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1 **Drivers of erosion and suspended sediment transport**
2 **in three headwater catchments of the Mexican Central**
3 **Highlands**

4

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17 **Abstract**

18 Quantifying suspended sediment exports from catchments and understanding suspended
19 sediment dynamics within river networks is important in areas draining erodible
20 material that contributes to the siltation of downstream reservoirs and to the degradation
21 of water quality. A one-year continuous monitoring study of water and sediment fluxes
22 was conducted in three upland subcatchments (3.0, 9.3, and 12.0 km²) located within
23 the Cointzio basin, in the central volcanic highlands of Mexico (Michoacán state). Two
24 subcatchments generated high sediment exports (i.e., Huertitas, 900-1500 t.km⁻².y⁻¹ and
25 Potrerillos, 600-800 t.km⁻².y⁻¹), whereas the third subcatchment was characterized by a
26 much lower sediment yield (i.e., La Cortina, 30 t.km⁻².y⁻¹). Such disparities in
27 subcatchment behaviours were associated with the presence of severely gullied areas in
28 Huertitas and Potrerillos rather than with rainfall erosivity indices. An adapted
29 classification of hysteretic patterns between suspended sediment concentration (SSC)
30 and discharge was proposed because 42% of flood events contributing to 70% of
31 sediment export were not discriminated by the classical clockwise/anticlockwise
32 typology. This new classification allowed identification of relationships in the
33 hydrosedimentary responses of successive floods. A stream transport capacity limit was
34 also detected during hydrograph recession phases. Overall, hydrosedimentary processes
35 proved to be seasonally dependent: sediment export was repeatedly limited by the
36 stream transport capacity during the first part of the rainy season, whereas a channel
37 minimum erosivity threshold was frequently reached at the end of the season.

38

39 *Keywords:* sediment yield; rainy season; sediment-discharge hysteresis; mountainous
40 catchments; volcanic soils.

41 **1. Introduction**

42 Accelerated soil erosion and subsequent fine sediment delivery to rivers are two major
43 environmental issues that increasingly concern land and water management authorities
44 throughout the world (Ongley, 1996). Soil loss is commonly associated with arable land
45 depletion and thus with a reduction in crop yields (Pimentel et al., 1995). In addition to
46 on-site effects, fine sediment supply leads to severe off-site impacts: Sediment can
47 accumulate on the riverbed and increase flooding potential, decrease reservoir storage
48 capacity, and degrade aquatic ecosystems by increasing water turbidity and by
49 mobilizing associated contaminants (Newcombe and McDonald, 1991; Owens et al.,
50 2005).

51 Upland areas are known to be important contributors to fine sediment production and
52 delivery to downstream reaches. Indeed, they often act as sediment source areas because
53 of their steep and deeply incised morphology (Dietrich and Dunne, 1978; Walling and
54 Webb, 1996; Sidle et al., 2000). Therefore, understanding the processes governing the
55 release of fine sediment from headwater catchments to lowland water bodies is
56 essential. The analysis also requires appreciation of the temporal and spatial variations
57 in upland-lowland linkages, as determined by (i) historic land use changes that often
58 continue to influence contemporary sediment dynamics (e.g., Wasson et al., 1998; Kasai
59 et al., 2005), and (ii) by the extent of connectivity between hillslopes and downstream
60 reaches, i.e., significance of sediment storage within channels, floodplains and
61 reservoirs (e.g., Fryirs and Brierley, 1999; Lang et al., 2003).

62

63 Various methods have been proposed in recent decades that investigate fine sediment
64 transport. Benefiting from the development of automated monitoring stations, numerous
65 studies have described the pattern of suspended sediment concentration during single

66 hydrologic events (e.g., Webb and Walling, 1982; Walling and Webb, 1983; Klein,
67 1984; Jeje et al., 1991; Mano et al., 2009). These works showed that, in most streams,
68 the bulk of sediment is transported during single floods and that the relationship
69 between suspended sediment concentration (SSC) and water discharge (Q) during a
70 storm is highly variable. Resulting SSC- Q hysteresis patterns have been widely
71 examined at the event scale in order to interpret geomorphic processes occurring
72 within catchments and to outline the spatial distribution of sediment sources (e.g.,
73 Klein, 1984; Williams, 1989; Lenzi and Marchi, 2000; Jansson, 2002). This integrative
74 tool is still frequently used in recent literature (e.g., Lefrançois et al., 2007; Sadeghi et
75 al., 2008; López-Tarazón et al., 2009; Smith and Dragovich, 2009). Another
76 increasingly used approach for the understanding of mechanisms controlling sediment
77 delivery consists in establishing statistical correlations between SSC and a set of
78 parameters such as, for instance, rainfall intensity, moisture initial conditions, sediment
79 load, and peak discharge (Seeger et al., 2004; Zabaleta et al., 2007; Nadal-Romero et
80 al., 2008; Oeurng et al., 2010). Still, such statistical methods may be usefully employed
81 together with physically based approaches to improve the understanding of sediment
82 dynamics in headwater catchments.

83

84 A large part of the global problems and the unresolved issues mentioned above are
85 experienced in the Mexican Central Plateau, which concentrates the majority of the
86 country's population (INEGI, 2006). This area underwent significant land use changes
87 during the last decades that induced an intensification of soil erosion (SEMARNAT-CP,
88 2003). This leads in turn to the degradation of surface water bodies and consequently to
89 enhanced water treatment costs (Vidal et al., 1985; Alcocer and Escobar, 1993). This

90 situation is particularly acute in the volcanic region located around Morelia (capital of
91 Michoacán state, ca. 1 million inhabitants).

92 Recent studies conducted in central Mexico provided significant insights about erosion
93 processes and soil loss at plot, hillslope, or subcatchment scales (e.g., Servenay and
94 Prat, 2003; Descroix et al., 2008; Viramontes et al., 2008; Bravo-Espinosa et al., 2009;
95 Vásquez-Méndez et al., 2010). However, so far, very few studies have addressed the
96 question of sediment delivery to rivers and sediment yields in Mexican basins
97 (Ramírez-León and Aparicio, 2009). This paper reports the results of high frequency
98 monitoring of discharge and suspended sediment carried out in the Cointzio basin, close
99 to the city of Morelia. Three headwater subcatchments of the basin (i.e., La Cortina,
100 Huertitas, and Potrerillos) with distinct characteristics (soil type, slope gradient, land
101 use) were equipped and surveyed all throughout 2009 to provide the first assessment of
102 the suspended sediment dynamics in volcanic mountainous headwaters of the Mexican
103 plateau.

104 The objectives of our work were (i) to quantify the fine sediment loss at the
105 subcatchment scale and compare the sensitivity to erosion of the three study sites, (ii) to
106 point out advantages and disadvantages of our high frequency monitoring for potential
107 applications in other similar conditions, and (iii) to enlarge the scope of our findings by
108 identifying the dominant processes driving suspended sediment transport in 1-10 km²
109 scale mountainous subcatchments under subhumid conditions.

110

111 2. Material and methods

112 2.1. Study area

113 The Cointzio River basin is located in the southern part of the Mexican Central Plateau,
114 where it meets the Trans-Mexican Volcanic Belt (Fig. 1). The region has a temperate
115 subhumid climate characterized by two contrasting seasons: the dry season lasting from
116 November to May and the wet season between June and October. Mean annual rainfall
117 reaches 770 mm in Morelia (period 1975-2005). Nearly 80% of the precipitation occurs
118 during the five months of the rainy season (Carlón-Allende et al., 2009). Rainfall is
119 generally dominated by high intensity localized storms, although less intense and more
120 widespread events also repeatedly occur.

121 The Cointzio River basin drains an area of 630 km² with altitudes ranging from 3 440 m
122 at the summit to 1 990 m at the outlet. The main watercourse is the *Rio Grande de*
123 *Morelia* river, which originates from moderate hillslopes in the eastern part of the basin
124 and flows across it until reaching the man-made reservoir of Cointzio (4 km², 65 Mm³)
125 located at the outlet. The reservoir was built in 1940 to provide water for domestic
126 consumption and agricultural needs. Given that it currently supplies 25% of the water
127 distributed in Morelia, its increasing siltation is a major concern for the region
128 (Susperregui et al., 2009).

129 Geology of the upper basin mainly consists of basalt and andesitic rocks produced by
130 Quaternary volcanic activity. The lower part of the area is underlain by alluvium and
131 lacustrine deposits. The presence of igneous material led to the formation of fine-
132 textured soils. Schematically, Andisols (i.e., black fertile soils formed in volcanic
133 silicate-rich ash) are prominent in upland parts of the basin, Acrisols (i.e., red acid soils
134 with high clay content) on the hillslopes and Luvisols (i.e., weathered soils with
135 accumulation of clay in a subsurface horizon) in the lowlands (FAO, 2006). Both

136 Andisols and Acrisols are known to be poorly resistant to water erosion when they
137 undergo land use changes (Poulenard et al., 2001; Bravo-Espinosa et al., 2009).

138 Hydrosedimentary fluxes were measured throughout 2009 with a high frequency (i.e.,
139 5-min) at the outlet of the three headwater catchments of the Cointzio basin; i.e.,
140 Huertitas (3.0 km²), La Cortina (9.3 km²), and Potrerillos (12.0 km²) (Fig. 1). These
141 three sites are characterized by contrasted landforms, morphologies, and soil types, as
142 detailed hereafter:

143 Huertitas and La Cortina are located in the eastern mountains of the basin. La Cortina is
144 underlain by Andisols, rich in organic matter and characterized by an excellent
145 microstructure under wet conditions. It constitutes a local reference in terms of good
146 ecological status. Its undulating landscape (mean slope 12%) is mainly covered by
147 forests (52%) and maize/avocado fields (46%; Table 1).

148 The Huertitas subcatchment (mean slope 18%) covers a lower range of altitudes and
149 relies exclusively on Acrisols. The catchment displays a severely gullied landscape on
150 6% of its area, with sparse vegetation and soils highly sensitive to water erosion (Fig. 2;
151 Table 1). Land use mainly consists of rangeland (65%) and cropland (28%).

152 Potrerillos is located in the southern part of the Cointzio basin, at the piedmont of a
153 volcanic formation (mean slope 15%), and soils are mainly Acrisols (60%) and
154 Andisols (40%). Channel incision and gullies are connected throughout the
155 subcatchment as in Huertitas. These degraded areas affect 1% of the subcatchment.
156 Land use in Potrerillos consists of a combination of cropland (40%), forests (37%) and
157 grassland (23%; Table 1). The three study sites are therefore representative of the
158 variety of environments found in upstream areas of Cointzio.

159 The river draining La Cortina is permanent with a substantial flow that is even observed
160 during the dry winter months. In Huertitas, waterflow is also perennial but the baseflow

161 contribution is very low in winter. In Potrerillos, the river is ephemeral and only active
162 during the five months of the rainy season.

163 Grain size of the suspended sediment transported in the subcatchments varies according
164 to the location and to the type of flood, but it is predominantly clay- and silt-sized.

165 *2.2. Field monitoring*

166 *2.2.1. Water discharge and suspended sediment measurements*

167 Two of the three monitoring sites (i.e., Huertitas and La Cortina) consist of a stable
168 channel section built of concrete and installed for this study. The third monitored site
169 (i.e., Potrerillos) was installed under a bridge. It is made up of a rectangular section
170 underlain by bedrock outcrops, and the local topography leads to phases of sediment
171 deposition and resuspension. This required careful data processing.

172 Water level was measured at a 5-min time step with Thalimede[®] OTT water level
173 gauges. At each station, between 10 and 15 discharge measurements were carried out
174 using the tracer dilution gauging method. Water discharge time series were determined
175 using continuous water level records and rating curves obtained by the dilution method
176 (see the technical note of Duvert, 2009, for details about the methodology used and its
177 associated uncertainties).

178 Time series of SSC were calculated using stage-triggered Teledyne ISCO[®] 3700
179 automatic water samplers containing 24 bottles of 1 liter each. At all sites, suspended
180 sediment sampling was performed at a depth of about 10 cm from the streambed and it
181 did not vary with stage. Suspended sediment concentrations under baseflow conditions
182 were also surveyed by means of manual samples collected daily around 6 p.m. by local
183 staff. The use of automatic turbidity sensors would have been preferable in the three
184 upland subcatchments. However, during the equipment installation phase in 2008, it

185 became apparent that this option was not feasible because of numerous field constraints.
186 Indeed, sedimentation frequently occurred in river sections at the outlet, and the water
187 depth in the channel was not sufficient during baseflow.

188 A Campbell CR800[®] datalogger was programmed to trigger sampling based on a stage-
189 variation threshold and using the following strategy: stations were visited every week
190 for collecting samples and replacing bottles when necessary; given this operational
191 constraint, we followed a trial-and-error process described by Gao (2008). Water level
192 monitoring had also been conducted throughout 2008 at the three stations (data not
193 reported in this paper); we used these time series to simulate an optimized sampling
194 frequency. The aim was to obtain reliable load estimates during small events without
195 oversampling large events in order to avoid exhausting the samplers' available bottles.
196 At all sites, the most appropriate water depth threshold appeared to be 5 cm for 5-min
197 time step requests. The algorithm checked whether water depth variation (either positive
198 or negative) exceeded 5 cm for each time step. When this condition was fulfilled,
199 sampling was initiated. The water depth value was then stored until again reaching
200 variations of ± 5 cm in the following time steps. The sampling conducted in 2009
201 confirmed the relevance of this setting: on average, 10 to 15 samples were collected
202 weekly in each station, and we were only confronted with an exhaustion of the 24
203 bottles on two occasions.

204

205 Collected samples were filtered in the laboratory of CIGA-UNAM in Morelia using
206 preweighed Standard Durieux[®] 0.7- μ m-diameter glass microfiber filter papers. The
207 filters were then dried for 2 h at 105°C and weighed with a high precision balance
208 (uncertainty ± 0.1 mg). In case of very high SSC, a known volume of sample was dried

209 during 24 h at 60°C and the residue was weighed. In this paper, all SSC measurements
210 refer to total suspended sediment (i.e., comprising mineral and organic fractions).

211

212 Annual suspended sediment yield (SSY, in tons) measured in 2009 was calculated using
213 Eq. (1):

$$214 \quad SSY = 0.3 \cdot \sum_{i=1}^n (Q \cdot SSC) \quad (1)$$

215 where SSC is the suspended sediment concentration (g.L^{-1}) (corresponding to a 5-min
216 frequency linear interpolation of data from automatic sampler and from manual
217 sampling), Q is the instantaneous discharge ($\text{m}^3 \cdot \text{s}^{-1}$) (5-min frequency), and n
218 corresponds to the number of 5-min intervals within a year.

219 Suspended sediment loads (SS loads) exported during single events were also estimated
220 using Eq. 1 with n corresponding to the number of 5-min intervals during the event of
221 interest. Finally, by calculating the ratio between the SS load and the stormflow runoff
222 volume for each event of the rainy season, an integrative SSC was obtained per event.

223

224 In terms of monitoring efficiency, 20 out of the 23 events recorded in 2009 were fully
225 sampled in La Cortina (i.e., 87%), 23 of 30 in Huertitas (i.e., 77%), and 33 of 41 in
226 Potrerillos (i.e., 80%). The 30 May 2009 event that occurred in Huertitas, and that
227 resulted in being the most intense of the season, could not be sampled because the water
228 level floating gauge remained trapped during the rising phase (peak flow could
229 nevertheless be documented by means of visual observation). Similarly, in Potrerillos,
230 the highest storm event that occurred on 21 July 2009 was not sampled because of an
231 early exhaustion of bottles. Uncertainties associated with these missing values are
232 discussed later (section 4.1).

233

234 Grain size distribution was also determined for four storm events composite samples as
235 an exploratory approach to link sediment yield to physical process settings. Samples
236 were analyzed with a Malvern[®] particle size analyzer after being submitted to a 2-min
237 ultrasonic agitation.

238 2.2.2. *Uncertainties associated with suspended sediment measurements*

239 As mentioned by Gao (2008), SSY estimates must be interpreted with care. Such
240 calculations involve several sources of errors:

241 First, SSY estimates require continuous discharge data, which implies uncertainties
242 related to (i) water depth measurements by automatic gauges, (ii) discharge
243 measurements for the rating curve construction, and (iii) calculation of discharges from
244 water level data through the rating curve. The sum of these uncertainties is usually
245 considered to reach 10-20% (European ISO EN Rule 748, 1997; Navratil et al., 2009).

246 Second, the use of an automatic sampler and thus of a single sampling point is
247 questionable: we assumed that, owing to the fine-grained size of sediment and to the
248 turbulent conditions prevailing in the monitoring sites, the particles would be well
249 mixed throughout the water column. An experimental investigation conducted by
250 Navratil et al. (2009) reported that the use of automatic sampling combined with
251 laboratory manipulations can lead to a ca. 20% underestimation of SSC values with an
252 additional centered error of 10-20%.

253 Third, the algorithm selected for the triggering of automatic samplers introduces another
254 bias: the representativeness of fine sediment sampling during a storm is indeed directly
255 dependent on the algorithm capacity to adequately cover the event (i.e., did the program
256 allow sampling during SSC peak?). Suspended sediment yield estimates depend thus on
257 the algorithm efficiency. Furthermore, the type of interpolation used to join all SSC
258 discrete values can be a source of additional errors.

259 2.2.3. *Rainfall measurement*

260 Each subcatchment was equipped with a HOBO[®] H07 tipping-bucket automatic rain
261 gauge (0.2 mm/pulse). The equipment provided complete and continuous rainfall
262 monitoring. In La Cortina and Potrerillos, 100% of the wet season was covered by
263 rainfall data. However, in Huertitas, records were only obtained during 95% of the year
264 because of several technical problems.

265 2.3. *Data analysis*

266 2.3.1. *Sediment detachment*

267 Several approaches were used to derive information on sediment dynamics from the
268 high frequency data sets. Based on the soil detachment theory (Quansah, 1981), a first
269 step of our analysis aimed at studying the relationship between rainfall intensity and SS
270 load at the event scale. Various authors (e.g., Poesen, 1985) reported that rainfall kinetic
271 energy (*KE*) can be used as an indicator of the potential ability of rain drops to detach
272 soil. Rainfall kinetic energy was then calculated for each event as a proxy of rainfall
273 erosivity (Salles et al., 2002), following the relation described by Brandt (1990):

274
$$KE_{mm} = \sum_i 8.95 + 8.44 \cdot \log_{10} I_i \quad (2)$$

275 where KE_{mm} is the volume-specific kinetic energy ($\text{J}\cdot\text{m}^{-2}\cdot\text{mm}^{-1}$), and I is the rainfall
276 intensity at the 5-min time step ($\text{mm}\cdot\text{h}^{-1}$).

277

278 To allow detection of correlations between the set of parameters, nine quantitative
279 variables were then derived for each rainfall–runoff event: (i) cumulative precipitation
280 depth during the event, (ii) maximum rainfall intensity in 5 min, (iii) kinetic energy
281 released by the rainfall, (iv) discharged volume during the stormflow event, (v) runoff

282 coefficient, (vi) maximum instantaneous discharge, (vii) maximum SSC, (viii) mean
283 SSC during the event, and (ix) SS load exported. Each event was also characterized by
284 two semiquantitative parameters: (x) the slope of hydrograph rising limb and (xi)
285 moisture/flood initial conditions (Table 2). Hydrographs were classified visually
286 according to the velocity of their rising phase (slow/fast). Initial moisture conditions
287 were classified using both precipitation and discharge data: a class was assigned to each
288 event, ranging from 0 (dry) to 3 (wet+++), depending on the initial moisture conditions
289 and on the extent of flood generation during the previous 24 h (Table 2). Finally, the
290 type of SSC- Q hysteretic pattern was considered (xii).

291 When testing relationships between parameters, data scattering rapidly appeared to
292 strongly affect the graphical analysis. Parameters were therefore plotted using
293 bilogarithmic axes.

294 2.3.2. *Sediment transport*

295 Individual flood events were analyzed in terms of SSC-discharge hysteretic patterns.
296 Processes contributing to the SS dynamics, i.e., sediment supply and remobilization of
297 deposited sediment, occur at very short timescales (Asselman, 1999; Gomi et al., 2005).
298 The hysteresis between SSC and discharge has been widely reported to be a useful tool
299 providing information on sediment sources and the mechanics of sediment delivery
300 (e.g., Jansson, 2002). In small basins, SSC usually presents a higher sensitivity to local
301 sources such as bank collapse, concentrated sediment inputs from gullies, etc., which
302 may complicate interpretations (Chappell et al., 1999; Lefrançois et al., 2007). On the
303 other hand, the more homogeneous precipitation that usually characterizes small
304 drainage areas could allow a less complex interpretation of rainfall data and, in turn, of
305 runoff and erosion dynamics.

306 Floods were classified according to their hysteretic pattern. The SSC- Q diagrams were
307 drawn with linear axes for both variables. We used an adapted version of the
308 methodology commonly described and based on the typology of Williams (1989),
309 which discriminates events into clockwise, counterclockwise, simultaneous and figure
310 eight shaped hysteretic loops. This adapted classification is presented in section 3.2.2.

311 2.3.3. *Factorial analysis*

312 Statistical tools offer an alternative and complementary approach to assess the
313 relationship between driving parameters and their consequences on sediment dynamics.
314 They define objectively the degree of correlation between variables through a
315 correlation matrix. A factorial analysis was therefore conducted on the sets of variables
316 compiled in the three subcatchments for each flood event. Our aim was to apply a
317 technique allowing the comparison of both quantitative and discrete parameters. The
318 factorial analysis for mixed data (FAMD) (Escoufier, 1979; Pagès, 2004), developed in
319 the R environment by Lê et al. (2008) through the FactomineR package, was selected.
320 This type of analysis allows the extension of a multiple factor analysis to mixed sets of
321 variables (Pagès, 2004). The RV coefficient, i.e., a multivariate generalization of the
322 Pearson coefficient (Robert and Escoufier, 1976), was chosen to estimate correlations
323 between variables. When variables were dependent (e.g., discharge peak and discharged
324 volume during a flood event), only one variable was analyzed.

325

326 3. Results

327 3.1. Precipitation, runoff and sediment transport

328 3.1.1. Precipitation

329 At the basin scale, precipitations occurred from mid-May 2009 until late October 2009.

330 The months of July and August were unusually dry, and the end of the rainy season

331 (i.e., September and October) provided higher rainfall than usual. Total rainfall depth

332 measured in the basin during 2009 reached 805 mm according to the Thiessen method

333 and using data from nine gauges available across the Cointzio basin (Anguiano-

334 Valencia, 2010). This value can be considered as a mean value compared to the long-

335 term rainfall database (400-1100 mm.y⁻¹) available at Santiago Undameo (1954-2004),

336 which is a station located just upstream from the Cointzio reservoir (Gratiot et al.,

337 2010).

338 Significant disparities were observed among the three subcatchments: in La Cortina,

339 annual precipitation reached 1230 mm, whereas it only reached 810 mm in Potrerillos

340 and 678 mm in Huertitas. As already mentioned, data in Huertitas only covered 95% of

341 the year, which may partially explain the lower volume recorded in this site. More

342 generally, catchments located at higher elevations received larger precipitation amounts,

343 probably because of orographic effects. The median rainfall intensities I_{50} recorded in

344 5 min throughout the rainy season differed among the sites: I_{50} amounted to 3.0 mm.h⁻¹

345 in Huertitas and La Cortina, and 4.8 mm.h⁻¹ in Potrerillos. In contrast, maximum

346 intensities recorded were higher in Huertitas (118 mm.h⁻¹) and La Cortina (113 mm.h⁻¹)

347 than in Potrerillos (72 mm.h⁻¹). Finally, in terms of kinetic energy release, La Cortina

348 experienced more intense events (KE_{mm} [min-max]: [92-763] J.m⁻².mm⁻¹), which was

349 explained by the generally higher volumes of rainfall characterizing this site. In

350 Huertitas and Potrerillos, KE_{mm} were lower and they remained in the same order of
351 magnitude (respectively, [58-520] $J.m^{-2}.mm^{-1}$ and [42-463] $J.m^{-2}.mm^{-1}$).

352 3.1.2. Discharge and suspended sediment flux

353 The three subcatchments are characterized by very distinct hydrological behaviours: La
354 Cortina hydrographs showed a high baseflow contribution to its total discharge
355 (baseflow ranged between 0.01 and 0.1 $m^3.s^{-1}$, i.e., 0.05-0.15 m water depth); whereas
356 in Huertitas, although the stream is perennial, baseflow was much lower ($< 1.10^{-3} m^3.s^{-1}$
357 during the dry season, i.e., 0.01-0.05 m water depth). In Potrerillos, the water flow is
358 ephemeral and characterized by successive flashflood events followed by fast recession
359 times. According to historical records available at the outlet of the 630- km^2 basin, mean
360 annual discharge during the period 1940-2002 was 2.3 $m^3.s^{-1}$. The mean discharge
361 recorded during 2009 only reached 1.3 $m^3.s^{-1}$, which was the second lowest value in
362 more than 60 years.

363 Hydrosedimentary patterns were also contrasted among the three study sites: La Cortina
364 experienced relatively low SSC, even during storm events ($SSC_{max} = 8 g.l^{-1}$), whereas
365 SSC peaks were much higher in Huertitas ($SSC_{max} = 55 g.l^{-1}$) and Potrerillos
366 ($SSC_{max} = 126 g.l^{-1}$).

367 Two estimates of annual SSY were calculated in Huertitas and Potrerillos. This is the
368 consequence of the incomplete sampling that occurred during the two major floods at
369 both sites. Lower values correspond to a calculation that is strictly based on the data
370 available, and upper values were estimated using the SSC peak estimations obtained for
371 these two ungauged events (Table 3).

372 Overall, SSY were found to be subcatchment dependent, with high values in Huertitas
373 ([900-1500] $t.km^{-2}.y^{-1}$) and Potrerillos ([600-800] $t.km^{-2}.y^{-1}$) contrasting with the
374 > 20 times lower output recorded in La Cortina (30 $t.km^{-2}.y^{-1}$). Huertitas and Potrerillos

375 showed a similar behaviour regarding sediment transport, and the slightly higher
376 specific yield recorded in Huertitas could result from the greater extent of gullied areas
377 (6% of the subcatchment area) generating high sediment inputs, as well as from steeper
378 slopes (Table 1). In terms of loads exported during single events, the highest sediment
379 bulk transport was measured in Potrerillos on 1 July 2009 (102 t.km^{-2}). The major event
380 recorded in Huertitas generated 41 t of sediment km^{-2} on 26 June 2009. In La Cortina, it
381 occurred on 14 July 2009 and reached 16 t.km^{-2} , contributing to half of the total load
382 exported in 2009 from this subcatchment.

383 *3.2. Analyzing suspended sediment dynamics*

384 *3.2.1. Hillslope particle detachment: comparison of rain intensity with SS loads*

385 Both KE_{mm} and maximal intensities of each rainfall event were compared to SSC peaks.
386 According to the two scatter plots presented in Fig. 3, each subcatchment followed a
387 very distinct behaviour. Relatively random relationships were found between the tested
388 parameters. High values of KE_{mm} were never associated with high SSC peaks (Fig. 3B).
389 In all sites, maximal intensities showed slightly better correlations with sediment output
390 values than KE_{mm} (Fig. 3A). In La Cortina and Huertitas, the heaviest storms were
391 comparable in terms of intensity but the catchment responses were highly different:
392 SSC peaks were much higher in Huertitas than in La Cortina (respectively, $[3-55] \text{ g.L}^{-1}$
393 and $[0.05-8] \text{ g.L}^{-1}$). Furthermore, significant SSC peaks were recorded in Potrerillos ($[2-$
394 $126] \text{ g.L}^{-1}$) despite lower maximum rainfall intensities.

395 *3.2.2. SSC-discharge hysteretic patterns*

396 The study sites are characterized by a remarkably fast runoff response to precipitation
397 input (hydrograph rising phase $< 5 \text{ min}$). A significant number of the storm events

398 generated an “overflow wave” within channels that propagated down to the
399 subcatchment outlet, inducing an instantaneous water level rise at the monitoring
400 station. On such occasions we could not determine whether the sediment peak was
401 leading the discharge peak or not. For that reason, the classical hysteresis typology had
402 to be adapted (Fig. 4). These flash floods represented 35% of the events recorded in La
403 Cortina in 2009, 54% in Potrerillos, and 69% in Huertitas. Such events were most likely
404 due to the occurrence of Hortonian overland flow on surfaces characterized by a low
405 permeability. Recession limbs were systematically more gradual.

406 Independent of location, a large majority of sedigraphs were found to maintain a high
407 SSC level during the hydrograph recession phase. This characteristic was observed in
408 100% of events recorded in La Cortina, 100% in Huertitas, and 94% in Potrerillos.
409 Consequently, the relation between SSC and discharge during the hydrograph falling
410 stage could not be used as a discriminating factor. The classification was then adapted
411 as follows:

412 (i) Lagging sediment peak events (referred to as “LaP” in Fig. 4): lag between the
413 sediment peak and the discharge peak with sediment concentrations remaining at a high
414 level during the recession phase. This situation corresponded to the absence of in-
415 channel sediment delivery and to the arrival of remote sediment from external sources,
416 i.e., hillslope erosion (Lenzi and Marchi, 2000; Orwin and Smart, 2004).

417 (ii) Simultaneous peak events (referred to as “SP” in Fig. 4): coincidence between
418 sediment peak and peak discharge with sediment maintaining high concentrations
419 during the recession phase.

420 (iii) Leading sediment peak events (referred to as “LeP” in Fig. 4): sediment peak
421 leading discharge peak with sediment maintaining at a high level during recession. Both
422 SP and LeP categories correspond to the remobilization and transport of in-channel

423 sediments (Jansson, 2002; Smith and Dragovich, 2009) followed by a supply from
424 distant sources (i.e., sediment still delivered during the falling phase). The possibility to
425 discriminate between SP and LeP was conditioned by the non occurrence of “wave-type
426 events.”

427 The classification of flood events through their hysteretic behaviour and their respective
428 contribution to total sediment exports is summarized in Fig. 5. In La Cortina (Fig. 5A),
429 the bulk of events exhibited a lagging SSC peak pattern, i.e., LaP events ($n = 14$). Two
430 events were identified as SP, and LeP hysteresis was only observed once, during the
431 event characterized by the highest peak discharge of the season. In Huertitas (Fig. 5B),
432 events showing an LaP behaviour were also the most frequent ($n = 14$); a significant
433 part of events exhibited SP hysteresis ($n = 7$), whereas during two events the sedigraph
434 was leading (LeP). In contrast, in Potrerillos (Fig. 5C), the majority of events were SP
435 ($n = 21$). Three events had an LeP pattern, whereas only five events were identified as
436 LaP.

437 Apart from these site-specific responses, a general pattern was found among the three
438 sites: SP and LeP events were clearly associated with high peak discharges and high SS
439 loads, and with low to moderate rainfall intensities. Although these occurrences
440 represented a minority of the sampled events, except in Potrerillos (average of 42%),
441 they contributed significantly to the annual sediment export from the catchments
442 (average of 70%; Fig. 5, small pie charts). In Potrerillos, 73% of SP and LeP events
443 were preceded by high floods in the previous hours, as illustrated in Fig. 6. The first
444 rainfall event began on 1 July 2009 at 4:30 p.m.; it resulted in a moderate catchment
445 response governed by LaP dynamics (Fig. 6B). The following heavier storm generated a
446 much higher sediment peak (SP event, Fig. 6C). In Huertitas, SP and LeP events were
447 not systematically associated with high flood antecedents. Figure 7 shows an example

448 of two successive stormflow events and illustrates another type of sediment dynamics.
449 In that case, the catchment responded to a first precipitation input by a high discharge
450 peak (SP event, Fig. 7B). The subsequent peak was much reduced in terms of fine
451 sediment export, but the sediment response clearly led the peak discharge (LeP event,
452 Fig. 7C). In La Cortina, no relationship was detected between flood antecedents and the
453 type of SSC- Q relation.

454 3.2.3. Factorial analysis

455 The analysis in La Cortina was performed after having removed one outlier flood
456 (corresponding to the major runoff event of the season). In each of the three sites, the
457 most significant relationship was detected between SS load and Q_{max} (RV coefficients of
458 0.77 in La Cortina, 0.68 in Huertitas, and 0.46 in Potrerillos). In La Cortina, a positive
459 correlation was also found, to a lesser extent though, between SSC peaks and Q_{max} (RV
460 0.48). Parameters associated with precipitation were absolutely not related to both
461 sediment and discharge parameters. In Huertitas and Potrerillos, no other significant
462 correlations were found. Overall, in the three sites, the statistical analysis underlined
463 very weak correlations between rainfall parameters and sediment load.

464 3.2.4. Comparing peak discharges with SS loads

465 Given their good correlation, Q_{max} and SS load values were plotted on a single log-log
466 graph (Fig. 8A). Scattering was high again, but we could identify significant trends.
467 Each subcatchment had clearly a distinct hydrosedimentary behaviour. The higher
468 erosion capacity observed in Potrerillos was confirmed. For equivalent peak discharges,
469 specific loads were higher at this site than at both other stations. Huertitas also produced
470 strong sediment exports whereas La Cortina experienced lower magnitude erosion
471 processes.

472 The grain size distribution of sediment was also investigated (Fig. 8B). The grey
473 triangle and the grey circle plotted in Fig. 8A correspond to events that occurred in
474 Potrerillos and for which particle sizes are known (respectively, P1 and P2 in Fig 8B).
475 Their distinct distribution on the diagram underlined the major dependence existing
476 between the magnitude of storm events and the size of particles transported.

477

478 **4. Discussion**

479 *4.1. Measurement uncertainties in responsive subcatchments*

480 Only one event was missed during the 2009 rainy season in both Huertitas and
481 Potrerillos. Those missing events introduced an uncertainty of $\pm 100 \text{ t.km}^{-2}.\text{y}^{-1}$ in
482 Potrerillos (14% uncertainty) and of $\pm 300 \text{ t.km}^{-2}.\text{y}^{-1}$ in Huertitas (25% uncertainty).
483 This underlines the strong difficulty to obtain accurate SSY estimates in such
484 responsive subcatchments. It also confirms the observations made by other authors that
485 the bulk of annual sediment export occurs during a single or a few high magnitude
486 events (e.g., Walling and Webb, 1983; Mano et al., 2009; Navratil et al., 2009).

487 *4.2. Which factors control the rates of erosion and sediment transport?*

488 Splash erosivity was not a process driving sediment export (Fig. 3). Neither intensity
489 nor overall energy of rainfall proved to be the main factor that triggered erosion
490 processes at the catchment scale. The poor quality of the relationships can probably be
491 explained by the high spatial variability of rainfall. Borga et al. (2008) recently pointed
492 out that flash flood monitoring requires rainfall estimates at spatial scales of 1 km or
493 even finer; such requirements can be met for instance by using weather radar networks.

494 The effects of vegetation on sediment erosion within hillslopes have also probably
495 affected the rainfall/sediment relationship in different ways.

496

497 Hysteretic pattern analysis was interpreted as a descriptor of the local conditions
498 existing close to the gauging stations rather than a hydrosedimentary behaviour
499 affecting the entire surface of the subcatchments. At a local scale, sediment stock
500 appeared to be limited in Huertitas and La Cortina (majority of LaP events, Fig. 5). This
501 was probably because of the locally incised morphology of those two subcatchments,
502 with accelerated flow preventing the local deposition of sediment within the channels.
503 We could not identify any sediment exhaustion effect. In Potrerillos, sediment stored in
504 the channel seemed to be locally continuously available, as demonstrated by a majority
505 of SP events and a higher amount of LeP events (Fig. 5). Distant sediment sources were
506 also active as no early sediment depletion was observed. These observations match with
507 results obtained in 2008 from scour chain surveys (unpublished data; see the
508 methodology described by Laronne et al., 1994), which indicated a succession of
509 scouring and deposition phases within the channel close to the gauging station in
510 Potrerillos.

511 However, at the subcatchment scale, temporary in-channel sediment storage was
512 evidenced in the three sites. This is confirmed by the occurrence of SP and LeP events
513 and by their highly significant contribution to the sediment export from all the stations
514 (Fig. 5). River networks and the connected gullies thus acted as very responsive
515 compartments characterized by successive phases of sediment storage and sediment
516 flush.

517 The succession of storms appeared to play a controlling role on generation of SP and
518 LeP events in most cases in Potrerillos and in a few cases in Huertitas. This “memory

519 effect” has already been documented by Jansson (2002) and Sayer et al. (2006). In Fig.
520 6, the first event (LaP) is thought to have provided a refilling of the channel storage.
521 The following storm gave rise to a SP event because of the remobilization of sediment
522 previously deposited within the channel (i.e., channel flush). All SSC recorded during
523 the falling limb of this second event reached particularly high values compared to their
524 associated discharges, already at recession level (e.g., last sample collected at 8:10 p.m.:
525 SSC reached 63 g.L^{-1} for a discharge of $0.46 \text{ m}^3.\text{s}^{-1}$). This probably indicates that
526 channels were transport-limited during recession. This argument is further discussed in
527 section 4.3.

528 In Fig. 7, the first event (SP) allowed a direct transit of sediments from eroded hillslopes
529 down to the subcatchment outlet. The subsequent sediment peak (LeP) probably
530 illustrates the resuspension of the small quantities of in-channel sediment deposited
531 during the preceding event; the lower SSC peak value was attributed to a pronounced
532 exhaustion of sediment available in the network (i.e., because of the high magnitude of
533 the previous event). Again, recession was concomitant with an external sediment
534 contribution from hillslopes (transport-limited state). This is consistent with results
535 reported by Evrard et al. (in review), which indicated that the proportion of new
536 sediment in the river channel decreased from ca. 100% to 20% after this event.

537 Overall, the study of sediment dynamics through hysteretic behaviour allowed
538 explanation, to a certain extent, of the processes occurring at the subcatchment scale.
539 Our results show that previous floods had an influence on sediment delivery, which can
540 be explained by an increase in hillslope–channel connectivity when moisture conditions
541 increased and when high quantities of sediment were available.

542

543 The study of the relationship between peak discharges and SS loads (Fig. 8A)
544 confirmed that each subcatchment followed a specific hydrosedimentary behaviour. The
545 potential bias implied by the comparison of some instantaneous values (i.e., Q_{max}) with
546 integrated ones (i.e., SS load) was most likely offset by the fact that, in these small
547 subcatchments, Q_{max} acted as a parameter integrating both rainfall and runoff features.

548 Huertitas and Potrerillos subcatchments experienced a higher vulnerability to erosion
549 and a higher reactivity to storms, whereas sediment was exported at a lower rate from
550 La Cortina. In Cointzio, the presence of gullied areas in subcatchments proved to play a
551 significant role in fine sediment erosion. In the first two subcatchments, historical
552 gullies provided a constant sediment supply to the river. One of the primary factors that
553 constrained suspended sediment delivery to outlets was therefore sediment availability.

554 Dense networks of historical gullies certainly increased the catchment connectivity, as
555 already reported by Tamene et al. (2006). Two other key factors were the steepness of
556 hillslopes and the proportion of cropland and rangeland within the subcatchments; both
557 factors being higher in Huertitas and Potrerillos than in La Cortina. Bravo-Espinosa et
558 al. (2009) recently established that the association of traditional cropping practices with
559 cattle grazing could lead to severe soil degradation in the Cointzio basin. We can
560 therefore hypothesize that the formation of gullies in Huertitas and Potrerillos was
561 triggered by those practices.

562 Overall, land degradation associated with historical human disturbance has been widely
563 recognized as a major driver of soil erosion in Mexico (e.g., Alcántara-Ayala et al.,
564 2006; Cotler and Ortega-Larrocea, 2006; Geissen et al., 2009). This linkage between
565 human-induced land use changes and soil degradation was also reported from numerous
566 other areas of the world (e.g., Wasson et al., 1998, in Australia; Zhang et al., 2004, in
567 China; Kasai et al., 2005, in New-Zealand; Valentin et al., 2008, in south-eastern Asia).

568 4.3. *In-channel transport processes*

569 Sediment export systematically increased with discharge (Fig. 8A). This process was
570 observed across the three sites. Consequently, the limiting factor at the subcatchment
571 scale was probably not the sediment availability. If that had been the case, a threshold
572 would have been observed in SS load values. As sediment transport was not limited by
573 sediment availability, the in-channel transport capacity appeared to be a driving factor
574 controlling the suspended sediment export rate. From a physical point of view, the
575 sediment transport capacity of a stream is directly related to flow velocity and to the
576 settling velocity of the particles transported (Engelund and Hansen, 1967; Dietrich,
577 1982). According to Stokes' law (Batchelor, 1967), a strong relationship exists between
578 the diameter of a particle and its settling velocity:

$$579 \quad w_s \propto D^2 \quad (3)$$

580 where w_s is the settling velocity of a spherical particle ($\text{m}\cdot\text{s}^{-1}$), and D is its diameter (m).
581 Particle diameter can thus reasonably be considered as a good proxy for estimating its
582 settling velocity. In an exploratory approach, study of grain size distribution of sediment
583 was performed for each site on individual floods. As shown in Fig. 8B, particle sizes
584 were very heterogeneous even within a single subcatchment, as suggested by the values
585 measured during two distinct events in Potrerillos (event 1: median diameter
586 $D_{50} = 24 \mu\text{m}$; event 2: $D_{50} = 6 \mu\text{m}$). Interstorm variability was even higher than intersite
587 variability. Grain size estimates in each subcatchment would thus require a complete
588 granulometric study that is beyond the scope of this paper. Flow discharge was
589 therefore conserved as an indirect indicator for the upward vertical turbulent velocity,
590 whereas SSC was considered as a broad indicator for the sediment settling flux (higher
591 SSC requiring higher energy to be transported).

592 A study of the relationship between SSC and Q was carried out in order to identify to
593 what extent the two parameters were associated and whether some subpatterns could be
594 identified from the available time series (Fig. 9). Among all SSC- Q data collected in
595 2009, values derived from the falling stages of the hydrographs were of particular
596 interest. While water flow was decreasing, high SSC values were indeed frequently
597 measured because of the severe hysteretic pattern generally observed. Such behaviour
598 was already deduced from the temporal analysis presented in section 4.2 and Fig. 6. The
599 limit in stream transport capacity should have been reached in such circumstances.
600 Figure 9 displays all SSC- Q values recorded during the 2009 rainy season. It
601 differentiates values occurring at falling stage from the others.

602 Independently of the location, the points recorded during recession phases were located
603 in the upper part of the scatter plots. In Potrerillos (Fig. 9A), these highest values as
604 well as a few others clearly defined an upper boundary that very likely corresponds to
605 the limit of stream transport capacity. The direct consequence of reaching this physical
606 constraint was the generation of a net sediment deposition in the channel (Jansson,
607 2002). This hypothesis supports the visual observations made in the field all throughout
608 the season. Erosive power of the stream was outlined by minimal values of detachment
609 capacity (lower boundary). This limit was approximately delineated, even though the
610 presence of two outliers can put its relevance into question (Fig. 9A).

611 In Huertitas (Fig. 9B) an upper boundary was also detected. Again, it was associated
612 with the in-channel transport capacity. The stream ability to erode and export sediment
613 was also clearly outlined: the lower boundary in Fig. 9B corresponds to the minimum
614 sediment load that the stream was able to dislodge from the riverbed. This finding
615 supports the results of section 4.2 that outlined that little material was stored within the
616 channel and that the streambed was preferentially eroded.

617 In La Cortina (Fig. 9C), both boundaries were also outlined, but the transport capacity
618 was much lower than in the two other sites. Again, this was consistent with findings of
619 section 4.2 (little sediment stored locally). Because of the relatively limited sediment
620 supply, the streambed is probably affected almost permanently by erosive conditions;
621 the highly incised morphology of the river channel in La Cortina could be a
622 consequence of this situation.

623 All the values defining the upper and lower limits were associated with distinct storm
624 events; it proves that a general behaviour was identified rather than transitory conditions
625 prevailing during a specific flood.

626 *4.4. Seasonality in sediment delivery*

627 Figure 10 shows the evolution of SSC values during the rainy season calculated for each
628 storm event. Despite a strong dispersion, mean SSC time series exhibited a decreasing
629 trend in all the subcatchments (Fig. 10A). Furthermore, this seasonal effect was neither
630 related to a change in peak discharges nor to a change in rainfall regime. This evolution
631 throughout the rainy season was even clearer in La Cortina and Huertitas. It probably
632 illustrates the progressive increase in the soil cover by vegetation in these partly
633 cultivated hillslopes (see Table 1), which is known to protect the soil against the erosive
634 action of rainfall. Similarly, sediment exported from Huertitas may not exclusively
635 originate from bare gullies (Evrard et al., in review).

636 In Huertitas, the highest mean SSC values were observed at the beginning of the wet
637 season (60 kg.m^{-3} on 15 May 2009). In Potrerillos and La Cortina, the most erosive
638 events occurred during the first part of the rainy season (respectively, 101 kg.m^{-3} on
639 1 July 2009 and 3 kg.m^{-3} on 14 July 2009). This outlines a progressive flush of the

640 channel sediment stock at the beginning of the rainy season (Hudson, 2003; Evrard et
641 al., in review).

642 Furthermore, a change was identified in La Cortina and Huertitas SSC records. SSC
643 values experienced a significant decrease even when associated with high discharge
644 peaks. This change affected all SSC data collected, as shown in Figs. 10B and 10C. At
645 both sites, SSC decrease was linked with an increase in baseflow contribution and
646 occurred from 3 August 2009 in La Cortina (Fig. 10B) and from 4 September 2009 in
647 Huertitas (Fig. 10C). Again, this remarkable change of the hydrosedimentary processes
648 probably illustrates the impact of land cover change through the rainy season.

649 *4.5. Comparison with other subcatchment sediment yields reported in the world*

650 We aimed at comparing our results to previous research carried out in small catchments
651 (1-10 km²). However, most of the references found in the literature report measurements
652 in mesoscale to large basins (i.e., > 100 km²). According to the few data available for
653 comparison, sediment export in La Cortina appeared to be low to moderate (Table 4); it
654 roughly corresponds to values measured in lowland areas under temperate climate
655 (Walling et al., 2002; Goodwin et al., 2003; Lefrançois et al., 2007; Smith, 2008). SSSY
656 estimates in Huertitas and Potrerillos were much higher, and they can be compared to
657 the loads exported from a mountainous subcatchment located in the northern Ethiopian
658 Highlands (Nyssen et al., 2008). However, sediment exports in Potrerillos and Huertitas
659 remain lower than export rates measured by Mathys et al. (2003) in highly erodible
660 marly terrains of the French Alps. Nevertheless, we hypothesized that the values we
661 found are representative of upstream catchments locally undergoing severe erosion
662 processes. Overall, our results provide very useful erosion estimates for small

663 mountainous catchments with a subhumid climate, which remain largely undocumented
664 in the literature.

665

666 **5. Conclusions**

667 For the first time, suspended sediment yields of three upland subcatchments located in
668 the Mexican Central Highlands were estimated during a whole year. Each subcatchment
669 exhibited a specific behaviour. Two catchments exported high sediment yields (i.e.,
670 Huertitas, [900-1500] t.km⁻².y⁻¹ and Potrerillos, [600-800] t.km⁻².y⁻¹). In contrast, the
671 third catchment generated a rather low sediment export (i.e., La Cortina, 30 t.km⁻².y⁻¹).

672 At the scale of the entire 630-km² basin, we could not derive any direct relationship
673 between rainfall intensity and sediment concentration. This can be explained by the high
674 spatial variability of rainfall and by the effect of the vegetation growth throughout the
675 season, which provided a protection to the soil against erosive rainfall. Erodible
676 sediment availability on hillslopes was identified as the main factor controlling
677 suspended sediment delivery. The occurrences of numerous active gullies in Huertitas
678 and Potrerillos provided a constant sediment source linked to the river network, which
679 explains the high SSY recorded at both stations. At the subcatchment scale, a
680 combination of various parameters was responsible for sediment control. Peak
681 discharges during floods were found to be significantly associated with exported loads;
682 discharge proved to be a controlling factor when sediment was not lacking. This limit in
683 stream transport capacity preferentially occurred during hydrograph falling limbs. A
684 minimum erosive power was detected in Huertitas and La Cortina. It was regularly
685 reached during floods. In these subcatchments, the role of seasonality was particularly
686 clear, with higher sediment export in the first months of the rainy season. This may be
687 attributed to the growth of the vegetation throughout the rainy season. The rapid

688 succession of several storms was also a cause for high sediment exports, and
689 particularly in Potrerillos. This was associated with a preliminary filling of the channel
690 storage, without compaction or drying out of particles, which was rapidly followed by a
691 channel flush; but it may also be due to a better connectivity between active gullies and
692 stream channels.

693 Further studies should now concentrate on a better characterization of fine sediment
694 settling flux within channels in order to improve our physical understanding of
695 deposition/resuspension dynamics at the subcatchment scale. Furthermore, the study of
696 nested subcatchments at the scale of the entire Cointzio basin should be carried out. It
697 would provide useful information on suspended sediment behaviour across mesoscale
698 river basins and contribute to improve hydrosedimentary models.

699

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932

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951

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956

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961

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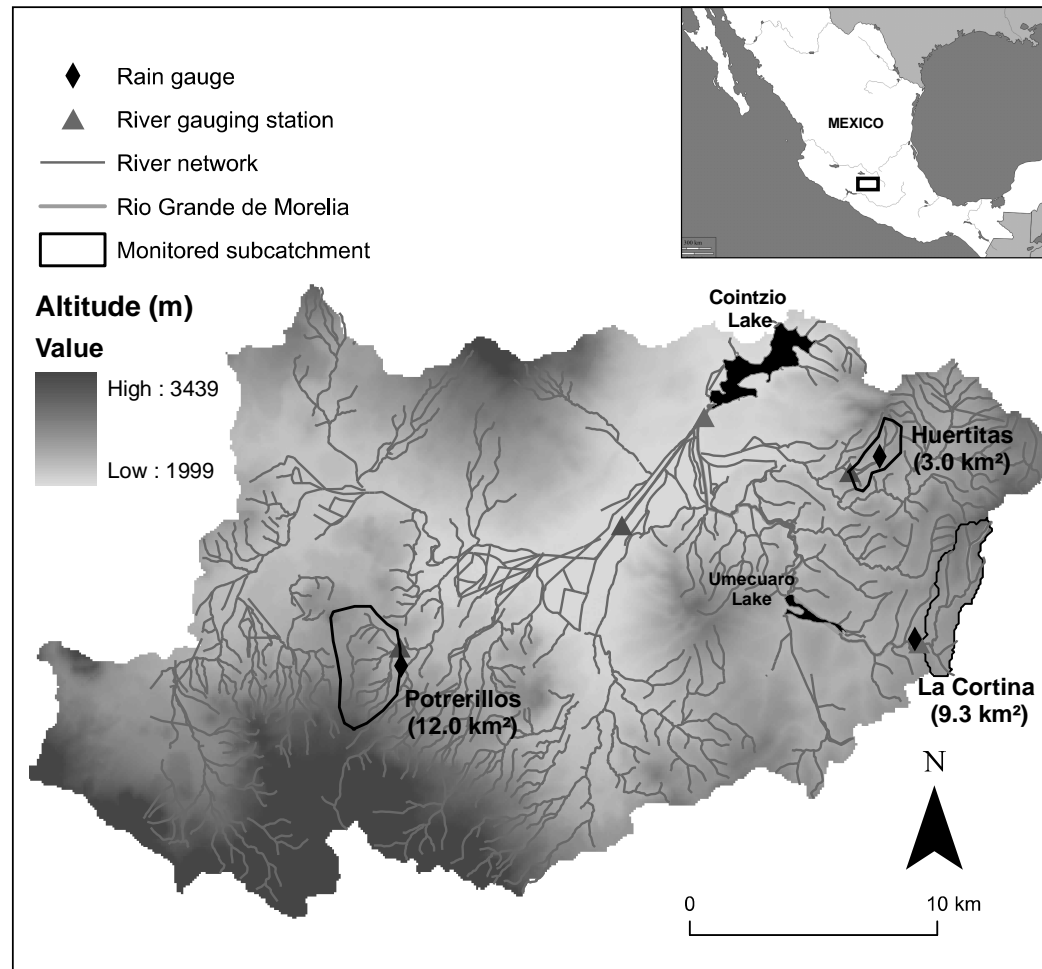
972

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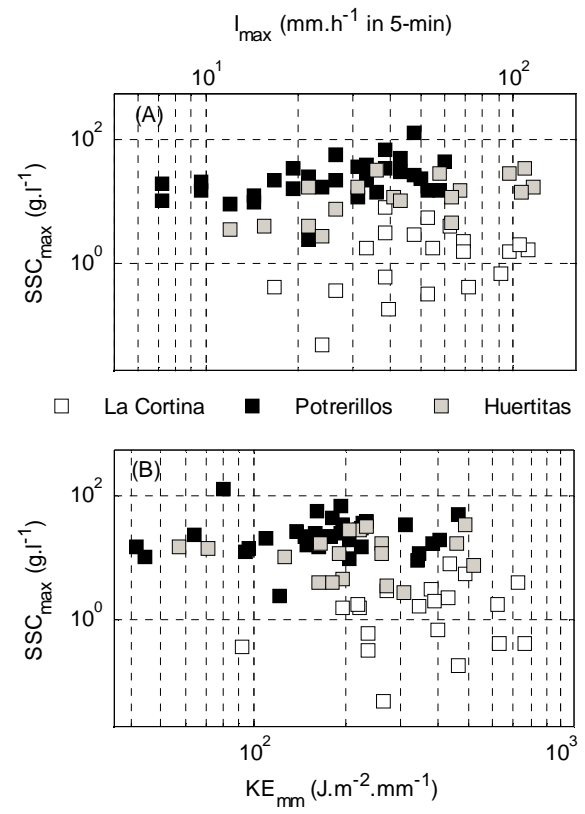
983 Fig. 1

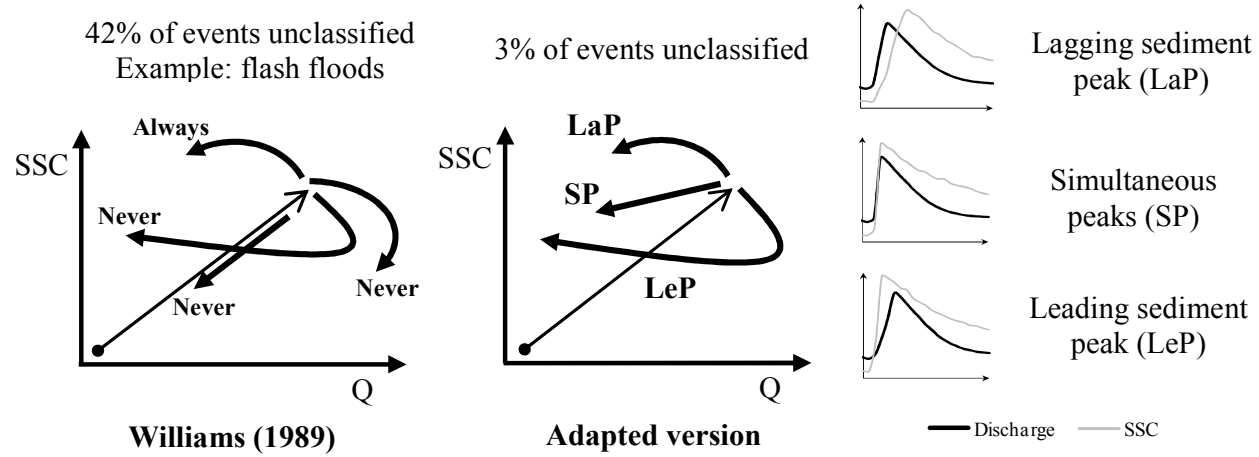


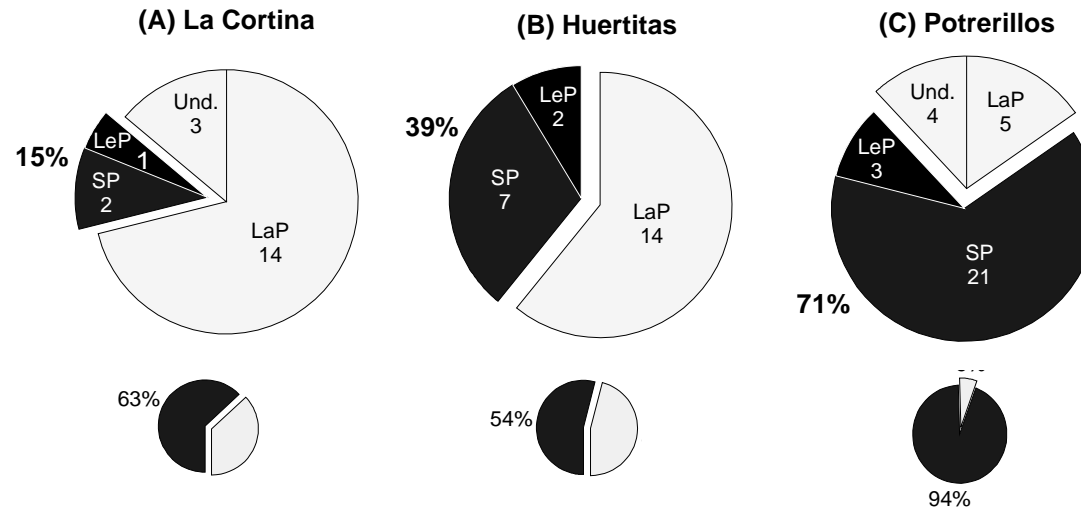
985 Fig. 2

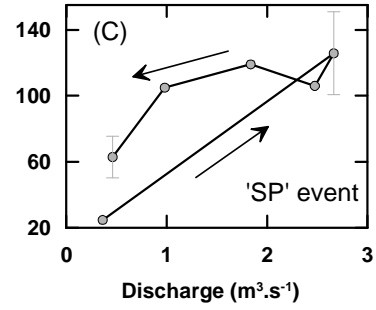
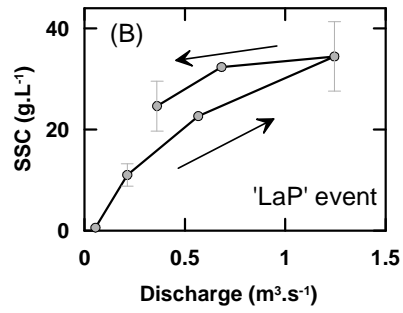
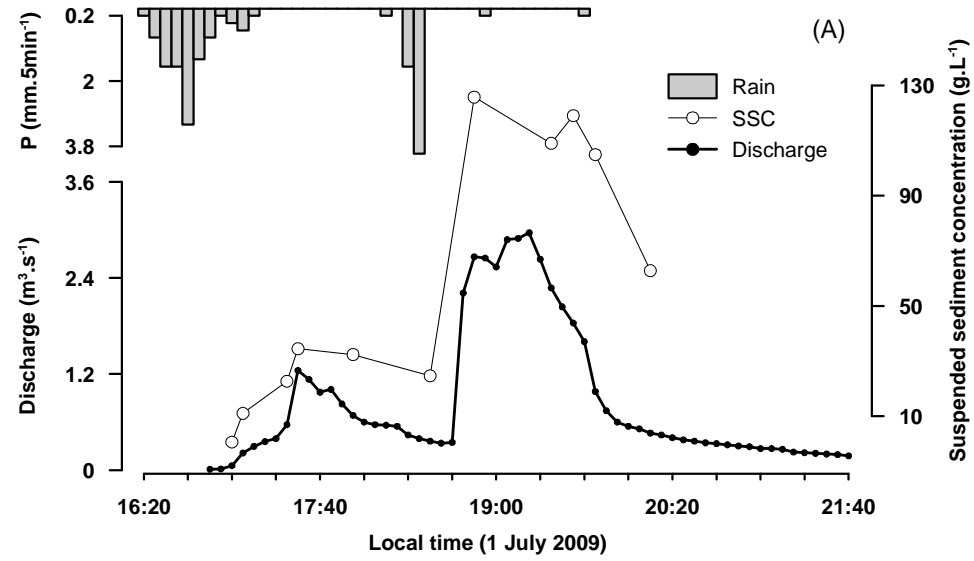


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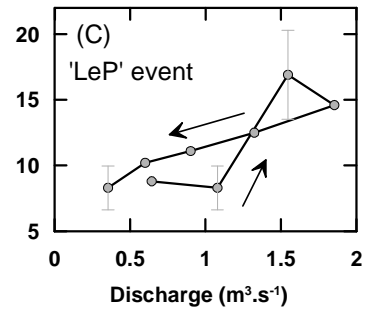
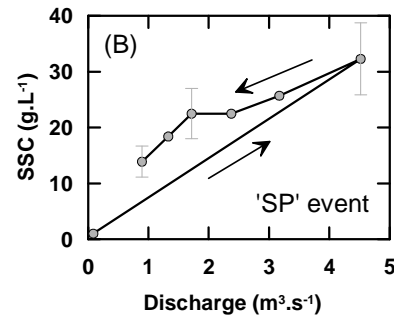
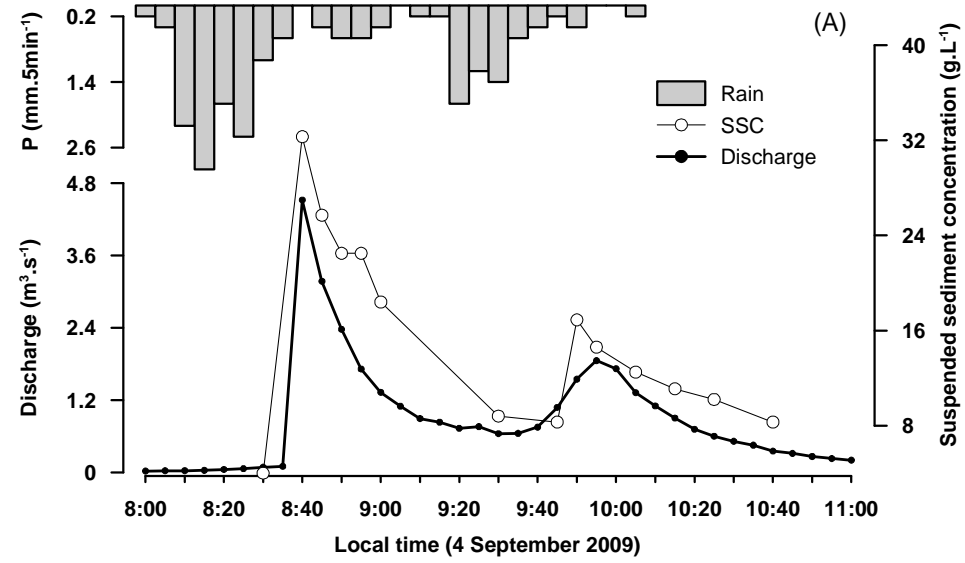


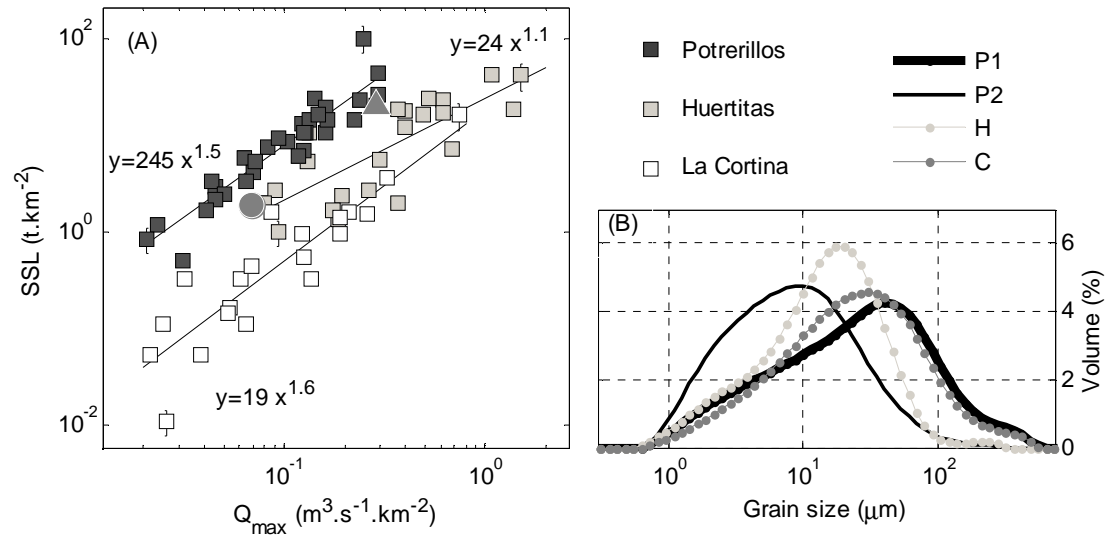


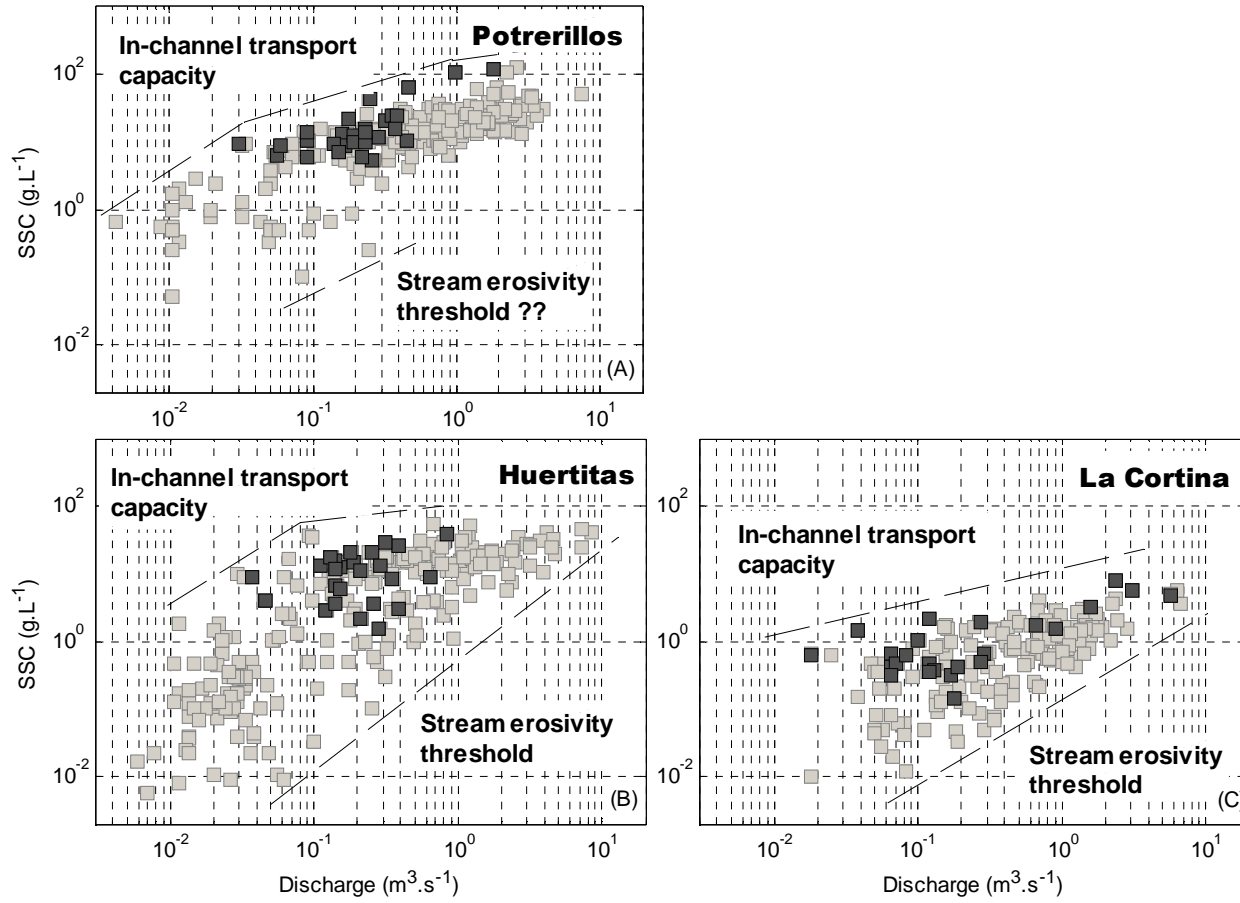


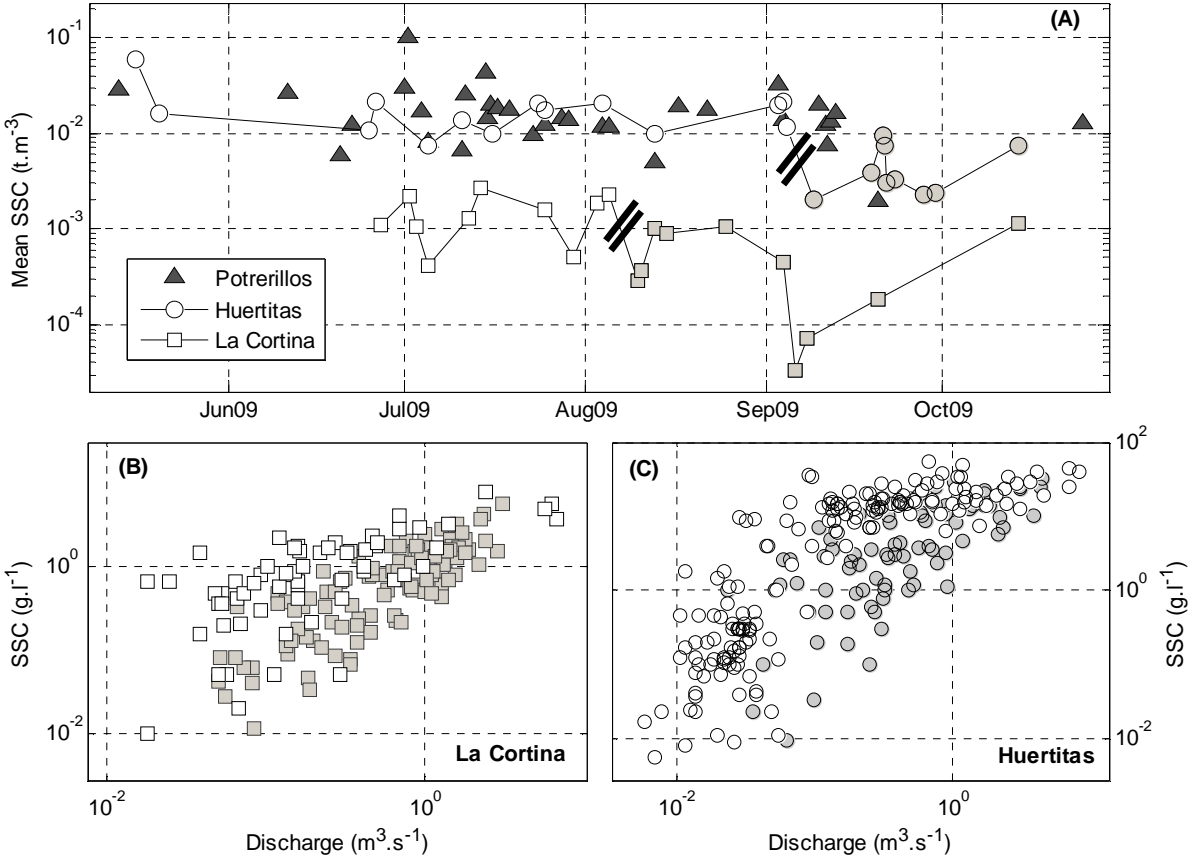


995 Fig. 7









1003 Table 1
 1004 Main characteristics of the three study sites^a
 1005

	Area (km ²)	Altitude range (m)	Mean slope (%)	Main land uses	Main soil types	Severely eroded areas (% of catchment surface)	Mean discharge during the dry season (L.s ⁻¹)	Mean discharge during the wet season (L.s ⁻¹)	Mean SSC (mg.L ⁻¹)
La Cortina	9.3	2250- 2700	12	Forest (52%), cropland (46%)	Andisols (100%)	0	10-30	100-200	5
Huertitas	3.0	2150- 2450	18	Rangeland (65%), cropland (28%), gullied (6%)	Acrisols (100%)	6	0.05-1	10-30	30
Potreriillos	12.0	2200- 2700	15	Cropland (40%), forest (37%), grassland (23%)	Acrisols (60%), Andisols (40%)	1	0	20-50	1000

1006
 1007 ^a Data from the three last columns were collected during monthly surveys carried out in 2007 and 2008. The high mean SSC value in Potreriillos
 1008 is a direct consequence of the ephemeral behaviour of the stream. Measurements could only be conducted immediately after storms and before
 1009 the streams dried out.

1010
1011
1012

Table 2
Semiquantitative parameters computed for each storm

Parameter	Description	Class
Flood	Hydrograph rising phase > 5 min	Slow
characteristic	Hydrograph rising phase < 5 min	Fast
Initial moisture conditions	Events without significant rainfall in the last 24 h	1 (dry)
	Significant rainfall (> 4 mm) without flood generation	2 (wet+)
	Significant rainfall (> 4 mm) with minor flood generation	3 (wet++)
	Significant rainfall (> 4 mm) with major flood generation	4 (wet+++)

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Table 3
Estimation of the suspended sediment yields exported from the three study sites in 2009

Station	2009 sediment delivery (t) ^a	Area (km ²)	Specific suspended sediment yield (t.km ⁻² .y ⁻¹) ^a
La Cortina	300	9.3	30
Huertitas	2600 ⁽¹⁾	3.0	900 ⁽¹⁾
	4600 ⁽²⁾		1500 ⁽²⁾
Potrerillos	7400 ⁽¹⁾	12.0	600 ⁽¹⁾
	9500 ⁽²⁾		800 ⁽²⁾

1017
1018
1019

^a (1) refers to low estimates and (2) refers to high estimates (including the expected contribution of ungauged events).

1020

Table 4

1021

Suspended sediment yields measured in other small catchments

1022

Subcatchment	Years of monitoring	Area (km ²)	SSY (t.km ⁻² .y ⁻¹)	Reference
Lower Smisby	1997-1999	2.6	80	Walling et al., 2002
Rosemaund	1997-1999	1.5	82	Walling et al., 2002
Stanley Cars	1999-2001	4.6	94	Goodwin et al., 2003
Moulin	1988-2000	0.9	5700	Mathys et al., 2003
Brusquet	1988-2000	1.1	80	Mathys et al., 2003
Moulinet	2002-2003	4.5	25	Lefrançois et al., 2007
Violettes	2002-2003	2.2	36	Lefrançois et al., 2007
May Zegzeg	1998-2001	2.0	560	Nyssen et al., 2008
Flyers Creek	2005-2006	1.6	8	Smith, 2008

1023