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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* (m³); *actual sediment*
199 *storage* (m³); *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

562 **References**

563

564 Allmendinger, N.E., Pizzuto, J.E., Potter, N., Johnson, T.E., Hession, W.C., 2005. The
565 influence of riparian vegetation on stream width, eastern Pennsylvania, USA. *Geol. Soc.
566 Am. Bull.* 117, 229–243.

567 Balooni, K., Kalro, A.H., Kamalamma, A.G., 2008. Community initiatives in building
568 and managing temporary check-dams across seasonal streams for water harvesting in
569 South India. *Agr. Water Manage.* 95, 1314–1322.

570 Boix-Fayos, C., Barberá, G.G., López-Bermúdez, F., Castillo, V.M., 2007. Effects of
571 check dams, reforestation and land-use changes on river channel morphology: case
572 study of the Rogativa catchment (Murcia, Spain). *Geomorphology* 91, 103–123.

573 Bombino, G., Tamburino, V., Zimbone, S.M., 2006. Assessment of the effects of check-
574 dams on riparian vegetation in the Mediterranean environment: A methodological
575 approach and example application. *Ecol. Eng.* 27, 134–144.

576 Bombino, G., Boix-Fayos, C., Gurnell, A.M., Tamburino, V., Zema, D.A., Zimbone,
577 S.M., 2014. Check dam influence on vegetation species diversity in mountain torrents
578 of the Mediterranean environment. *Ecohydrology* 7, 678–691.

579 Bombino, G., Gurnell, A.M., Tamburino, V., Zema, D.A., Zimbone, S.M., 2009.
580 Adjustments in channel form, sediment calibre and vegetation around check dams in the
581 headwater reaches of mountain torrents, Calabria, Italy. *Earth Surf. Proc. Land.* 34,
582 1011-1021. ISSN: 0197–9337.

583 Bombino, G., Gurnell, A.M., Tamburino, V., Zema, D.A., Zimbone, S.M., 2007. A
584 method for assessing channelization effects on riparian vegetation in a Mediterranean
585 environment. *River Res. Appl.* 23, 613–630.

586 Bombino, G., Gurnell, A.M., Tamburino, V., Zema, D.A., Zimbone, S.M., 2008.
587 Sediment size variation in torrents with check dams: effects on riparian vegetation.
588 *Ecol. Eng.* 32, 166–177.

589 Castillo, V.M., Mosch, W.M., García, C.C., Barberá, G.G., Cano, J.N., López-
590 Bermúdez, F., 2007. Effectiveness and geomorphological impacts of check dams for
591 soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain).
592 *Catena* 70, 416–427.

593 Brooks, G.R. and Lawrence, D.E., 1999. The drainage of the Lake reservoir and
594 downstream geomorphic impacts along River, Saguenay area, Quebec, Canada.
595 *Geomorphology* 28,141–168.

596 Cerdà, A., Keesstra, S.D., Rodrigo-Comino, J., Novara, A., Pereira, P., Brevik, E.,
597 Gimenez-Morera, A., Fernandez-Raga, M., Pulido, M., Proma, D.S., Jordán, A., 2017.
598 Runoff initiation, soil detachment and connectivity are enhanced as a consequence of
599 vineyards plantations. *J. Environ. Manage.* DOI:10.1016/ j.jenvman.2017.07.036.

600 Conesa, G.C., García, L.R., 2010. Bed scouring-sedimentation balance induced by
601 check dams in semi-arid catchments with different lithology. In *Check dams,*
602 *morphological adjustments and erosion control in torrential streams*, ed. C. Conesa-
603 García and M.A. Lenzi Nova Science Publishers. New York, 283–306.

604 Corenblit, D., Tabacchi, E., Steiger, J., Gurnell, A.M., 2007. Reciprocal interactions and
605 adjustments between fluvial landforms and vegetation dynamics: a review of
606 complementary approaches. *Earth Science Reviews* 84, 56–86.

607 Cruz, H.A., Hinojosa Guzmán, M.D., Izquierdo Marín, O., 2014. Evaluación de Obras
608 De Retención De Azolves En El Área De Influencia De La Presa “Sanalona”, En El
609 Ejido De Imala, Municipio De Culiacán. Informe Final. Fábricas de agua del centro de
610 Sinaloa, Universidad Autónoma Chapingo, Chapingo, México.

611 Doolittle, W.E., 1985. The use of check dams for protecting downstream agricultural
612 lands in the prehistoric Southwest: a contextual analysis. *J. Anthropol. Res.* 41, 279–
613 305.

614 Dhital, Y.P., Kayastha, R.B., Shi, J., 2013. Soil bioengineering application and practices
615 in Nepal. *Environ. Manage.* 51, 354–364.

616 Fernández-Raga, M., Palencia, C., Keesstra, S., Jordán, A., Fraile, R., Angulo-Martínez,
617 M. and Cerdà, A., 2017. Splash erosion: A review with unanswered questions. *Earth-
618 Sci. Rev.* 171, 463–477.

619 Food and Agriculture Organization of the United Nations/United Nations Educational,
620 Scientific and Cultural Organization (FAO/UNESCO). 1988. Soil Map of the World.
621 Revised Legend. World Soil Resources Report 60. Rome, Italy.

622 Fujieda, M., Kudoha, T., Cicco, V., Calvarcho, J.L., 1997. Hydrological processes at
623 two subtropical forest catchments: the Serra do Mar, São Paulo, Brazil. *J. Hydrol.* 196,
624 26–46.

625 Giménez-Morera, A., Ruiz-Sinoga, J.D., Cerdà, A., 2010. The impact of cotton
626 geotextiles on soil and water losses from mediterranean rainfed agricultural land. *Land
627 Degrad. Dev.* 21, 210–217.

628 Gurnell, A.M., Petts, G.E., 2002. Island-dominated landscapes of large floodplain
629 rivers, a European perspective. *Freshwater Biol.* 47, 581–600.

630 Gurnell, A.M., Petts, G.E., 2006. Trees as riparian engineers: the Tagliamento River,
631 Italy. *Earth Surf. Proc. Land.* 31, 1558–1574.

632 Guyassa, E., Frankl, A., Zenebe, A., Poesen, J., Nyssen, J., 2017. Effects of check dam
633 on runoff characteristics along gully reaches, the case of Northern Ethiopia. *J. Hydrol.*
634 545, 299–309

635 Hassanli, A.M., Nameghi, A.E., Beecham, S., 2009. Evaluation of the effect of porous
636 check dam location on fine sediment retention (a case study). *Environ. Monit. Assess.*
637 152, 319–326.

638 Heede, B.H., 1978. Designing gully control systems for eroding watersheds. *Environ.
639 Manage.* 2, 509–522

640 Keesstra, S.D., Bouma, J., Wallinga, J., Tiftonell, P., Smith, P., Cerdà, A.,
641 Montanarella, L., Quinton, J.N., Pachepsky, Y. van der Putten, W.H., Bardgett, R.D.,
642 Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O., 2016. The significance of soils and
643 soil science towards realization of the United Nations Sustainable Development Goals.
644 *Soil* 2, 111–128.

645 Keesstra, S., Pereira, P., Novara, A., Brevik, E.C., Azorin-Molina, C., Parras-Alcántara,
646 L., Jordán, A., Cerdà, A., 2016. Effects of soil management techniques on soil water
647 erosion in apricot orchards. *Sci. Total Environ.* 551, 357–366.

648 Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A.,
649 2018. The superior effect of nature based solutions in land management for enhancing
650 ecosystem services. *Sci. Total Environ.* 610, 997–1009.

651 Lenzi, M.A., Comiti, F., 2003. Local scouring and morphological adjustments in steep
652 channels with check-dam sequences. *Geomorphology* 55, 97–109.

653 Masselink, R.J., Heckmann, T., Temme, A.J., Anders, N.S., Gooren, H., Keesstra, S.D.,
654 2017. A network theory approach for a better understanding of overland flow
655 connectivity. *Hydrol. Process.* 31, 207–220.

656 Marmontel, C.V.F., Lucas-Borja, M.E., Rodrigues V.A., Zema D.A., 2018. Effects of
657 land use and sampling distance on water quality in tropical headwater springs (Pimenta
658 creek, São Paulo State, Brazil). *Sci. Total Environ.* 622, 690-701.

659 Li, G.X., Li, Z.B., Wei, X., 2007. Two key physical characteristics indexes of farmland
660 sediment for check dams in Loess Plateau. *Res. Soil Water Conser.* 14, 218–221.(In
661 Chinese)

662 Mekonnen, M., Keesstra, S.D., Stroosnijder, L., Baartman, J.E.M., Maroulis, J., 2015.
663 Soil conservation through sediment trapping: A review. *Land Degrad. Dev.* 26, 544–
664 556.

665 Mol, G and Keesstra, S.D., 2012. Soil science in a changing world. *Curr. Opin. Env.*
666 *Sust.* 4, 473–477.

667 Nichols, M.H., Polyakov, V., Nearing, M.A., Hernandez, M., 2016. Semiarid watershed
668 response to low-tech porous rock check dams. *Soil Sci.* 181, 275–282.

669 Novara, A., Keesstra, S., Cerdà, A., Pereira, P., Gristina, L., 2016. Understanding the
670 role of soil erosion on CO₂-C loss using ¹³C isotopic signatures in abandoned
671 Mediterranean agricultural land. *Sci. Total Environ.* 550, 330–336.

672 Novara, A., Gristina, L., Saladino, S.S., Santoro, A., Cerdà, A., 2011. Soil erosion
673 assessment on tillage and alternative soil managements in a Sicilian vineyard. *Soil Till.*
674 *Res.* 117, 140–147.

675 Nyssen, J., Veyret-Picot, M., Poesen, J., Moeyersons, J., Haile, M., Deckers, J., Govers,
676 G., 2004. The effectiveness of loose rock check dams for gully control in Tigray,
677 northern Ethiopia. *Soil Use Manage.* 20, 55–64

678 Parras-Alcántara, L., Lozano-García, B., Brevik, E.C., Cerdá, A., 2015. Soil Organic
679 Carbon Stocks Assessment in Mediterranean Natural Areas: A Comparison of Entire
680 Soil Profiles and Soil Control Sections. *J. Environ. Manage.* 155, 219–228.

681 Pérez-García, Eduardo, A.; Meave, Jorge, A.; Cevallos-Ferriz, Sergio, R. S., 2012. Flora
682 and vegetation of the seasonally dry tropics in Mexico: origin and biogeographical
683 implications. *Acta Botánica Mexicana*, 100, 149-193.

684 Poepl, R.E., Keesstra, S.D., Maroulis, J., 2017. A conceptual connectivity framework
685 for understanding geomorphic change in human-impacted fluvial systems.
686 *Geomorphology* 277, 237–250.

687 Porto, P., and J. Gessler. 1999. Ultimate bed slope in calabrian streams upstream of
688 check dams: Field study. *J. Hydraul Eng-ASCE.* 125,1231-1242.

689 Polyakov, V., Nichols, M., McClaran, M., Nearing, M.A., 2014. Effect of check dams
690 on runoff, sediment yield and retention on small semi-arid watersheds. *J. Soil Water*
691 *Conserv.* 69, 414–421.

692 Porto, P. and Gessler, J., 1999. Ultimate bed slope in Calabrian streams upstream of
693 check dams: field study. *J. Hydraul Eng-ASCE.* 125, 1231–1242.

694 Prosdocimi, M., Jordán, A., Tarolli, P., Keesstra, S., Novara, A., Cerdà, A., 2016. The
695 immediate effectiveness of barley straw mulch in reducing soil erodibility and surface
696 runoff generation in Mediterranean Vineyards. *Sci. Total Environ.* 547, 323–330.

697 Prosdocimi, M., Jordán, A., Tarolli, P., 2016. Soil water erosion on Mediterranean
698 vineyards: A review. *Catena* 141, 1–21.

699 Quiñonero-Rubio, J.M., Nadeu, E., Boix-Fayos, C., de Vente, J., 2016. Evaluation of
700 the effectiveness of forest restoration and check-dams to reduce catchment sediment
701 yield. *Land Degrad. Dev.* 27, 1018–1031,

702 Ramos-Diez, I., Navarro-Hevia, J., Fernández, R.S.M., Díaz-Gutiérrez, V., Mongil-
703 Manso, J., 2016a. Analysis of methods to determine the sediment retained by check
704 dams and to estimate erosion rates in badlands. *Environ. Monit. Assess.* 188, 1–14.

705 Ramos-Diez, I., Navarro-Hevia, J., Fernández, R.S.M., Díaz-Gutiérrez, V., Mongil-
706 Manso, J., 2016b. Geometric models for measuring sediment wedge volume in retention
707 check dams. *Water Environ. J.* 30, 119–127.

708 Ramos-Diez, I., Navarro-Hevia, J., Fernández, R.S.M., Díaz-Gutiérrez, V., Mongil-
709 Manso, J., 2017a. Evaluating methods to quantify sediment volumes trapped behind
710 check dams, Saldaña badlands (Spain). *Int. J. Sediment Res.* 32, 1–11.

711 Ramos-Diez, I., Navarro-Hevia, J., Fernández, R.S.M., Díaz-Gutiérrez, V., Mongil-
712 Manso, J., 2017b. Final analysis of the accuracy and precision of methods to calculate
713 the sediment retained by check dams. *Land Degrad. Dev.* DOI: 10.1002/ldr.2778.

714 Rodrigo-Comino, J.R., Quiquerez, A., Follain, S., Raclot, D., Le Bissonnais, Y., Casalí,
715 J., Pereira, P., 2016. Soil erosion in sloping vineyards assessed by using botanical
716 indicators and sediment collectors in the Ruwer-Mosel valley. *Agr. Ecosyst. Environ.*
717 233, 158–170.

718 Romero-Díaz, A., Alonso-Sarriá, F., Martínez-Lloris, M., 2007. Erosion rates obtained
719 from check-dam sedimentation (SE Spain). A multi-method comparison. *Catena* 71,
720 172–178.

721 Wang, H.W., Shih, S.S., Yang, S.C., 2009. Where will all the sediments go?
722 Impressions from Balin Dam Failure in Taiwan. In: *The 4th International Yellow River*
723 *Forum*, October 20–23, 2009, Zhengzhou, China.

724 Xu, X.Z., Zhang, H.W., Zhang, O.Y., 2004. Development of check-dam systems in
725 gullies on the Loess Plateau, China. *Environ. Sci. Policy* 7, 79–86.

726 Xu, X.Z., Liu, Z.Y., Xiao, P.Q., Guo, W.Z., Zhang, H.W., Zhao, C., Yan, Q., 2015.
727 Gravity erosion on the steep loess slope: Behavior, trigger and sensitivity, *Catena* 135,
728 231–239.

729 Xu, X.Z., Li, M.J., Liu, B., Kuang, S.F., Xu, S.G., 2012. Quantifying the effects of
730 conservation practices on soil, water, and nutrients in the Loess Mesa Ravine Region of
731 the Loess Plateau, China. *Environ. Manag.* 49, 1092–1102

732 Zema, D.A., Bombino, G., Boix-Fayos, C., Zimbone, S.M., Fortugno, D., 2014.
733 Evaluation and modelling of erosion and sedimentation around check dams in a
734 Mediterranean torrent (Calabria, Southern Italy). *J. Soil Water Conserv.* 69, 316–329.

735 Zema, D.A., Bombino, G., Denisi, P., Lucas-Borja, M. E., Zimbone, S.M., 2018.
736 Evaluating the effects of check dams on channel geometry, bed sediment size and
737 riparian vegetation in Mediterranean mountain torrents. *Science of The Total*
738 *Environment* 642, 327-340.

739 Zeng, Q.L., Yue, Z.Q., Yang, Z.F., Zhang, X.J., 2009. A case study of long-term field
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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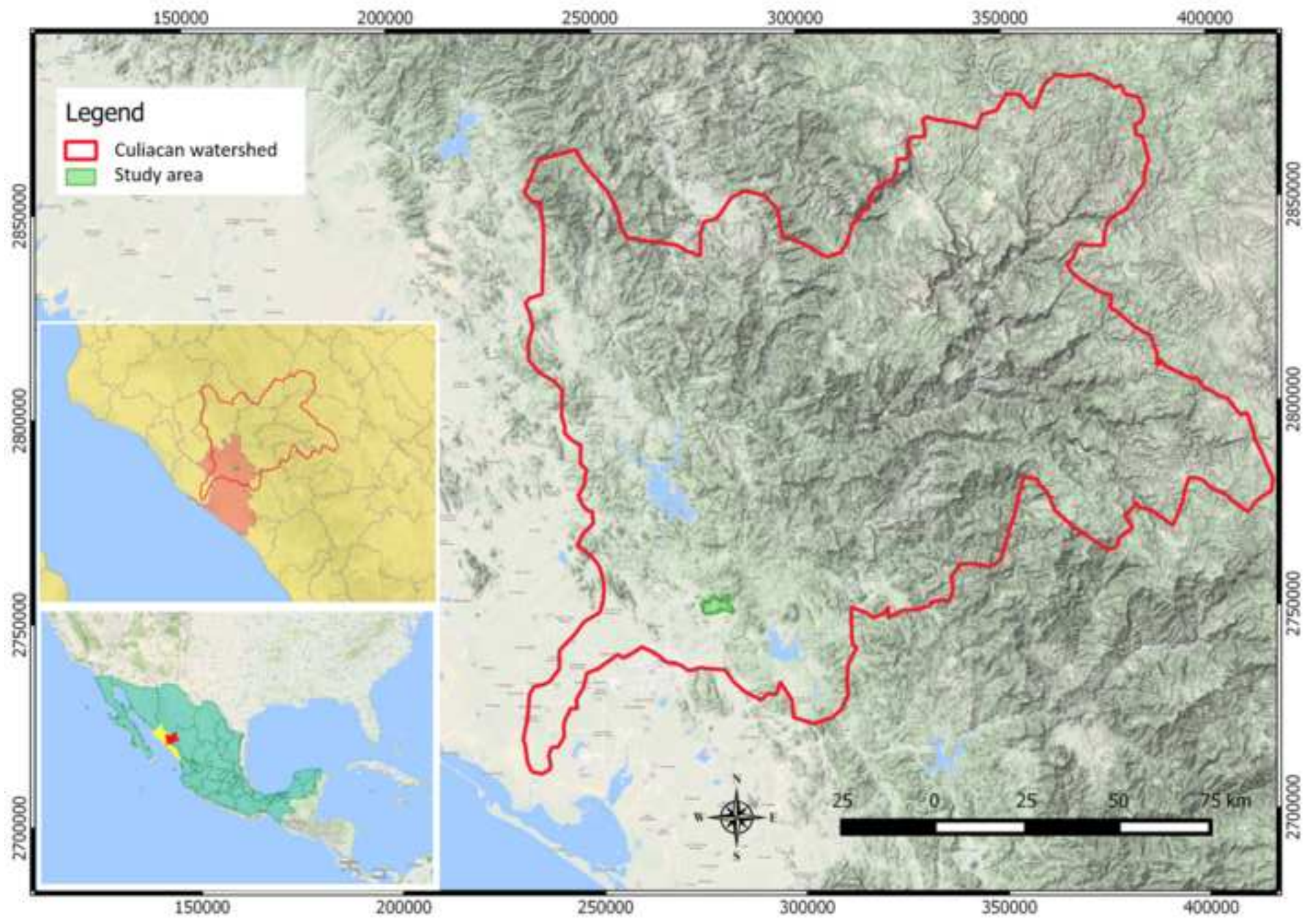


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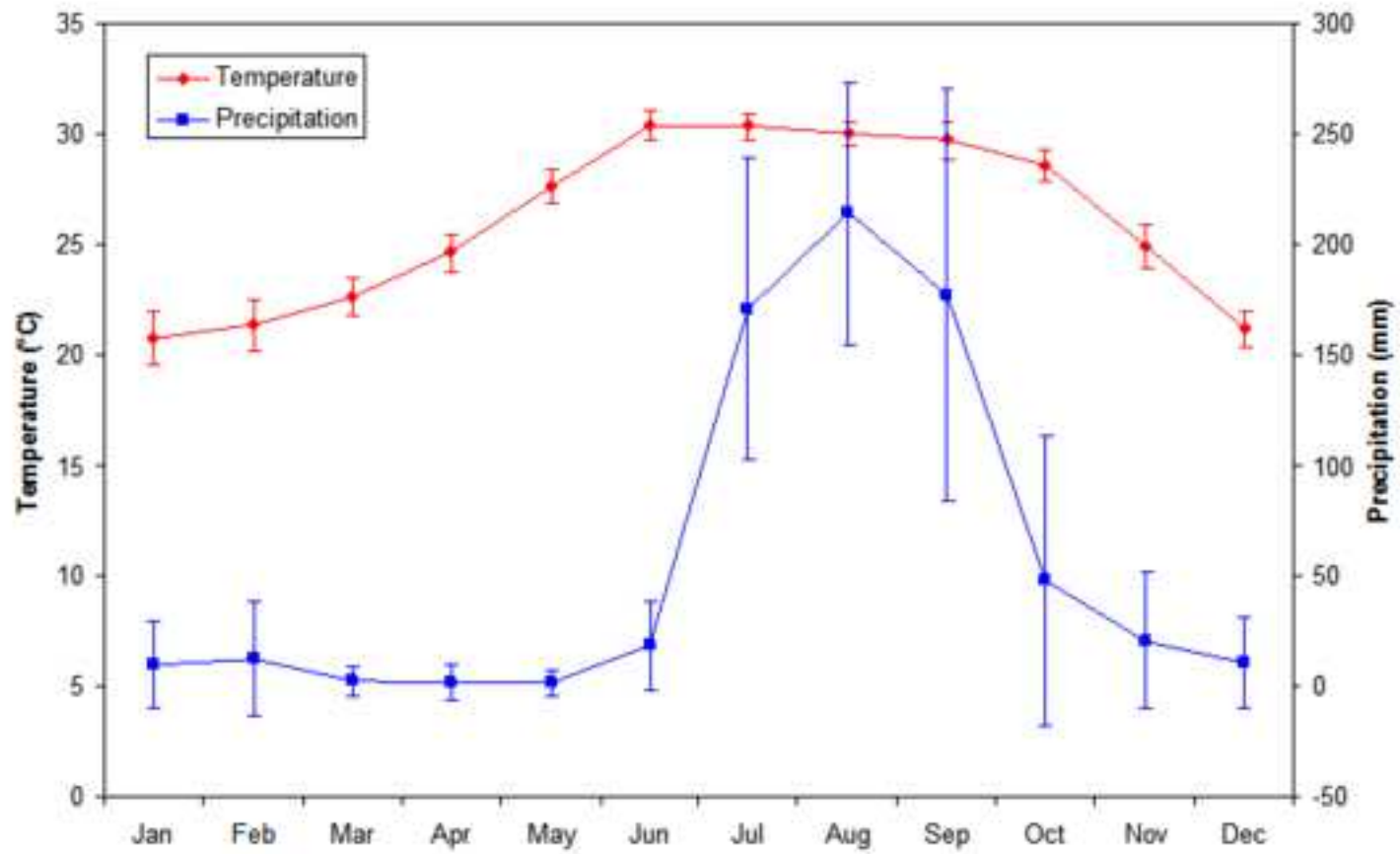


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Figure 4
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Figure 5 a

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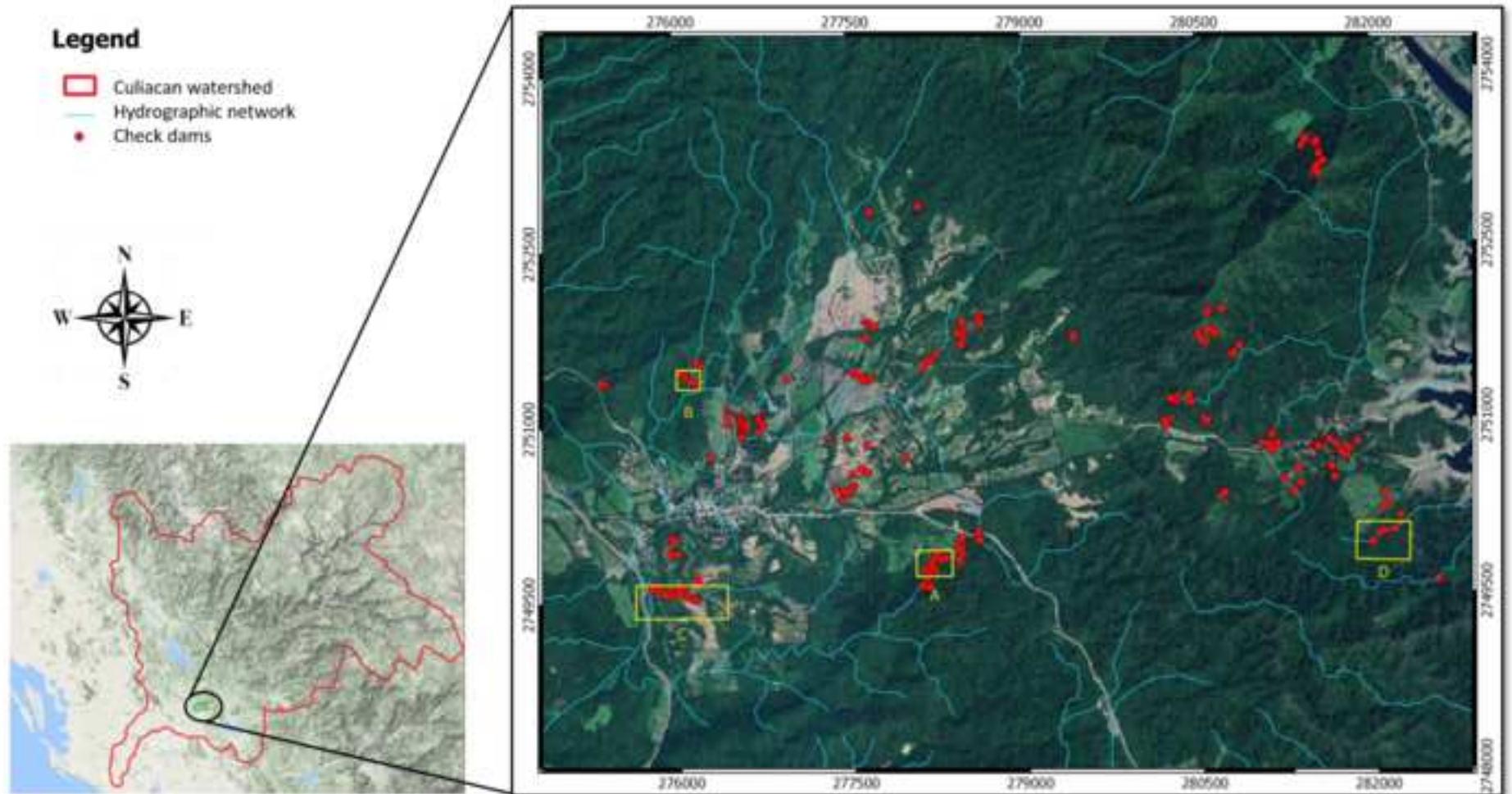


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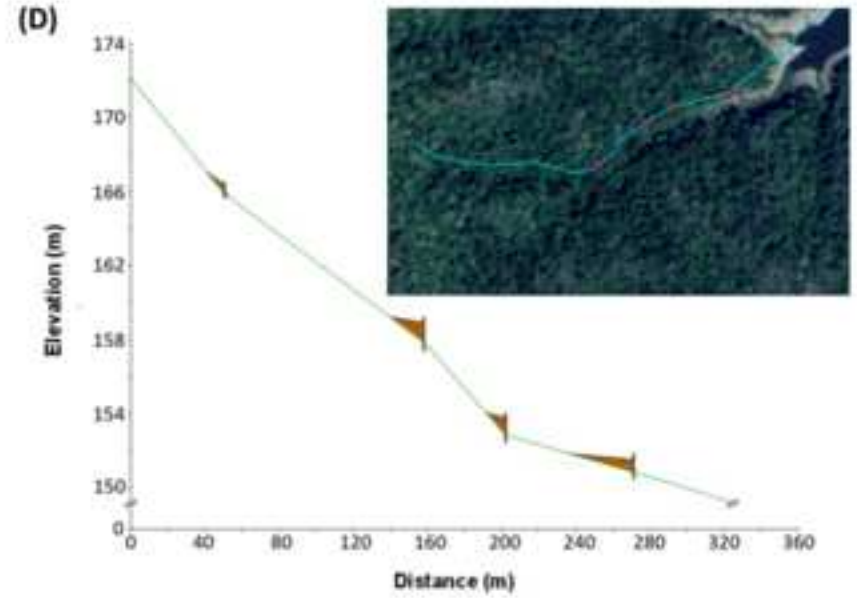
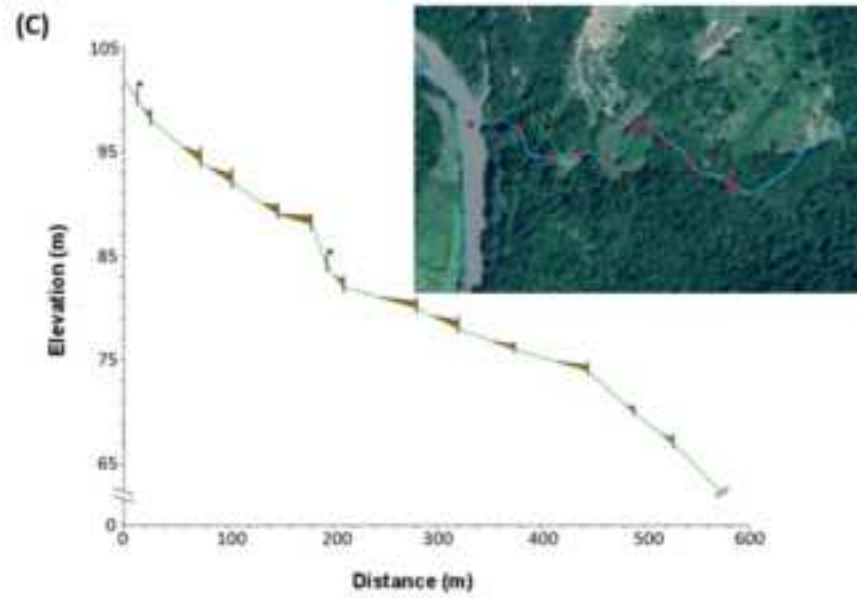
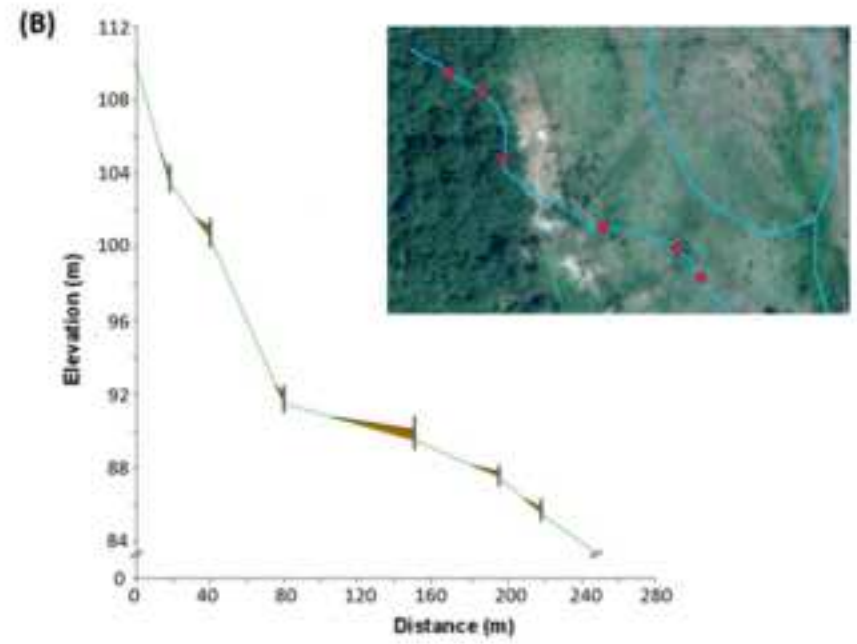
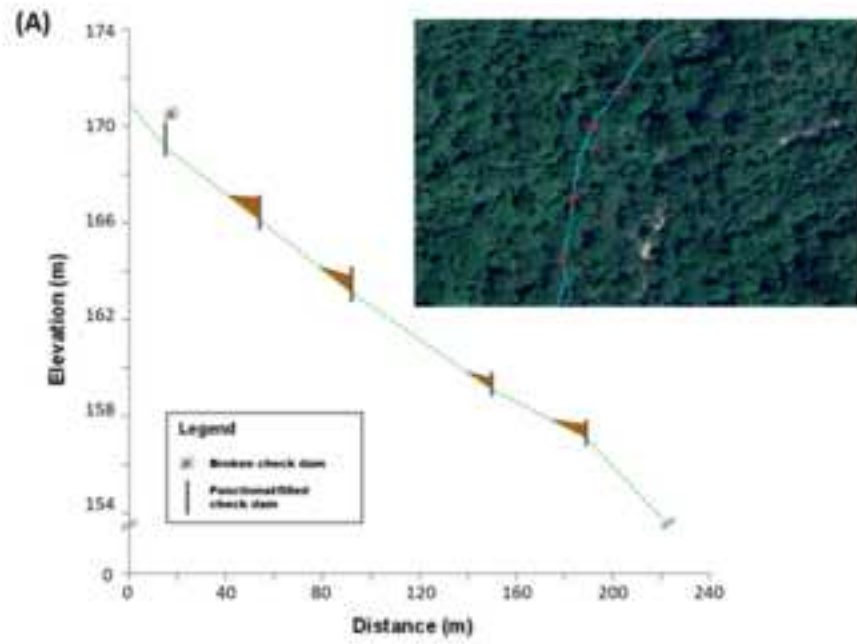


Figure 6

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