dams investigated in the Culiacan
762 watershed (Mexico).

763

764 Figure 2 - Annual trends (mean \pm std. dev.) of precipitation and mean temperature
765 measured at the meteorological station of Culiacan in the period 1995-2015.

766

767 Figure 3. Stone check dam failure (broken) in the Culiacan watershed (Mexico).

768

769 Figure 4. A working gabion check dam in the Culiacan watershed (Mexico).

770

771 Figure 5. Map (a) as well as longitudinal original and regulated profiles (b) of four
772 check dam staggered series in the Culiacan watershed (Mexico).

773

774 Figure 6. Annotated schematic showing side and oblique views of a typical stone check
775 dam in the Culiacan watershed (Mexico).

Figure 1
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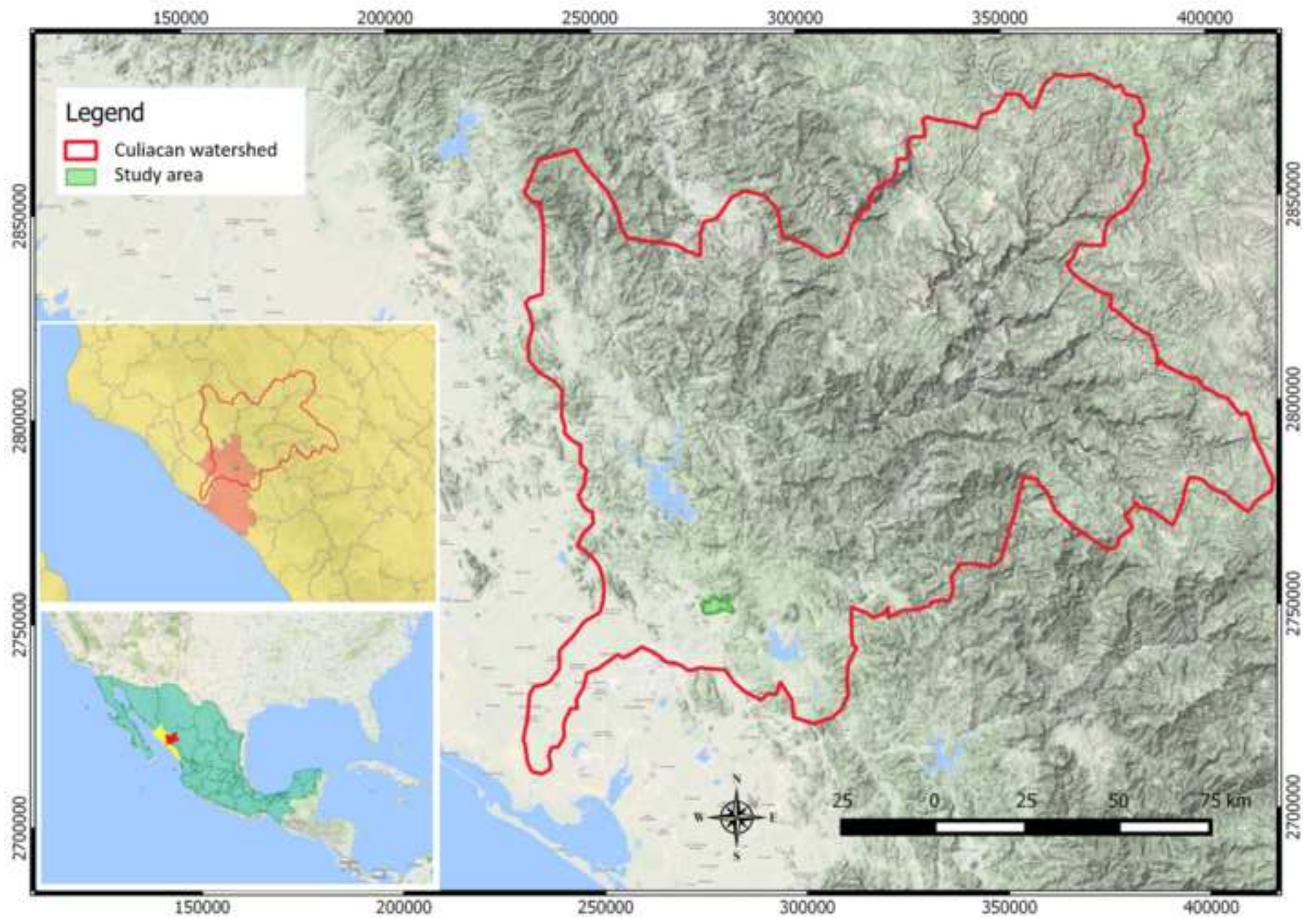


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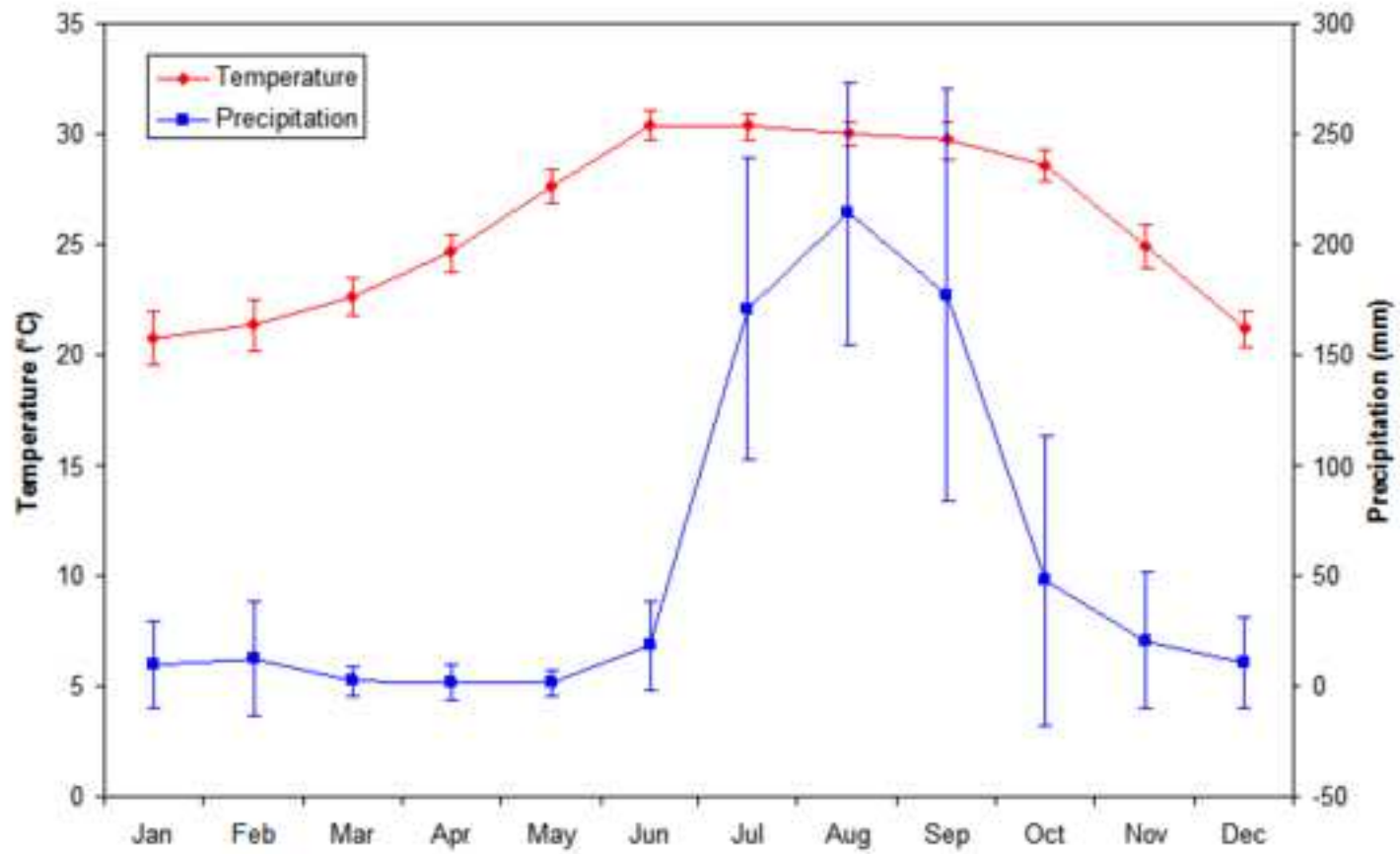


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Figure 5 a

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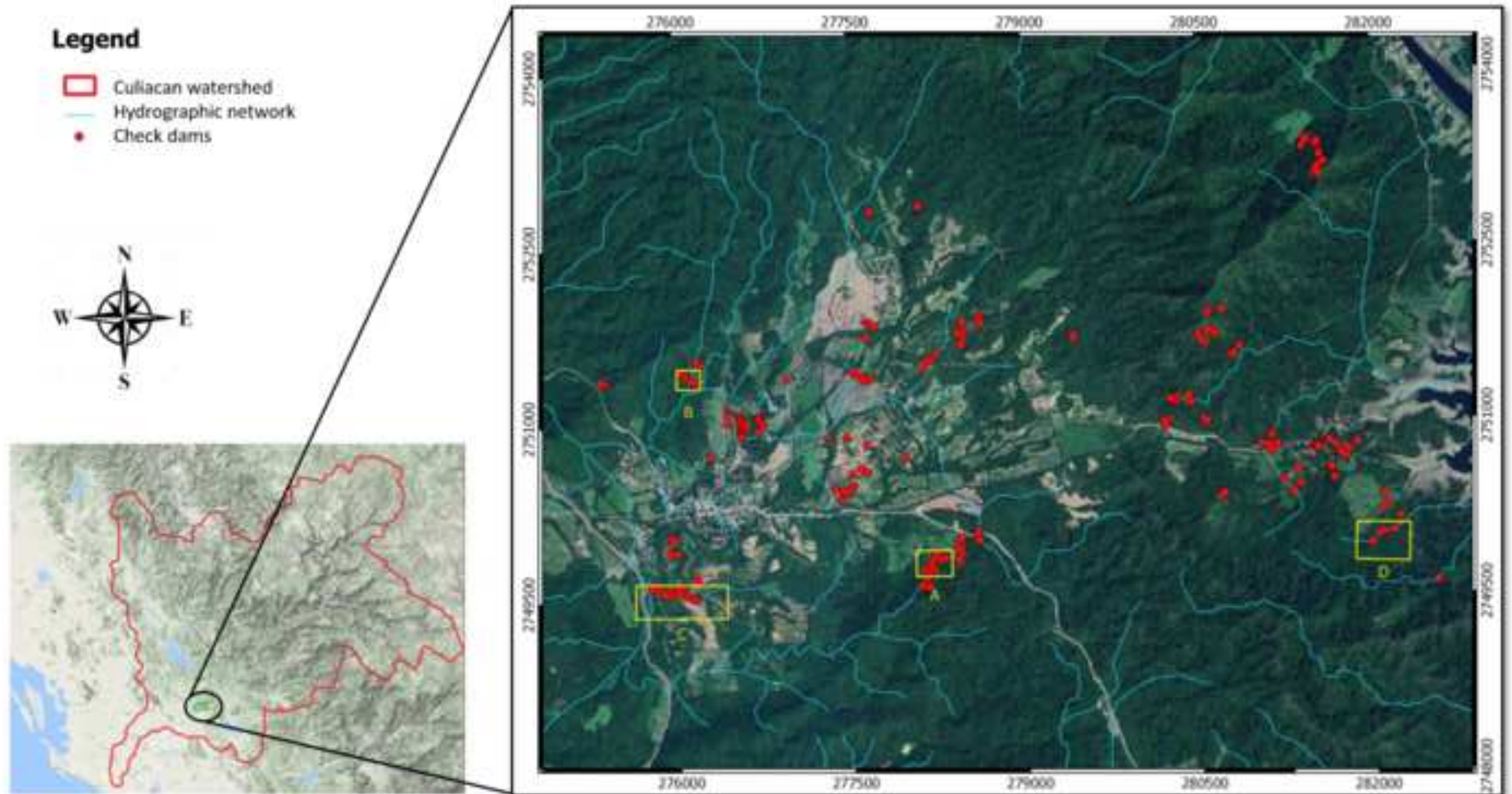


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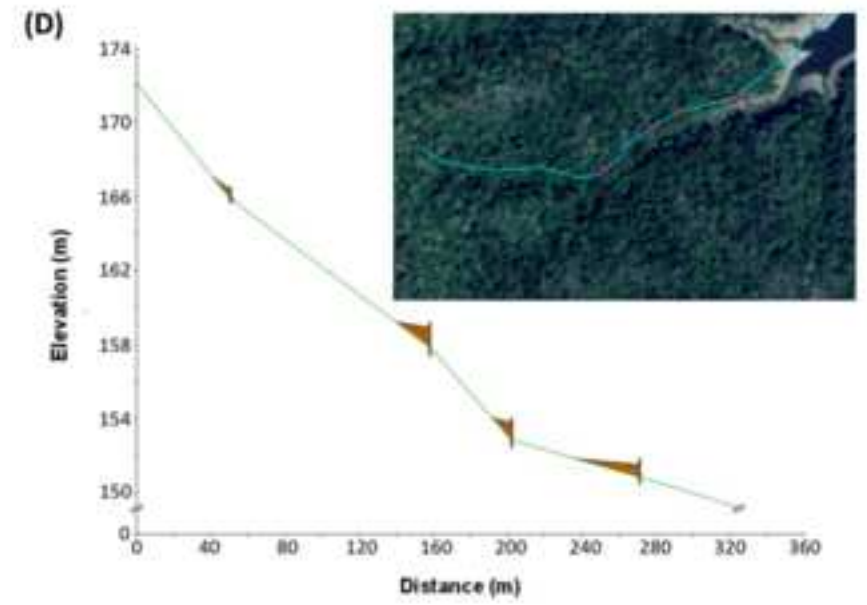
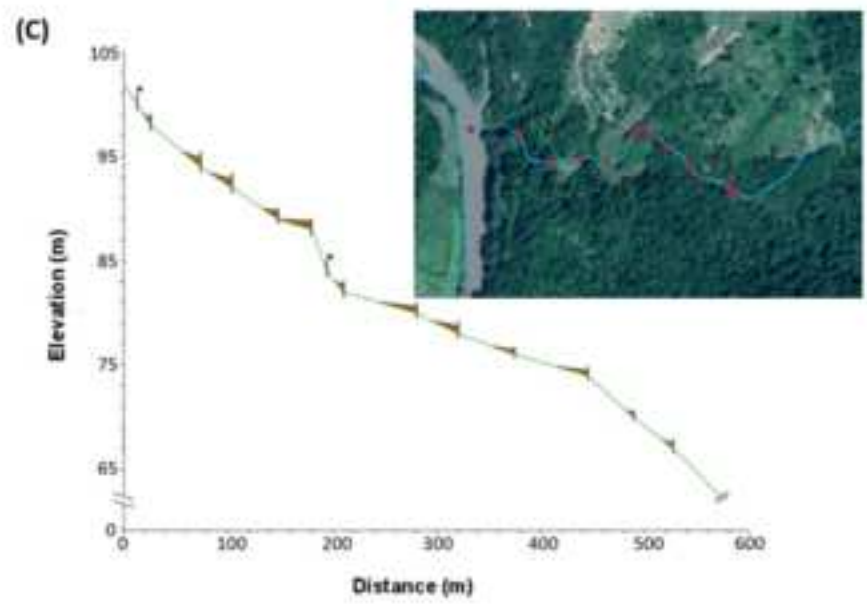
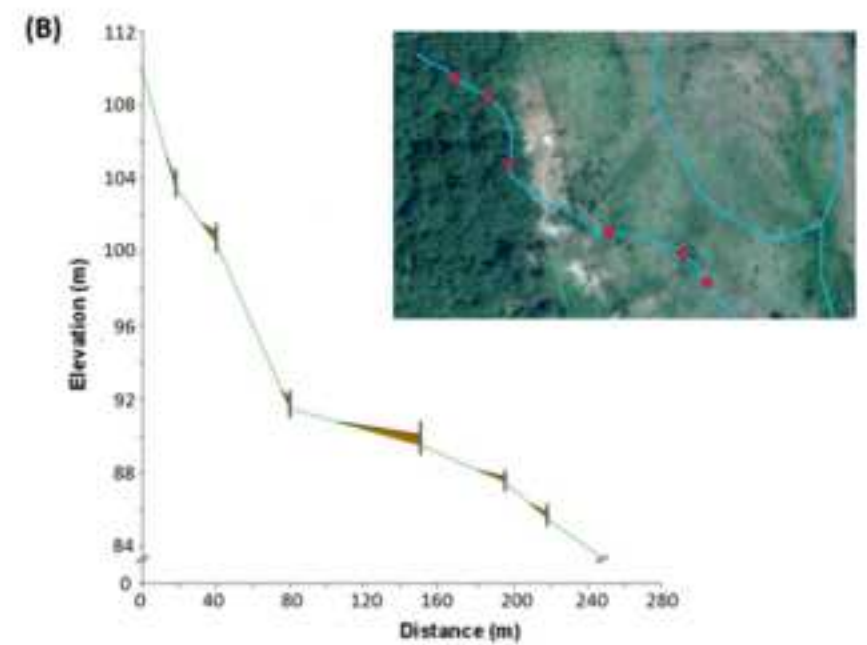
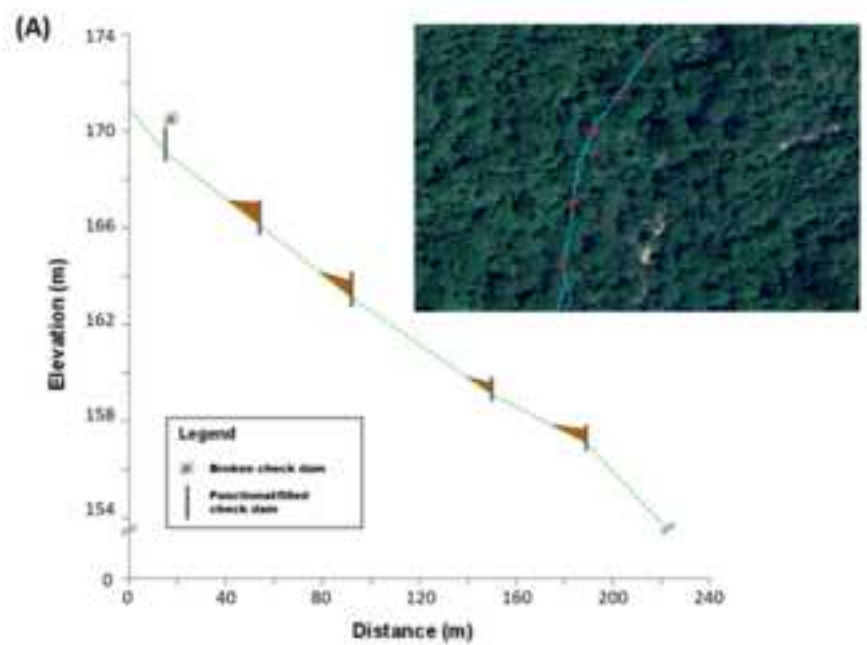


Figure 6

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