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1 **Geomorphic and vegetation changes in a meandering dryland river regulated by a large**
2 **dam, Sauce Grande River, Argentina**

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16
17 **Abstract**

18 This paper investigates post-dam geomorphic and vegetation changes in the Sauce Grande
19 River, a meandering dryland river impounded by a large water-conservation dam. As the dam
20 impounds a river section with scarce influence of tributaries, sources for fresh water and
21 sediment downstream are limited. Changes were inspected based on (i) analysis of historical
22 photographs/imagery spanning pre- (1961) and post-dam (1981, 2004) channel conditions for
23 two river segments located above and below the dam, and (ii) field survey of present channel
24 conditions for a set of eight reference reaches along the river segments. Whilst the
25 unregulated river exhibited active lateral migration with consequent adjustments of the
26 channel shape and size, the river section below the dam was characterized by (i) marked
27 planform stability (93 to 97%), and by (ii) vegetation encroachment leading to alternating yet
28 localized contraction of the channel width (up to 30%). The present river displays a moribund,
29 stable channel where (i) redistribution of sediment along the river course no longer occurs and
30 (ii) channel forms constitute a remnant of a fluvial environment created before closing the
31 dam, under conditions of higher energy. In addition to providing new information on the
32 complex geomorphic response of dryland rivers to impoundment, this paper represents the

33 very first geomorphic assessment of the regulated Sauce Grande and therefore provides an
34 important platform to underpin further research assessing the geomorphic state of this highly
35 regulated dryland river.

36 *Keywords:* flow regulation; geomorphic changes; vegetation changes; dryland rivers; Sauce
37 Grande River; Paso de las Piedras Dam

38

39 **1. Introduction**

40 Drylands — which include dry-subhumid, semiarid, arid, and hyperarid regions — cover 40%
41 of the Earth's surface and contain almost 40% of the global population (UNEM, 2011).

42 Population growth and changing living standards force increased water allocation for urban,
43 agricultural and industrial use (Young and Kingsford, 2006; Schmandt et al., 2013). As a

44 result, water resources in drylands tend to be heavily exploited through dams, weirs, canals,
45 and other structures (Davies et al., 1994). Although most dams in drylands are multipurpose

46 dams, with hydropower and flood control as common primary functions, many of them

47 operate as water-conservation structures to support irrigation and/or drinking water supply.

48 Water- conservation dams maintain the reservoir as full as possible and impound the entire

49 runoff volume in periods of reservoir filling (Petts, 1984). Thus, the disparity between natural

50 and regulated flow regimes may be particularly striking in drylands (Walker et al., 1995).

51 One particular concern is that dryland fluvial processes (and therefore the fluvial response to

52 impoundment) may be very different from those generally accepted in more humid regions

53 (Tooth, 2000b, 2013; Nanson et al., 2002). Dryland rivers are characterized by extreme

54 variability in flow and sediment transport (Davies et al., 1994; Bunn et al., 2006; Young and

55 Kingsford, 2006). Long periods of little or no flow are interspersed with floods of high,

56 sometimes extreme magnitude (Tooth and Nanson, 2000), short duration (Graf, 1988), and

57 low predictability (Poff and Ward, 1989). Floods control erosion, transport, and deposition

58 processes (Bull and Kirkby, 2002) and therefore constitute the major determinant of dryland
59 channel shape and size (Tooth, 2000b). As morphogenetic floods exhibit highly skewed
60 frequency (Tooth, 2000b), complete adjustment of dryland channel form to process is
61 sometimes inhibited (Bull and Kirkby, 2002). Feedback mechanisms between channel form
62 and process are rarely found in drylands (Tooth, 2000a), and therefore researchers have a
63 tendency to presume that dryland rivers are in an unstable, nonequilibrium state (Tooth and
64 Nanson, 2000).

65 The unstable character of natural dryland rivers challenges assessing the impacts of flow
66 regulation on dryland channel forms. Notable advances on the complex response of dryland
67 rivers to impoundment have been made in the United States and Australia, as well as in
68 central Asia, South Africa, and South America in minor extent. For example, Friedman et al.
69 (1998) found that regulated braided rivers in the American Great Plains tend to narrow owing
70 to vegetation encroachment (such as has occurred in the Orange River, South Africa;
71 Blanchon and Bravard, 2007), whereas meandering rivers tend to reduce their migration rates
72 (e.g., the upper Missouri; Shields et al., 2000). In the American Southwest (e.g., Green River;
73 Merritt and Cooper, 2000; Grams and Schmidt, 2002), the most common response to
74 impoundment involved reduced channel capacity by aggradation and vegetation invasion of
75 lateral deposits, such as has occurred in dryland rivers of Australia (e.g., Cudgegong River;
76 Benn and Erskine, 1994), the Mediterranean Basin (e.g., Medjerda River in Tunisia; Zahar et
77 al., 2008), and South America (e.g., Chubut River in Argentina; Kaless et al., 2008). The
78 studies cited above, among many others, have certainly contributed to the understanding of
79 form to process relationships in regulated dryland rivers. Yet most of the previous research
80 has centred on locations where tributaries contribute water and sediment below the dam, and
81 very few studies have investigated geomorphic adjustments in flood-driven, regulated dryland
82 rivers where tributary influence below the dam is scarce.

83 This paper examines geomorphic and vegetation adjustments in a meandering dryland river
84 where (i) flow regulation is extreme and (ii) sources for flow and sediment below the dam are
85 limited to erratic reservoir discharges and reworked local alluvium because the river flows
86 without influence of tributaries. It aims to address two fundamental questions: (i) how do
87 flood-driven, dryland channels adjust their morphology in highly regulated, low stream power
88 settings with scarce influence of tributaries? and (ii) how does riparian vegetation interact
89 with (and react to) altered river hydrology and morphology in dry, highly regulated fluvial
90 settings? The study centres on the Sauce Grande River below the Paso de las Piedras Dam
91 (central-eastern Argentina), where prior geomorphic assessment is limited to reconstructions
92 of Quaternary fluvial processes at the broad scale of the river basin. Change in channel
93 geometry (planform and cross section) and riparian vegetation structure are quantified
94 simultaneously above and below the dam using a sequence of rectified aerial photographs and
95 high-resolution imagery spanning pre- and post-dam channel conditions. Changes as a
96 function of distance downstream from the dam are also examined.

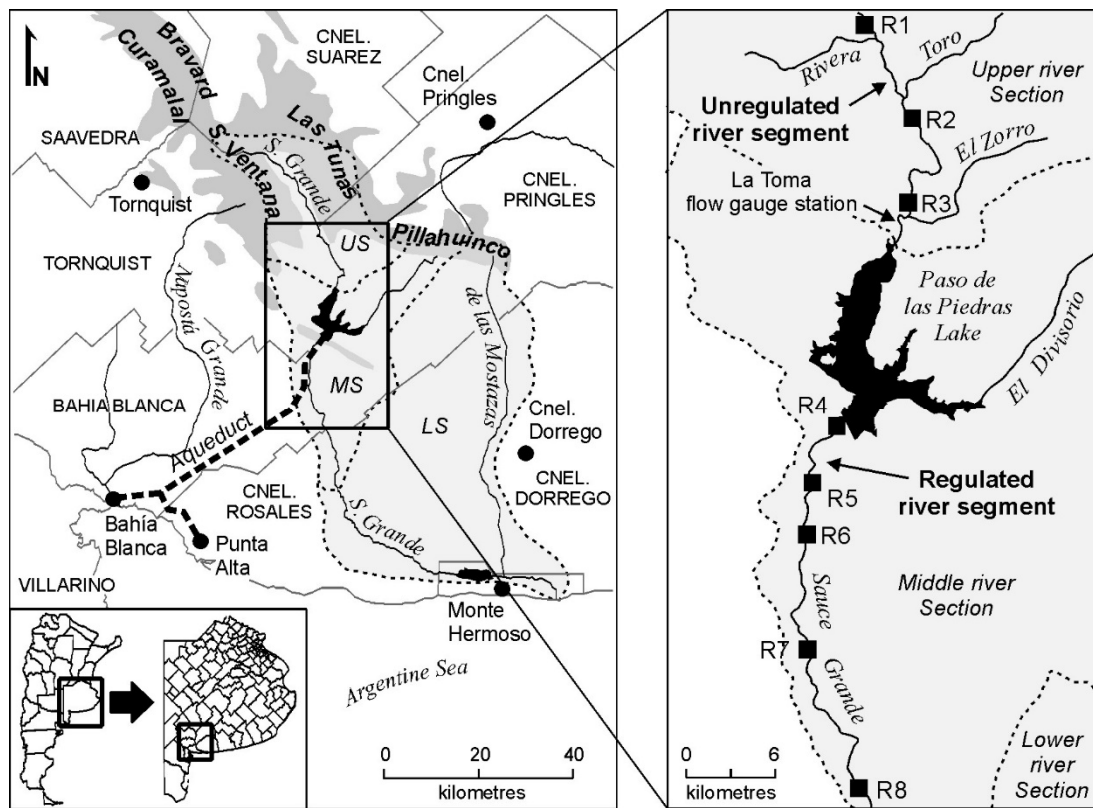
97

98 **2. Materials and methods**

99 *2.1. Study site*

100 The Sauce Grande River collects its waters on the eastern slope of the Sierra de la Ventana
101 Range and flows down into the Atlantic Ocean draining a basin area of ~4600 km² (Fig. 1).
102 The climate in the majority of the river basin is dry-subhumid. Mean annual rainfall decreases
103 from 800 mm in the uplands to 640 mm in the lowlands, and mean annual potential
104 evapotranspiration is 1030 mm (Paoloni et al., 1972). Interannual rainfall variability is
105 marked and linked primarily to alternating phases of ENSO (Scian, 2000), inducing episodes
106 of drier- and wetter-than-normal climate (Campo et al., 2009; Bohn et al., 2011). Recurrence

107 of drought and increasing water demand owing to population growth very seriously impact on
 108 local water resources (Andrés et al., 2009).

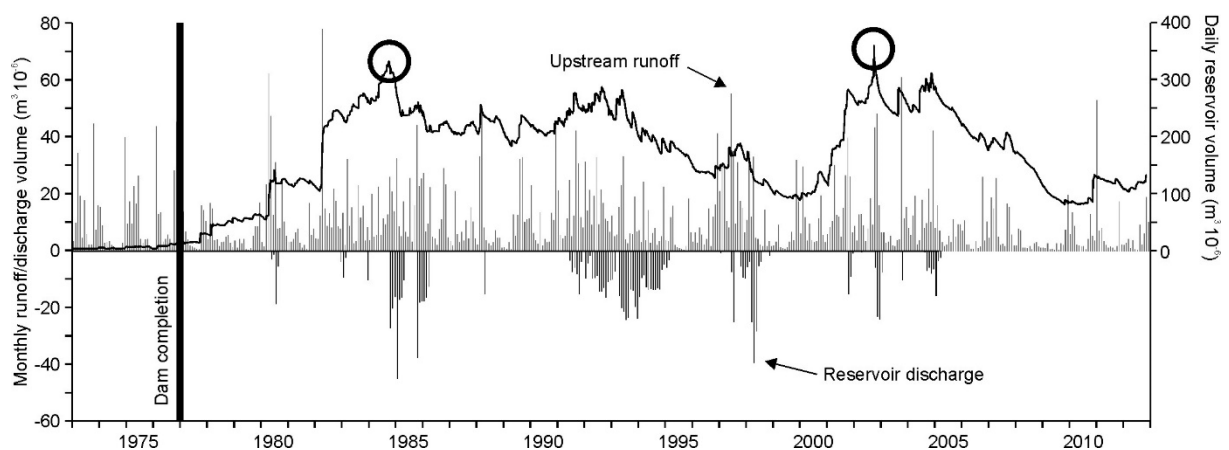


109
 110 Fig. 1. Map of the Sauce Grande River basin showing main regional features (left) and the
 111 river segments selected for analysis (right). The location of reference river reaches (R)
 112 each river segment is also illustrated. US, MS and LS in the left map designate the upper,
 113 middle, and lower river sections, respectively.

114 *2.1.1. Hydrological context*

115 The natural river flow regime is perennial flashy (rainfed) and event-driven. Mean daily flow
 116 (1910-1947) is $3.4 \text{ m}^3 \text{ s}^{-1}$, but floods may reach more than $1000 \text{ m}^3 \text{ s}^{-1}$ in a few hours (Schefer,
 117 2004). The Paso de las Piedras Dam (initiated in 1972 and completed in 1978) impounds the
 118 middle river section for water supply to the cities of Bahía Blanca and Punta Alta (Fig. 1). Its
 119 reservoir has a surface area of 36 km^2 and a maximum storage capacity of $328 \text{ m}^3 \cdot 10^{-6}$ for 25
 120 m depth (Schefer, 2004). Annual yield to meet water demand is $65 \text{ m}^3 \cdot 10^{-6}$; this is about 60%
 121 of the mean annual inflow volume ($107.2 \text{ m}^3 \cdot 10^{-6}$). The remaining volume is conserved within

122 the reservoir to assure water supply in periods of drought; flow release downstream occurs
 123 only in periods of full storage. Water is conducted either through the bottom gate (controlled
 124 flow releases) or through the overflow spill weir (uncontrolled release).
 125 Figure 2 illustrates monthly runoff volumes at La Toma (Fig. 1) and monthly volumes of
 126 reservoir discharge as a surrogate of flow magnitude upstream and downstream from the dam.
 127 Gauged and estimated reservoir discharges indicate that the reservoir has absorbed the full
 128 range of inflow volumes over 19 years of record (48%). In years recording reservoir
 129 discharges, annual runoff volumes were reduced by 54%, annual maxima were reduced by
 130 42%, and annual minima were reduced by 86%. The reservoir history registers only two
 131 episodes of overflow spills (1984 and 2002), during which the flood wave was attenuated by
 132 31 and 34%, respectively. In the absence of flow release, downstream flow averages $0.26 \text{ m}^3\text{s}^{-1}$
 133 ¹ and originates from reservoir seepage below the dam structure. Except for some ephemeral
 134 tributaries, the Sauce Grande River receives no permanent flow inputs until its confluence
 135 with de las Mostazas Creek (lower river section; Fig. 1) about 110 river km downstream from
 136 the dam closure.

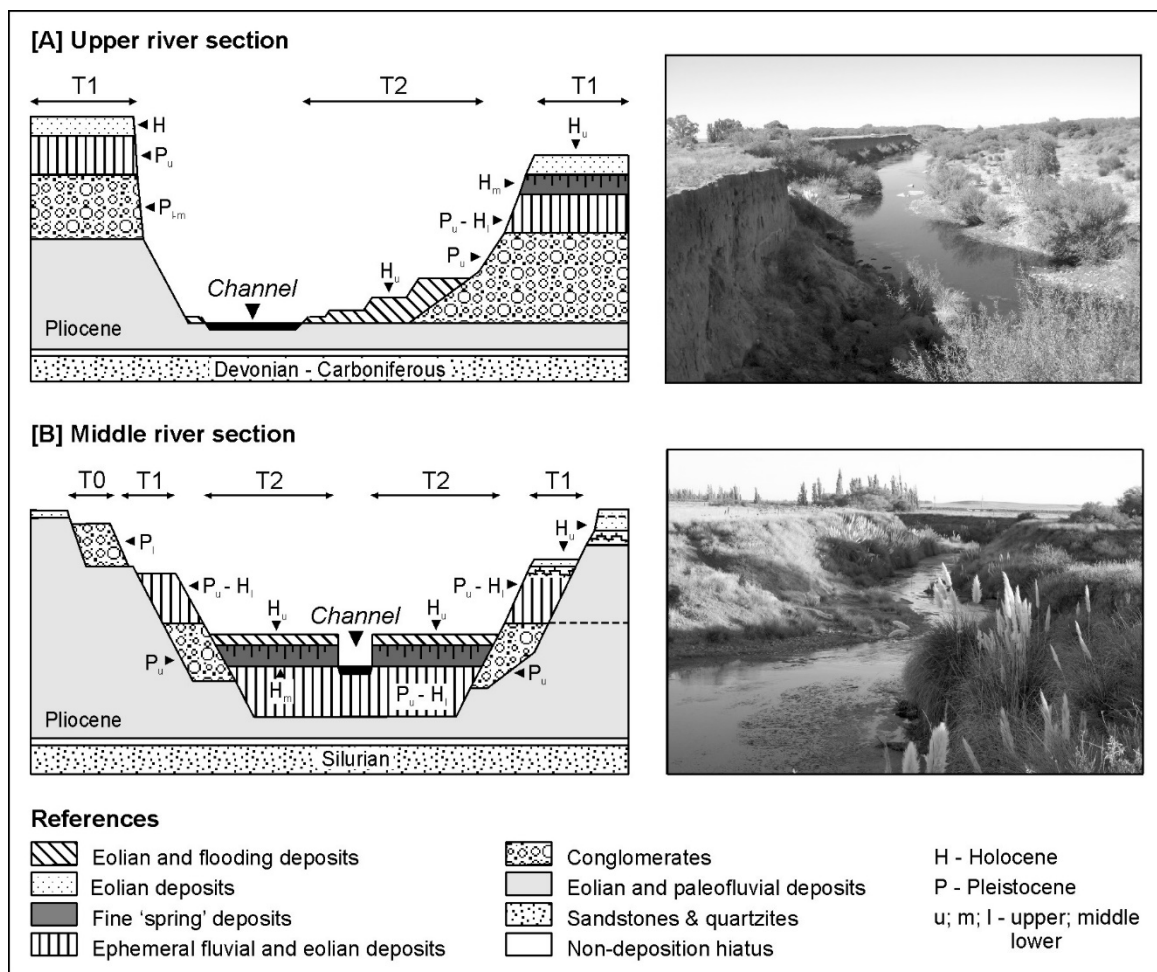


137
 138 Fig. 2. Monthly runoff volume upstream from the dam and monthly volumes of reservoir
 139 discharge over the period 1973-2012. Upstream runoff volumes were estimated from rainfall
 140 using the GR2M model (Makhlouf and Michel, 1994). Monthly volumes of reservoir
 141 discharge over the period 1973-1988 were calculated by solving the reservoir water balance

142 equation (missing data). Daily reservoir volumes were illustrated to provide an idea of the
 143 hydrological magnitude of the dam relative to that of the river. Circles indicate episodes of
 144 overflow spills.

145 *2.1.2. Geomorphic context*

146 In its upper-middle course, the Sauce Grande River exhibits clear meandering patterns, low
 147 longitudinal gradient (0.002, in average), and pool-riffle bed morphology. It flows on the
 148 bottom of a broad and deeply incised valley (Rabassa, 1982) excavated on Pliocene-
 149 Pleistocene loess deposits (Quattrocchio et al., 1993). Three terrace remnants along the valley
 150 (T0 to T2; Fig. 3) give evidence of at least three superimposed sequences of valley incision
 151 and compound fill, including gravitational, aeolian, and ephemeral fluvial deposits (Zavala
 152 and Quattrocchio, 2001; Quattrocchio et al., 2008).



153
 154 Fig. 3. Schematic cross sections of the Sauce Grande River showing typical geomorphic and

155 geologic characteristics within the upper and middle river sections. Geologic features were
156 modified from Borromei (1991), Zavala and Quattrocchio (2001), and Quattrocchio et al.
157 (2008). Not to scale.

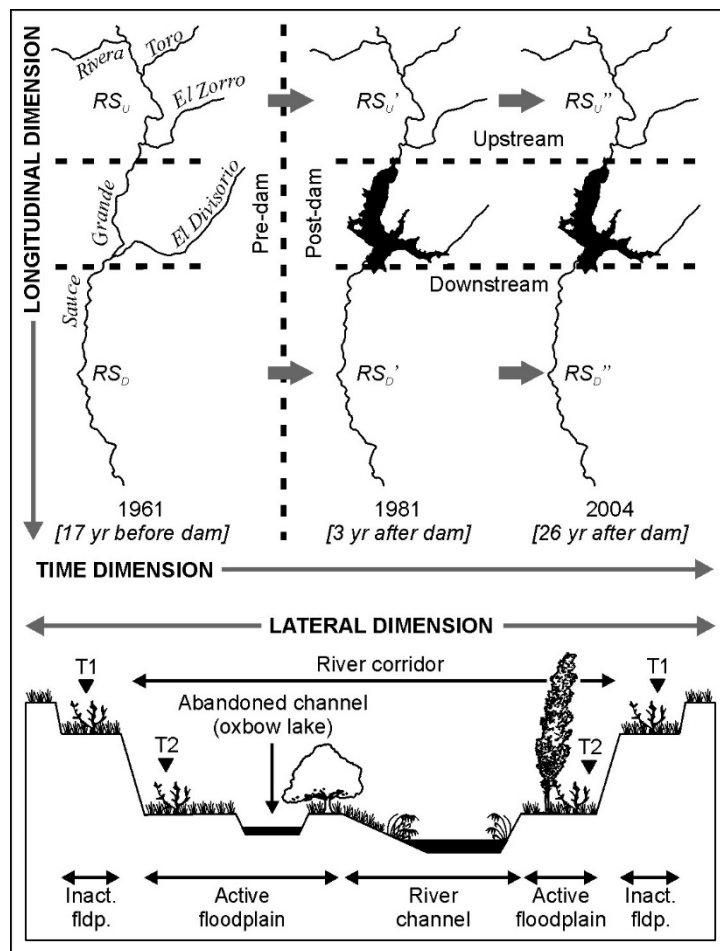
158 Downstream variations in channel forms and size are apparent (Fig. 3) and conceivably linked
159 to the attenuation of floods and flow transmission losses characteristic of dryland
160 environments (Tooth, 2000a). In the upper section, the river channel is wide, shallow, and
161 develops on the bottom of the incised valley. Migration of the meanders and point bar
162 building outward led to formation of small terrace steps that have changed the original
163 configuration of the valley bottom. In the middle river section, the valley broadens markedly,
164 the terraces lose altitude, and the degree of confinement decreases. The river flows through a
165 narrow, deep, and tortuous channel that constitutes a remnant of an ancient braided
166 morphology (Borromei, 1991). Former braids were covered by aeolian deposits, and the
167 present floodplain constitutes an abandoned portion of the original braided channel.

168

169 *2.2. Scales of analysis*

170 This paper quantifies post-dam geomorphic and vegetation changes across multiple scales
171 (Fig. 4). Changes with time were inspected using a chronological sequence of historical aerial
172 photographs (1961, 1981) and high-resolution imagery (Ikonos, 2004) defining two
173 comparative periods. The first period (1961-1981) spans a pre-disturbance phase,
174 characterized by unregulated flow conditions, and a phase of early disturbance linked to dam
175 completion in 1978 and initial filling of the reservoir (Fig. 2). The second period (1981-2004)
176 spans the post-disturbance phase where the dam controls the magnitude, frequency, duration,
177 and variability of downstream flows. Changes from unregulated to regulated river conditions
178 for a given time step were inspected by contrasting two river segments located above and
179 below the dam (~26- and 41-km length, respectively). In addition, field-based descriptions of

180 present channel conditions (2011-2012) were performed for eight reference reaches of 1-km
 181 length located above (3 reaches) and below (5 reaches) the dam (Fig. 1).



182
 183 Fig. 4. Spatial and temporal scales used in geomorphic and vegetation analysis. Quantification
 184 of change within the regulated river segment (RS_D) is performed with time ($RS_D \rightarrow RS_D''$) and
 185 with respect to the unregulated river segment upstream (RS_U). Upstream and downstream
 186 river segments were delineated by the extent of the river corridor in each time step.

187

188 2.3. GIS- and field-based analyses

189 We have mapped fluvial forms and land cover types within each river segment and for each
 190 time step used in analysis using ArcGIS (ESRI©). Mapped fluvial forms included the river
 191 channel and major floodplain features such as abandoned meanders, oxbow lakes, and
 192 terraces (Fig. 4). In this paper, the term ‘river corridor’ encompasses the river channel

193 (delimited by the top portions of cutbanks and point bars) and the active floodplain, i.e., *the*
194 *alluvial surface next to the channel, separated from the channel by banks, and built on*
195 *materials transported and deposited by the present regime of the river* (Graf, 1988, p. 214).
196 Mapped land cover types include: (i) surfaces with none or little vegetation (bare surfaces);
197 (ii) surfaces covered by water; (iii) agricultural lands, including crops and pastures; (iv)
198 grasslands, dominated by graminoid species of *Stipa* and important associations of pampas
199 grasses (*Cortaderia seollana*); and (v) woodlands, clearly dominated by native species of
200 willow (*Salix humboldtiana*). In vegetation analysis, the term ‘riparian vegetation’ refers
201 explicitly to grasses and woods developing within the river corridor. Field-based analysis of
202 present channel conditions in the reference reaches used the stream reconnaissance scheme
203 devised by Thorne (1993) and included: (i) survey of the channel geometry (slope, planform,
204 and cross section); (ii) description of channel forms and materials, and (iii) interpretation of
205 vertical and lateral relations of channel to floodplain.

206

207 *2.4. Quantification of geomorphic and vegetation changes*

208 *2.4.1. Geomorphic changes*

209 Geomorphic analysis considered two aspects of the channel geometry: the channel planform
210 and the channel width as indicator of channel capacity. Quantification of planform change
211 used measures of channel activity (Wellmeyer et al., 2005). Overlay of channel bank lines
212 between consecutive time steps [$T_1 : T_2$] provided three distinct types of channel area: (i) the
213 area occupied during both time periods (planform stability), (ii) the area occupied only in the
214 second time step (channel creation), and (iii) the area occupied only in the first time step
215 (channel abandonment). Percent of channel stability, creation, and abandonment were
216 calculated relative to total channel area in T_1 . Rates of channel creation (or abandonment)
217 were calculated as channel area gained (or lost) in $T_1 : T_2$ divided by the time interval length

218 $[T_2 - T_1]$. To determine rates of stream lateral migration in terms of length per unit time
219 (Shields et al., 2000), we measured the area enclosed by successive stream centrelines (active
220 migration area, A_m). Rates of stream lateral migration were then calculated as the ratio of A_m
221 to the stream centreline length in T_1 , divided by the time interval length $[T_2 - T_1]$.
222 Quantification of width change used series of transects splitting the channel every 200 m of
223 channel length. This provided two types of measure: absolute channel width, given by the
224 length of each transect, and relative channel width, calculated as the area enclosed between
225 consecutive transects divided by channel length. Differences in width $[w]$ between
226 consecutive time steps $[w_{T_2} - w_{T_1}]$ provided a net measure of channel narrowing (negative
227 differences) or widening (positive differences) along each river segment.

228 *2.4.2. Vegetation changes*

229 Changes in the composition of the fluvial corridor were inspected by overlaying successive
230 land cover maps. This provided a measure of the proportion (%) of riparian landscape gained
231 or lost by each land cover type. The direction and the strength of land cover changes with
232 time were assessed based on cross-tabulation of results and interpretation of transition
233 diagrams. Changes in riparian vegetation were measured in terms of (i) surface area gained or
234 lost by each vegetation type (changes in vegetation structure) and (ii) transitions to (or from)
235 other landscape units (vegetation dynamics). This permitted identification of patterns of
236 vegetation establishment (nature and extent) along the river course and with time.

237

238 *2.5. Error analysis*

239 Errors in quantification of geomorphic and vegetation change originate from (i) distortions in
240 the geometry of aerial photographs used as a data source and (ii) digitizing procedures.
241 Scanned aerial photographs were first corrected for scale and terrain distortions using ground
242 control point orthorectification in ErMapper. Orthorectification used high-resolution imagery

243 (2004) and a 10-m contour-derived DEM (Casado et al., 2010). Orthorectified photographs
244 were then transformed in ArcGIS using the adjust transformation algorithm as it optimizes for
245 global and local accuracy. The RMSE from transformation of single photographs averaged
246 2.2 m (SD = 1.8 m) for 1961 photographs and 1.2 m (SD = 1.0 m) for 1981 photographs;
247 mean RMSE for all photographs was 1.7 m (SD = 1.5 m). Errors associated with digitizing
248 procedures were estimated using the method of Downward (1994). Positional errors were
249 calculated from redigitizing the same feature 50 times using 2004 Ikonos imagery as source.
250 For a digitizing scale of 1:2500, errors averaged 0.7 m (SD = 0.4 m). Mean errors from
251 transformation of the photographs and digitizing procedures can be accumulated to give a
252 total mean error of 2.4 m. The total error margin for an exceedance probability of 10% is 4.8
253 m.

254

255 **3. Results**

256 *3.1. Geomorphic change*

257 *3.1.1. Planform change*

258 The unregulated river exhibited marked channel activity (Table 1; Fig. 5). Although new
259 channel surfaces were created by meander migration (10.6%) and cutoff (2.1%), the period
260 1961-1981 was characterized by abandonment of channel surfaces owing to meander
261 translation (15.1%; Fig. 5, Ex. 1) and abandonment of meander bends (3.1%; Fig. 5, Ex. 2).
262 Channel activity during the period 1981-2004 was clearly dominated by meander extension
263 and translation. High percentages of channel abandonment (19.8%) indicate a tendency to
264 channel straightening. Yet increased bend amplitude in some river sections was notable (Fig.
265 5, Ex. 3), and three major cutoffs in the middle-lower river segment (Fig. 5, Ex. 4) give
266 evidence of the geomorphic effectiveness of floods during the second comparative period.

267

268 Table 1

269 Rates of channel and stream activity within the unregulated and regulated river segments by
 270 comparative period

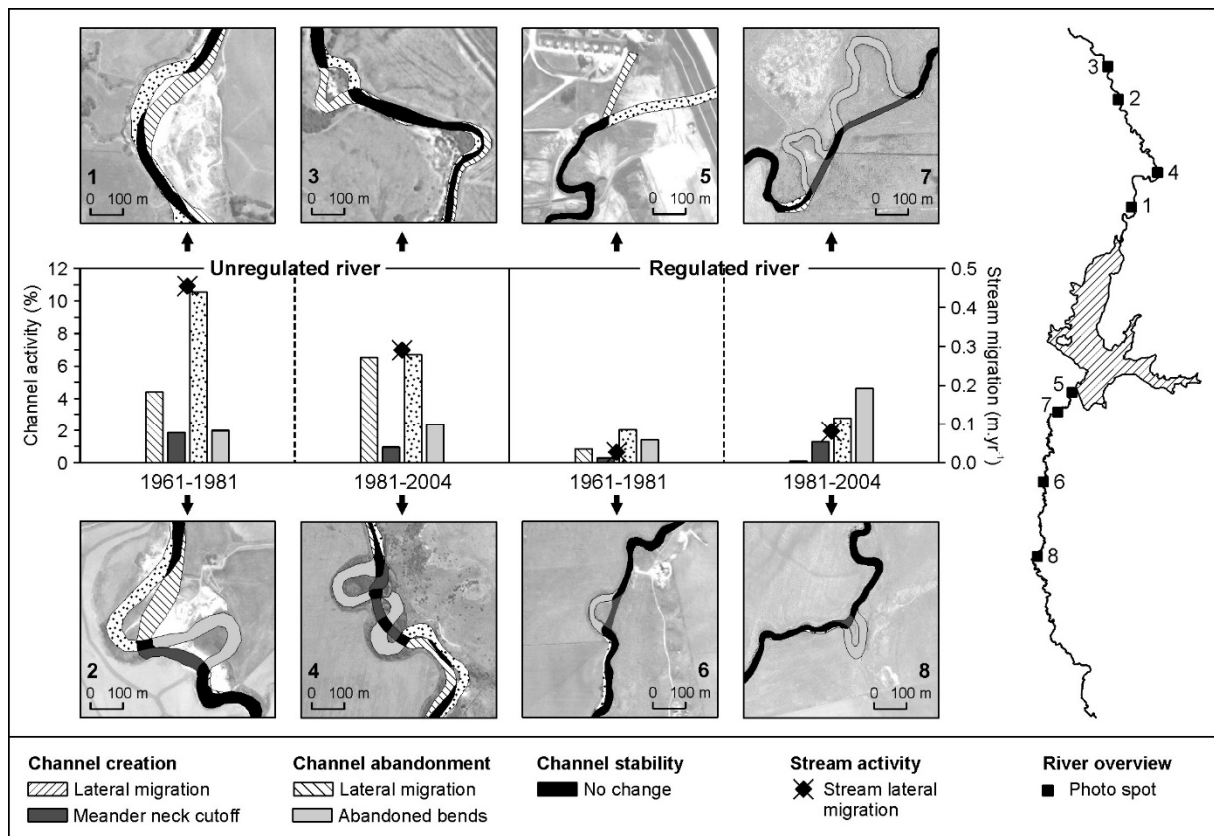
		Unregulated river segment		Regulated river segment	
		1961-1981	1981-2004	1961-1981	1981-2004
<i>Channel migration (m^210^{-2})</i>					
Channel creation	By lateral migration	52.3	49.2	3.3	3.3
	Meander cutoff	10.2	4.1	1.1	1.1
Channel abandonment	By lateral migration	74.7	81.2	7.9	7.9
	Abandoned bends	15.1	11.1	5.5	5.5
<i>Stream lateral migration (m^{-1})</i>		0.31	0.26	0.02	0.06

271 Conversely, the river channel below the dam exhibited marked planform stability during both
 272 comparative periods (93 to 97%). Channel activity during the period 1961-1981 was closely
 273 related to waterworks conducted in the vicinity of the dam (e.g., deviation of the river course
 274 from its original position to the dam outlet; Fig. 5, Ex. 5). Localized translation of meander
 275 bends occurred in the middle-upper river segment, and two abandoned bends were observed
 276 at river km 2 and 13 below the dam. Whereas the cutoff morphology in the first case suggests
 277 a human-related origin, the latter was conceivably cutoff by high flows occurring during the
 278 pre-disturbance phase (Fig. 5, Ex. 6). Meander cutoff and abandonment of meander bends
 279 were dominant processes during the post-disturbance phase (1981-2004). Yet four out of five
 280 cutoffs displayed a human-related origin (e.g., two major cutoffs facilitate canalization of dam
 281 spills; Fig. 5, Ex. 7). Percentage of channel abandonment was five times that of channel
 282 creation (7.4 and 1.4%, respectively), and the channel sinuosity was reduced by 2.7%.

283 *3.1.2. Width change*

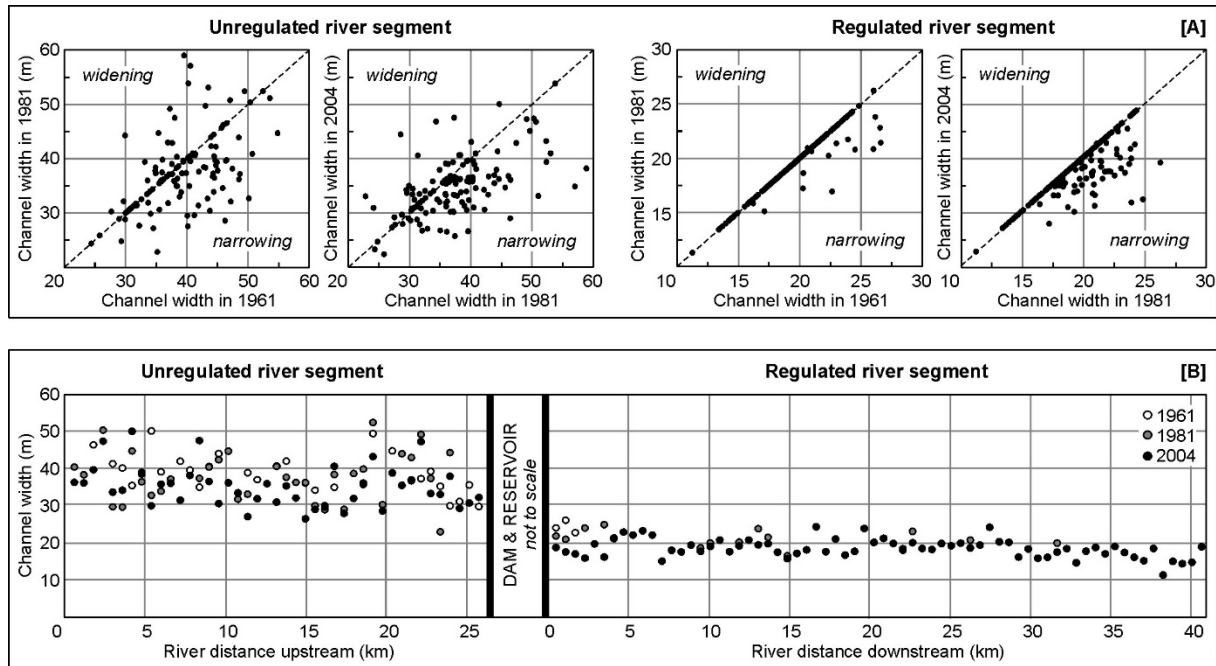
284 Upstream from the dam, coupled channel widening and narrowing occurred during both
 285 comparative periods with a tendency to narrowing during the second comparative period (Fig.
 286 6). Width changes occurred most likely in river sections exhibiting active lateral migration.
 287 Thus, many channel sections narrowed owing to lateral accretion and outward migration of

288 meander bends (up to 50% during 1961-1981, and up to 60% during 1981-2004), and river
 289 sections dominated by cut bank erosion increased in width by up to 62% (1961-1981) and
 290 55% (1981-2004). Below the dam, the channel revealed a tendency to narrowing during both
 291 comparative periods (Fig. 6). The period 1961-1981 was characterized by marked contraction
 292 of the channel width (12 to 33%) owing to deviation and artificial straightening of the river
 293 course in the vicinity of the impoundment. During the period 1981-2004, the channel width
 294 contracted in 31 sites (15% of cases). The percentage of channel narrowing decreased in the
 295 downstream direction from 44 to 4% and responded to two distinct, localized processes.
 296 Immediately below the dam and over ~4 river km, the channel narrowed by between 9 and
 297 44% owing to artificial meander cutoff, building of artificial levees, and other dam-related
 298 waterworks. Downstream from river km 4, the position of bank lines remained relatively
 299 unchanged. However, contraction of the channel width (6 to 30%) was inferred by vegetation
 300 encroachment over former bare channel surfaces.



301
 302 Fig. 5. Channel and stream activity within the unregulated and regulated river segments by

303 comparative period. Boxes provide an overview of major planform changes above and below
 304 the dam per comparative period. The scheme on the right shows the relative situation of major
 305 planform changes within each river segment.
 306



307
 308 Fig. 6. [A] Scatterplots comparing the river channel width between consecutive time steps,
 309 and [B] river channel width as a function of time and distance downstream. Channel width
 310 was calculated as a function of channel area divided by 200-m length along each river
 311 segment. The hashed central line in [A] indicates a situation of no change between
 312 consecutive time steps. Data in [B] were reduced to improve readability (1 point every 600 m
 313 of channel length). The error margin for an exceedance probability of 10% is 4.8 m.

314
 315 *3.2. Vegetation changes*

316 An overall tendency to vegetation growth was observed simultaneously upstream and
 317 downstream from the dam (Table 2). Yet there were marked upstream-downstream
 318 differences concerning (i) the spatial extent of vegetation growth, (ii) the nature of vegetation
 319 transitions, and (iii) the patterns of vegetation establishment.

320 First, the expansion of woodlands within the river corridor downstream from the dam was
 321 four times smaller than that observed within the unregulated river upstream (91 and 397%
 322 between 1961 and 2004, respectively), and the surface area occupied by woodlands in 2004
 323 was 53% of that observed upstream (Table 2). Yet the proportion of woodlands as percentage
 324 of total river corridor surface area in 2004 was similar for both river environments (23 and
 325 28%, respectively).

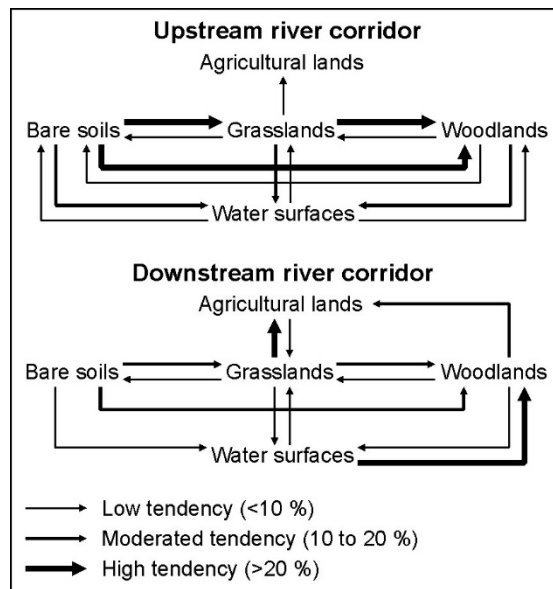
326 Table 2

327 Surface area by land cover type within the unregulated and regulated river segments per time
 328 step; rates of change with time were calculated based on absolute surface differences per time
 329 interval; highest percentages of change by cover type are indicated in bold

Cover type	Surface area (ha)			Difference (ha)		Rate of change (%)	
	1961	1981	2004	1961-81	1981-04	1961-81	1981-04
<i>Unregulated river segment upstream from the dam</i>							
Agricultural lands	24.9	10.7	8.8	-14.2	-1.9	-57.0	-18.0
Water surfaces	50.4	149.9	157.3	99.4	7.4	197.1	4.9
Bare soils	66.1	33.3	10.9	-32.8	-22.4	-49.6	-67.3
Grasslands	250.2	192.7	121.8	-57.5	-70.9	-23.0	-36.8
Woodlands	23.4	28.5	116.4	5.1	87.9	21.8	308.0
<i>Regulated river segment downstream from the dam</i>							
Agricultural lands	12.7	45.1	86.8	32.4	41.6	255.2	92.2
Water surfaces	28.8	26.9	20.8	-1.9	-6.1	-6.6	-22.7
Bare soils	1.0	2.1	0.2	1.1	-1.9	102.4	-92.8
Grasslands	191.3	155.5	96.5	-35.8	-59.0	-18.7	-37.9
Woodlands	32.4	36.6	62.0	4.2	25.4	12.9	69.3

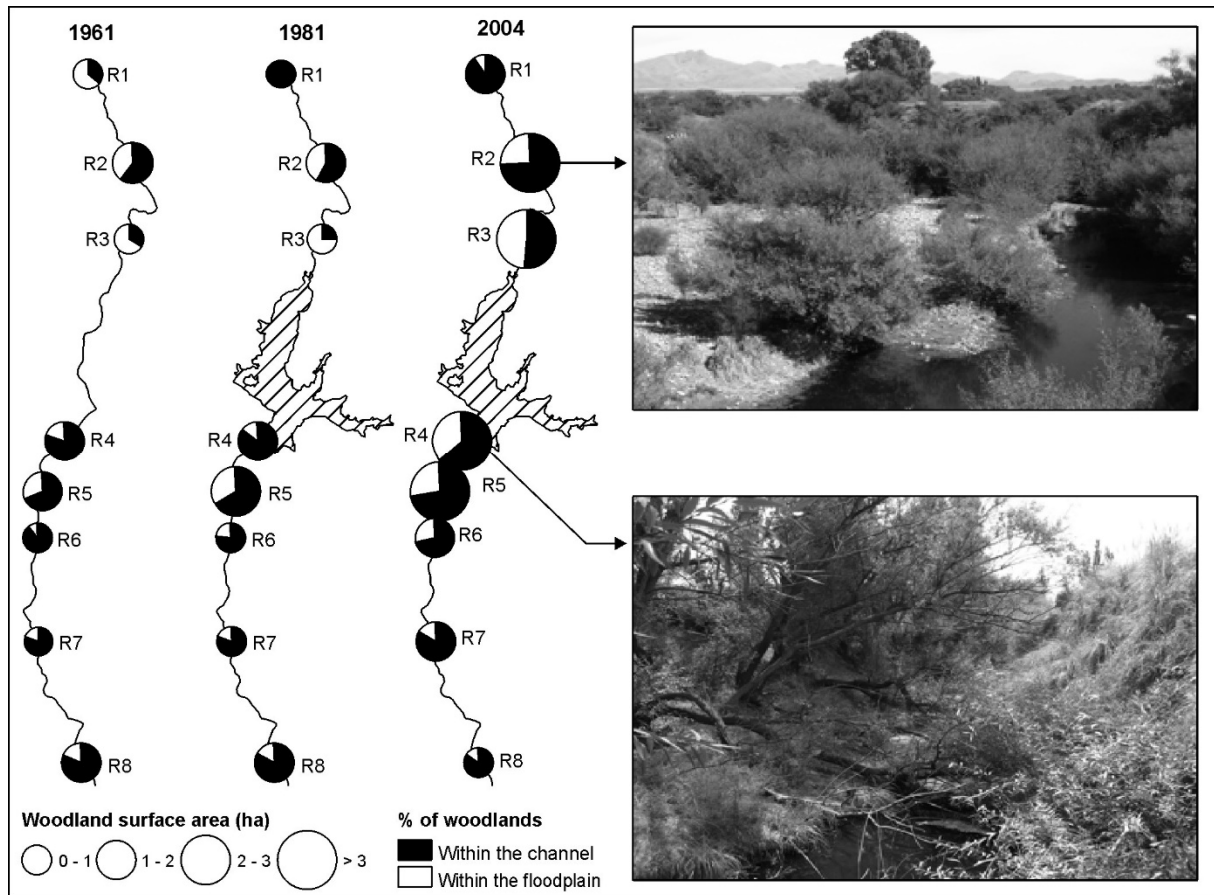
330 Second, the river corridors upstream and downstream from the dam revealed contrasting
 331 trends in vegetation dynamics (Fig. 7). Other than the expansion of agricultural lands over
 332 grasslands (583% between 1961 and 2004; Table 2), the most important transitions
 333 downstream occurred from water surfaces to woodlands (38%). This suggests a tendency for
 334 woody vegetation establishment within the river channel, near to the water surface. A
 335 moderated tendency for woody vegetation growth over former bare banks (18%) and

336 grasslands (16%) was also identified. Yet the expansion of woodlands over these landscape
 337 units was notably less significant than that observed within the river corridor upstream from
 338 the dam (Fig.7). Upstream, woodlands expanded within the river channel and the floodplain,
 339 covering 33% of former grasslands and 57% of former bare banks.



340
 341 Fig. 7. Trends in vegetation dynamics within the river corridors upstream and downstream
 342 from the Paso de las Piedras Dam. Trends were calculated from transitional diagrams of
 343 landscape units by comparative period.

344 Third, woody vegetation establishment within the river corridor downstream from the dam
 345 was discontinuous, decreased in the downstream direction, and constrained almost exclusively
 346 to the river channel. Analysis at the scale of the reference reaches (Fig. 8) revealed three
 347 distinct patterns of woody vegetation establishment with distance from dam closure: (i)
 348 immediately downstream from the dam and over ~10 river km, woody vegetation develops
 349 within the channel and adjacent to the water surface forming extensive and continuous
 350 alignments (e.g., R4 and R5); (ii) downstream thereafter, woody vegetation develops in a
 351 narrow and discontinuous strip along the stream over ~20 river km (e.g., R6 and R7); (iii)
 352 downstream from river km 30, channel vegetation is dominated by grasslands and alternating
 353 alignments of young willows developing near the water surface (e.g., R8).



354

355 Fig. 8. Surface area occupied by woodlands by river reach (R) and time step. Pie charts
 356 differentiate percentages of woody vegetation developing within the river channel and the
 357 floodplain. Photos provide an example of vegetation encroachment within the channel
 358 upstream and downstream from the dam.

359

360 3.3. Present channel conditions

361 Present channel forms clearly differentiate river reaches located above and below the dam.

362 The river channel above the dam (Fig. 9) is broad and shallow ($27 < w:d < 37$), and the

363 floodplain is well developed for much of the river course. Channel width averages 53 m (± 16

364 m), and floodplain width averages 135 m with high variation (± 94 m). The channel

365 morphology is clearly meandering for all reaches; variations in sinuosity ($1.1 < 1.5$), meander

366 wavelength ($150 \text{ m} < 600 \text{ m}$), and meander width ($20 \text{ m} < 200 \text{ m}$) are probably linked to local

367 variations in slope and degree of confinement within the incised valley. Bed material is coarse

368 in riffles (cobbles and coarse gravel) and finer in pools (small gravels, sand and silt); banks
369 are composed of noncohesive deposits in point bars (sand and gravel) and of layered,
370 cohesive paleofluvial and aeolian deposits in cut banks (fine sand, silt and clay). Bank profiles
371 reveal active cut bank erosion including bank undercut and toe scour (especially in R3; Fig.
372 9); channel sections exhibiting vertical banks display coupled toe accumulation by mass
373 wasting. Lateral accretion in point bars is a more dominant process. Outward migration of the
374 meanders led to formation of terrace steps contained within the valley, and hence
375 topographically lower than the preincision surface.

376 The river channel below the dam is narrow and deep ($7 < w:d < 10$), and the floodplain is
377 much reduced (Fig. 10). Mean channel width is 21 m (± 6 m), and mean floodplain width is 53
378 m (± 30 m). Except for R5 where meanders are very tortuous ($S = 2.8$), sinuosity increases in
379 the downstream direction from 1.3 to 2.2. Bed material is composed of small gravel in riffles
380 and of silt/clay in pools; banks exhibit cohesive layers of fine 'spring' and ephemeral fluvial-
381 aeolian deposits. Bank profiles display stable conditions for most river reaches, except for R4
382 where mass wasting occurs in vertical banks with little vegetation cover. Immediately below
383 the dam, any evidence of channel activity is related to human intervention. For example,
384 artificial bed deepening in R4 facilitates evacuation of dam outlets and spills, and artificial
385 levees (built by dredging floodplain material) prevent bank overflowing. Outside the vicinity
386 of the impoundment, bed deposition of very fine materials (silt/clay and organic matter) leads
387 to localized reduction of the channel depth (e.g., R6; Fig. 10).

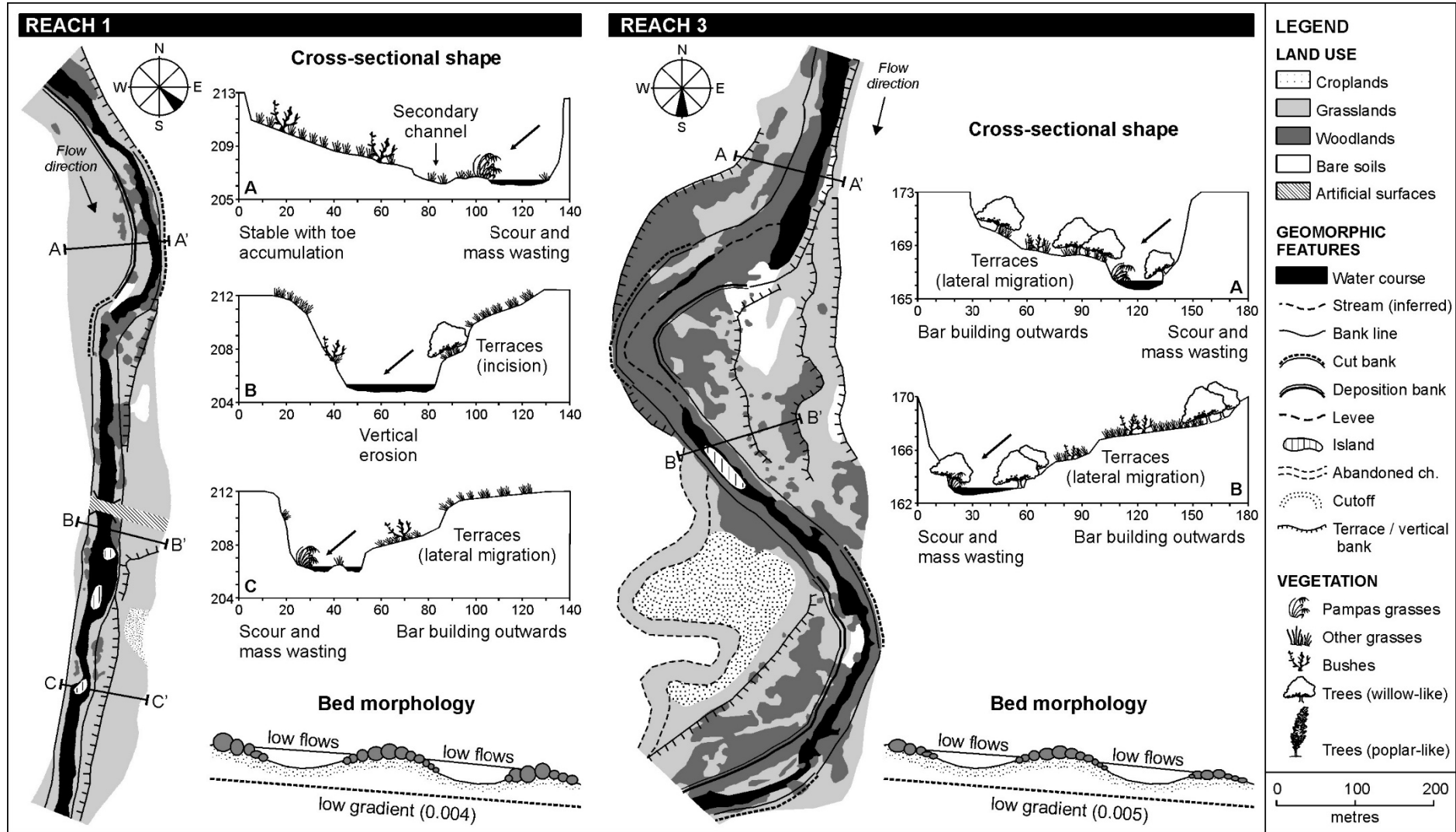


Fig. 9. Geomorphic features, land cover types, and representative cross sections for two reference reaches located upstream from the Paso de las Piedras Dam. The locations of the reference reaches along the unregulated river segment upstream are shown in Fig. 1.

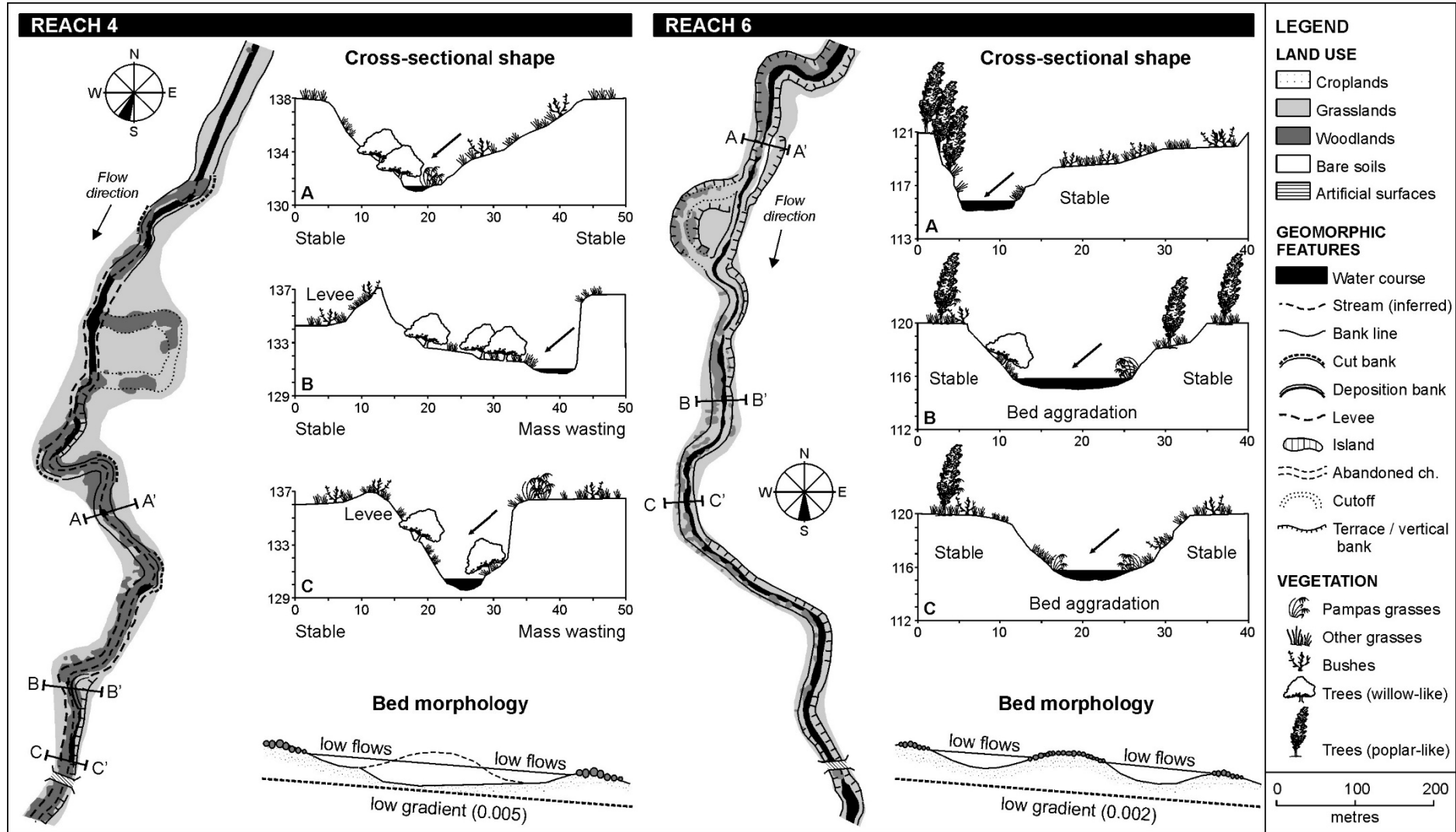


Fig. 10. Geomorphic features, land cover types, and representative cross sections for two reference reaches located downstream from the Paso de las Piedras Dam. The locations of the reference reaches along the regulated river segment downstream are shown in Fig. 1.

388 **4. Discussion**

389 *4.1. Geomorphic response of the Sauce Grande River to flow regulation*

390 The construction and operation of the Paso de las Piedras Dam led to substantial changes in
391 the hydrology of the Sauce Grande River downstream. The frequency and magnitude of
392 floods were dramatically reduced, and the permanence of low flows increased significantly.

393 Although the sediment trapping efficiency of the reservoir may be assumed as near 100%
394 (Petts, 1984; Williams and Wolman, 1984), this study postulates that under conditions of
395 extreme reduction in flow discharge, the impacts of the dam on the sediment transport
396 capacity of the stream were more significant than those on the sediment load.

397 If reduction in flow discharge is greater than that in sediment load, then one would expect a
398 dominance of aggradation processes over erosion and scour (Petts, 1979; Brandt, 2000), as
399 well as a tendency to channel narrowing and vegetation encroachment over bank deposits
400 increasing the channel roughness (Petts and Gurnell, 2005). The geomorphic response of the
401 Sauce Grande River, however, was characterized by (i) marked channel stability, (ii)
402 vegetation encroachment reflecting (and influencing) channel stability, and (iii) localized
403 reduction of the pre-dam channel capacity owing to vegetation growth. The following
404 sections expand on these findings and compare the geomorphic response of the Sauce Grande
405 River to other impounded rivers in dryland regions (Table 3).

406 *4.1.1. Channel stability*

407 One of the most common consequences of impoundment of meandering rivers in drylands is
408 the reduction of lateral migration rates (e.g., the upper Missouri and many other meandering
409 rivers within the American Great Plains; Table 3). Within the regulated Sauce Grande,
410 however, lateral channel migration was not reduced but inhibited. Any evidence of lateral
411 channel activity constrained to the phase of pre- and early disturbance and major planform
412 changes observed during the post-disturbance phase — such as meander cutoff and

413 abandonment of meander bends — revealed a human-related origin in 80% of cases. Planform
 414 stability has been reported for very few meandering rivers (e.g., the lower Murray; Table 3)
 415 and appears to be a more common consequence within regulated braided rivers (e.g., Orange
 416 and Durance rivers; Table 3).

417 Moreover, studies on impounded dryland rivers subject to reduced and overloaded flows have
 418 reported a substantial reduction of the channel capacity owing to lateral and vertical accretion
 419 (e.g., Rio Grande, Green, and Medjerda rivers; Table 3). In opposition, the regulated Sauce
 420 Grande displayed relative stability of the channel cross section. A marked contraction of the
 421 channel width was apparent over the first 4 river km below the dam closure. Yet channel
 422 narrowing was closely linked to deviation and artificial straightening of the river course,
 423 building of artificial levees, and other dam-related waterworks. Downstream from river km 4,
 424 the position of bank lines remained relatively unchanged for the three time steps used in
 425 photointerpretation analysis (i.e., a true reduction of the channel width by redistribution of
 426 sediment within the channel was not observed). Channel narrowing was inferred, however, by
 427 vegetation growth within the channel. Changes in channel depth involved localized deposition
 428 of very fine materials (silt/clay and organic matter). Although bed aggradation conceivably
 429 led to local variations in channel depth and slope, sediment deposition is negligible compared
 430 to that commonly reported in literature and will rapidly reverse during the next episode of
 431 flow release.

432 Table 3

433 Examples of geomorphic changes of regulated dryland rivers by world region

River	Impoundment	Purpose	Channel adjustments*	Citation
<i>North America</i>				
Colorado (Colorado)	Glen Canyon (1963)	Multipurpose	d ^{+/+} , bed armouring/aggradation, w ⁻ , CC ⁻ , s ⁻ , marsh development	Howard and Dolan (1981); Stevens et al. (1995); Grams et al. (2007)

Green (Colorado; Utah)	Flaming Gorge (1962)	Hydropower	d^- , $w^{+/+}$, n^+ (vegetation encroachment), bar stabilisation, island formation, terrace formation, planform change from meandering to shallow braided	Andrews (1986); Merritt and Cooper (2000); Grams and Schmidt (2002)
Dry Creek (California)	Warm Springs (1982)	Multipurpose	d^+ , w^- , CC^- , lateral migration $^-$, n^+ (vegetation encroachment)	Gordon and Meentemeyer (2006)
Bill Williams	Alamo (1968)	Flood control	w^- , CC^- , n^+ (vegetation encroachment), invasion of exotic species	(Shafroth et al. (2002); Stromberg et al. (2012)
Great Plains	Several	Multiple	w^- (braided rivers), lateral migration $^-$ (meandering rivers), vegetation growth/decrease relative to fluvial style	Friedman et al. (1998)
Upper Missouri (Montana)	Fort Peck (1940)	Hydropower; flood control	d^+ , w^- , bank instability $^+$, lateral migration $^-$	Darby and Thorne (2000); Shields et al. (2000); Simon et al. (2002)
Rio Grande (New Mexico)	Cochiti (1973)	Flood / sediment control	d^+ , bed coarsening, w^- , S^+ , bars and islands reduced, planform changes from braided to meandering, channel-floodplain disconnection	Richard and Julien (2003)
	Elephant Butte (1915)	Irrigation; hydropower	$d^{+/-}$, w^- (lateral accretion), CC^- , terrace formation, meander cutoff, disconnection from tributaries	Everitt (1993); Schmidt and Everitt (2000)
<i>Mediterranean Basin</i>				
Medjerda (Tunisia)	Sidi Salem (1981)	Flood control	d^+ , w^- , CC^- , n^+ (vegetation encroachment)	Zahar et al. (2008)
Ebro (Spain)	Ebro (1945); Yesa (1959)	Water supply; irrigation; hydropower;	w^- , river corridor width $^-$, lateral migration $^-$, n^+ (vegetation encroachment)	Magdaleno and Fernandez (2010)
Durance (France)	Serre Ponçon (1960) and others	Hydropower ; irrigation ; water supply	d^- , w^- , CC^- , n^+ (vegetation encroachment), planform stability	Lefort and Chapuis (2012)
<i>Central Asia</i>				
Yellow (China)	Sanmenxia (1960)	Flood and sediment control	$d^{+/-}$, $w^{+/+}$, CC^- , $s^{+/-}$, S^+ , Planform changes from braided to wandering and from wandering–braided to wandering–meandering (direction of channel adjustment varies with time)	Chien (1985); Wang and Hu (2004); Wang et al. (2007); Ma et al. (2012)

Australia

Cudgegong (NSW)	Windamere (1984)	Irrigation; water supply	$d^{+/-}$, localized bed coarsening-fining, $w^{-/0}$, CC^{-} , n^{+} (vegetation encroachment)	Benn and Erskine (1994)
Mangrove Creek (NSW)	Mangrove Creek (1981)	Water supply	$d^{+/-}$, w^{-} (lateral accretion), CC^{-} , n^{+} (vegetation encroachment)	Sherrard and Erskine (1991)
Upper Murray (NSW)	Hume (1925); Dartmouth (1928)	Irrigation; water supply	d^{+} , w^{+} (bank erosion), lateral migration ⁺ , anabranching	Tilleard et al. (1994)
Lower Murray (SA)	Locks 2 & 3	Navigation; irrigation	$d^{+/-}$, $w^{-/+}$, $s^{0/+/-}$, planform stability	Thoms and Walker (1993)
<i>South Africa</i>				
Orange	Vanderkloof & Gariep (1970's)	Hydropower; irrigation	Main channel planform stability, filling of secondary braids, n^{+} (vegetation encroachment)	Blanchon and Bravard (2007)
<i>South America</i>				
Chubut (Argentina)	Florentino Ameghino (1963)	Hydropower	d^{+} , w^{-} (lateral accretion), CC^{-} , n^{+} (vegetation encroachment), terrace formation	Kaless et al. (2008)
San Juan (Argentina)	Ullum	Multipurpose	d^{+} , localized armouring, bed instability, $s^{-/+}$	Grimalt and Grimalt (2005)

434 *[d] is channel depth, [w] is channel width, [CC] is channel capacity, [n] is channel
435 roughness, [s] is channel slope, and [S] is stream sinuosity. The direction of change is
436 indicated by [o] no significant change, [+] increase, and [-] decrease.

437 Two interrelated processes explain marked planform and cross section stability in the river
438 section below the dam. First, the morphology of the unregulated Sauce Grande is driven by
439 floods of high relative magnitude and low frequency common to most dryland rivers (Graf,
440 1988; Tooth, 2000b; Nanson et al., 2002; Tooth, 2013). Since the Paso de las Piedras Dam
441 retains nearly the full range of floods, the processes promoting migration of meanders bends
442 and adjustments of the channel cross section downstream were heavily truncated. As a result,
443 the broad morphology of the regulated Sauce Grande remained unchanged since dam closure
444 and is likely to exhibit stable conditions until a geomorphically significant flow event occurs.
445 Second, reduction of the magnitude and frequency of morphogenetic flows should promote
446 channel aggradation. However, and as reported by Petts (1979), channel aggradation below
447 dams requires introduction of sediment from tributaries and/or redistribution of sediment

448 within the channel. Within the regulated Sauce Grande both processes are unlikely. The river
449 below the dam flows for the majority of its course without influence of tributaries and, in the
450 absence of reservoir discharges, sources for water and sediment are limited to (i) reservoir
451 seepage, (ii) groundwater inflows, and (iii) overland flow along the river course. Combined
452 with the endogenous production of organic matter, these processes could explain bed
453 deposition of very fine materials. On the other hand, redistribution of sediment within the
454 regulated river channel is unlikely because the regulated flow is incompetent to rework the
455 pre-dam channel forms.

456 4.1.2. *Vegetation dynamics*

457 In opposition to what was expected, results revealed a synchronized tendency to afforestation
458 of the river corridor upstream and downstream from the dam. Vegetation growth involved
459 establishment of woody species such as willows (*Salix humboldtiana*, native species) and
460 poplars (*Populus sp.*, exotic species) and conceivably responded to a cycle of wetter climate
461 that affects central-eastern Argentina since the 1970s (Penalba and Vargas, 2004). As argued
462 by Braatne et al. (2008), cycles of dry and wet climate drive episodes of decline and recovery
463 in riparian communities, and the authors outlined that *these natural cycles provide a variable*
464 *baseline upon which impacts of damming and flow-regulation are superimposed* (p. 278).

465 Moreover, results revealed that the extent of the riparian zone downstream from the dam has
466 been reduced for much of the river course (and keeps reducing) because of the progression of
467 agricultural lands over the floodplain. The interacting influence of land use changes appends a
468 second factor superimposing the effects of dam operation on riparian vegetation.

469 Irrespective of climate and land use changes influencing vegetation dynamics at the scale of
470 the river basin, vegetation structure and successions along the river corridor are primarily
471 driven by a combination of hydrologic and geomorphic factors (Hupp and Osterkamp, 1996;
472 Hughes, 1997; Corenblit et al., 2007). Accordingly, altered hydrology and morphology within

473 the regulated Sauce Grande explain upstream-downstream differences in the spatial extent of
474 vegetation growth, in the nature of vegetation transitions, and in patterns of vegetation
475 establishment with distance downstream. .

476 *Hydrologic factors.* Flow regulation caused two major changes in the river hydrology below
477 the dam that have had direct influence on patterns of vegetation establishment. First, and as
478 reported for many regulated rivers in dryland regions (Table 3), the maintenance of base flow
479 levels has encouraged vegetation to establish on the channel bed and banks. Second, the
480 reduction of the magnitude and frequency of floods resulted in a disruption of lateral
481 processes of river-floodplain connectivity (productivity and disturbance) maintaining riparian
482 succession and diversity (Ward and Stanford, 1995; Ward, 1998). Recruitment of riparian
483 pioneers no longer occurs, and woody vegetation establishes within the main channel, near to
484 the water surface. In contrast to other impounded rivers in drylands, where altered flood
485 regimes caused substantial changes in the composition of riparian communities (e.g., invasion
486 of exotic, drought-tolerant species in the Green and Bill Williams rivers; Table 3), the quasi-
487 suppression of floods in this agricultural stream has encouraged farmers to extend their
488 practices to the river channel. At present, the floodplain is no longer 'active' and the riparian
489 zone is much reduced because of the advancement of agricultural lands.

490 *Geomorphic factors.* Downstream differences in patterns of vegetation establishment clearly
491 reflect (and influence) channel planform stability. Channel migration promotes establishment
492 of riparian pioneers by providing new bare and moist surfaces suitable for vegetation
493 establishment and growth (Hupp and Osterkamp, 1996; Friedman et al., 1998; Tockner et al.,
494 2010). Within the river upstream, this aspect was evidenced by landscape transitions from
495 bare bank surfaces to woodlands (57%). Downstream from the dam, lateral channel stability
496 prevented formation of new channel surfaces suitable for vegetation establishment, and
497 therefore vegetation development was constrained to the pre-dam channel shape. Immediately

498 below the dam, the valley-like channel forms permitted proliferation of willows over riparian
499 surfaces that are no longer subject to flood disturbance. Farther downstream, the channel is
500 narrower and deeper, which makes the area available for vegetation establishment relatively
501 small. Hence, willows develop discontinuously near the water surface where the bank slope
502 decreases and the soil moisture is high. This aspect explains the high percentage of transitions
503 from water surfaces to woodlands (38%) within the river corridor downstream.

504 *4.1.3. Reduced channel capacity*

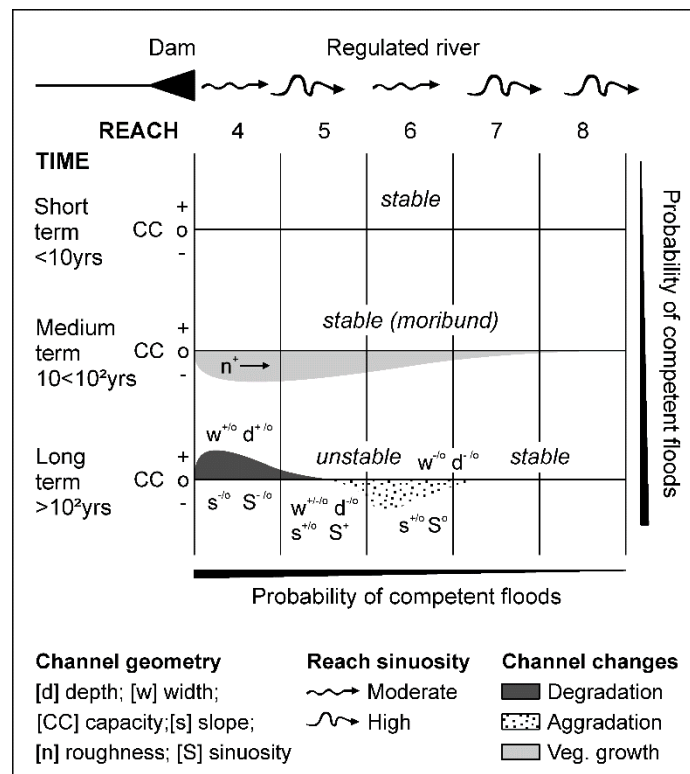
505 Most studies on regulated dryland rivers have documented reduced channel capacity owing to
506 channel aggradation, with vegetation invasion and stabilisation of lateral deposits (e.g.,
507 Mangrove Creek and Cudgegon River in Australia, Chubut River in Argentina, Mejerda River
508 in Tunisia, and many others; Table 3). Within the regulated Sauce Grande, where
509 redistribution of sediment no longer occurs and so stable conditions prevail, reduced channel
510 capacity was primarily related to alternating yet localized vegetation encroachment on the
511 channel banks. Vegetation encroachment was apparent over the first 10 river km below the
512 dam, there where the pre-dam channel shape provided suitable surfaces for vegetation
513 establishment. Downstream thereafter, the channel is too narrow to allow vegetation growth,
514 and discontinuous patterns of vegetation establishment prevailed. In channel sections with
515 little vegetation, field survey revealed formation of small terrace edges on channel banks (e.g.,
516 R6, Fig. 10). Although these terraces are too small to be captured by photointerpretation
517 analysis, they suggest that the banks that have been mapped as a basis for measuring width
518 were conceivably pre-dam banks that have been abandoned as a result of narrowing. If these
519 banks were abandoned, then they would not display any changes in width, but the river would
520 have formed a narrower channel within the abandoned banks. This aspect is evidenced by the
521 fact that the river is actively wandering within the channel (Table 1) and hence suggests that it
522 has created a new, narrower channel within the old one.

523 4.2. Present geomorphic state

524 The present river constitutes a low-energy stream characterized by marked channel stability.
525 The floodplain is reduced or absent for much of the river course, and vegetation encroachment
526 on channel banks leads to localized contraction of the pre-dam channel capacity. As outlined
527 above, marked channel stability responds to extreme flow regulation in a river section where
528 the influence of tributaries is scarce. Yet the dam history registers erratic, albeit significant
529 episodes of reservoir discharge and two episodes of overflow spill that resulted in
530 downstream flooding. The question at this point is why these episodes of relative high flow
531 did not initiate channel adjustments? We have two possible explanations for apparent channel
532 stability during periods of flow release from the dam. First, the river channel in the vicinity of
533 the dam has been strongly altered by humans to facilitate evacuation of reservoir discharges
534 (e.g., artificial channel deepening, meander cutoff, levee building). Humans have done what
535 the river would have done by itself; the difference in this instance is that the sediment
536 recovered was not redistributed downstream but rather deposited into the levees constructed
537 along the river course to prevent overbank flowing. Second, vegetation growth alongside the
538 stream has conceivably increased the channel roughness and the resistance to erosion of bank
539 materials. In dryland rivers, where complexity and irregularity in morphology, hydrology, and
540 riparian vegetation are the norm (Sandercock et al., 2007), biostabilisation of channel banks
541 and maturation of individuals may contribute to increased thresholds for geomorphic activity
542 (Corenblit et al., 2010).

543 In opposition to these assumptions, however, artificial levee building has been reported to
544 increase rates of bank erosion because the unconsolidated sediment was easily eroded once
545 bank-full flows occurred (Leeks et al., 1988). Furthermore, the comprehensive review of
546 Tooth (2000b) on dryland rivers outlined that *even channels heavily vegetated with perennial*
547 *or ephemeral trees, shrubs and grasses are sometimes subject to flood-related changes* (p.

548 83). These aspects raise two important questions. First, even if vegetation did provide an
 549 element of resistance to bank erosion, was the maturation of individuals rapid enough to
 550 prevent the levees from being eroded? Second, even if channel banks were biostabilised, was
 551 vegetation establishment significant enough to increase thresholds of geomorphic activity? As
 552 reported by Petts (1980), the potential for change in regulated rivers depends not only on the
 553 channel morphology and materials, but also on the frequency and intensity of competent
 554 discharges below the dam. In drylands, this aspect is particularly relevant because a
 555 'competent discharge' may be an infrequent, large flood unrepresentative of a more common
 556 range of floods (Tooth, 2000b). Accordingly, marked channel stability within this highly
 557 regulated dryland river may be interpreted within a model of channel adjustment relative to
 558 the frequency and intensity of competent floods with time and distance from dam closure
 559 (Fig. 11).

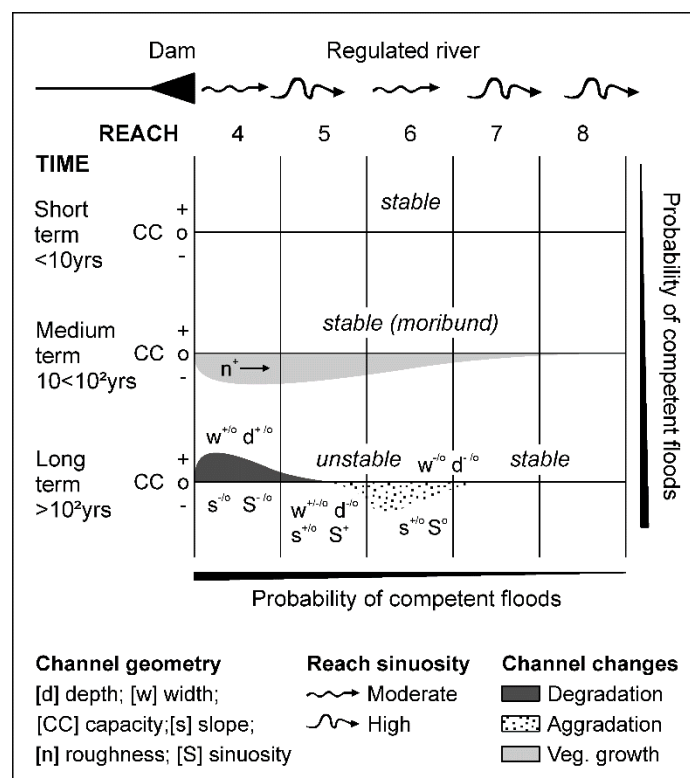


560

561 Fig. 11. Adjustment of the channel morphology to extreme flow regulation below water-
 562 storage reservoirs in drylands. The model of adjustment (modified from Petts, 1979) considers

563 the potential for change relative to the frequency and intensity of competent floods with time
 564 and distance from dam closure. The direction of change is indicated by [o] no significant
 565 change, [+] increase, and [-] decrease.

566 The unregulated Sauce Grande is in a transient, unstable state (sensu Tooth and Nanson,
 567 2000) where complete adjustment of form to process is inhibited until a geomorphically
 568 significant flood event occurs. After impoundment by a large surface-area, water-storage
 569 reservoir such as Paso de las Piedras, competent floods downstream are unlikely. The channel
 570 morphology will not change, and downstream flows will simply accommodate within the
 571 existing channel form. As the regulated Sauce Grande receives no major tributaries, the
 572 probability of competent floods decreases with distance downstream and so stability will
 573 prevail throughout all reaches (Fig. 11).



574

575 Fig. 11. Adjustment of the channel morphology to extreme flow regulation below water-
 576 storage reservoirs in drylands. The model of adjustment (modified from Petts, 1979) considers
 577 the potential for change relative to the frequency and intensity of competent floods with time

578 and distance from dam closure. The direction of change is indicated by [o] no significant
579 change, [+] increase, and [-] decrease.

580 In addition to enhancing the variability of natural flows (small floods are absorbed within the
581 reservoir, and large floods are either absorbed or markedly reduced), reservoir operations are
582 affected by the effects of ENSO-related cycles of drier- (or wetter-) than-normal climate.

583 Reservoir discharges during dry spells are unlikely, and if a reservoir discharge is to occur, its
584 magnitude will be most likely below the threshold for geomorphic activity. Thus, the time-lag
585 before channel changes initiate may be considerably longer than in more humid rivers having
586 the propensity to accommodate change, and longer than in dryland rivers regulated by dams
587 having less effects on the frequency and intensity of competent floods downstream. In the
588 absence of competent floods with time, the channel morphology will not change and the river
589 will exhibit stable, moribund conditions. Thorne et al. (1996) defined moribund channels as
590 those that are not strictly alluvial because *the observed channel form is the result of processes*
591 *that operated in the past under conditions of higher energy and/or more abundant sediment*
592 *supply, so that the geometry and features of the channel are relics of a fluvial environment*
593 *that no longer exists* (p. 471). Accordingly, channel forms will not reflect the regulated flow
594 regime but the effects of the last major flood before closing the dam, and the only remarkable
595 change throughout the reaches will be determined by vegetation invasion and stabilisation of
596 channel banks in sections where the pre-dam channel shape allows vegetation establishment
597 (Fig. 11). Assuming that dam operation procedures will not change in the future, moribund
598 stability will remain indefinitely and *if recovery is to occur at all, further human intervention*
599 *through river restoration is essential* (Thorne et al., 1996, p. 471).

600 Yet a geomorphically significant flood is likely to occur with time (Fig. 11). If so, degradation
601 may occur immediately below the dam (reach 4) increasing channel depth and width.

602 Differential erosion by meander migration may produce localised changes of the channel

603 width in reach 5. Given the low energy of the river section below the dam, the eroded material
604 will be deposited in reach 6 and, within the distal reaches, the channel morphology will not
605 change. Tooth (2000a) reported that in dry, lowland zones with absence of tributaries,
606 channels were stable because of the effects of flow transmission losses and attenuation of
607 flood hydrographs. Although the most obvious spatial comparison contrasts river reaches
608 upstream and downstream from a dam (Braatne et al., 2008), channel stability in this low-
609 gradient lowland river section probably existed prior to dam closure and will remain unless a
610 high-magnitude, low-frequency flood event occurs.

611

612 **5. Conclusions**

613 This paper provided a detailed geomorphic and vegetation assessment within an impounded
614 meandering dryland river where (i) flow regulation is extreme and (ii) the influence of
615 tributaries in the river section below the dam is scarce. In addition to providing new
616 information on the complex geomorphic response of dryland rivers to impoundment, it
617 provides the first geomorphic assessment of the regulated Sauce Grande River. Results from
618 this investigation revealed that aside from human-related adjustments of the channel planform
619 and cross section, the river response to upstream impoundment was characterized by marked
620 channel stability. Because the reservoir impounds nearly the full range of flows and the
621 totality of sediment delivered from the headwaters, redistribution of sediment in the river
622 section below the dam no longer occurs and stable conditions prevail. The present river
623 morphology constitutes a remnant of a fluvial environment created before closing the dam,
624 and the only remarkable change observed since dam closure was reduced channel capacity
625 owing to vegetation encroachment on the channel banks. Vegetation growth alongside this
626 much-reduced stream has been encouraged by maintenance of base flow levels and reduced
627 flood disturbance. Yet vegetation develops only in river sections where the pre-dam channel

628 shape is large enough to allow establishment of pioneers. In other words, vegetation
629 establishment is influenced by (and reflects) channel stability.
630 These findings serve as an important platform to enable further research assessing the present
631 geomorphic state of the regulated Sauce Grande River, and they lead to a number of
632 additional questions that require further attention. While the temporal dimension could be
633 assessed robustly, the spatial dimension requires further research efforts to understand the
634 nature of the relationships between form and process within the regulated river as well as the
635 influence of transmission losses (evaporation and infiltration) and attenuation of the flood
636 hydrograph on the downriver channel morphology. One major challenge for further research
637 is the lack of historical flow data along the river course. This makes estimations of pre- and
638 post-dam channel hydraulics very difficult to achieve. Thus, detailed field observations and
639 sediment analyses will be required to identify temporal and spatial variations in the
640 relationship between stream power and critical thresholds for geomorphic effectiveness of
641 regulated flows below the dam. Similarly, this study outlined some interconnections between
642 regulated flow, channel forms, and vegetation dynamics. However, detailed vegetation
643 analyses are required to assess the complex mechanisms by which vegetal successions in this
644 regulated river influence (and are influenced by) channel morphology.

645

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655

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