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

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Abstract

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

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

1. Introduction

Drylands — which include dry-subhumid, semiarid, arid, and hyperarid regions — cover 40% of the Earth's surface and contain almost 40% of the global population (UNEM, 2011). Population growth and changing living standards force increased water allocation for urban, agricultural and industrial use (Young and Kingsford, 2006; Schmandt et al., 2013). As a result, water resources in drylands tend to be heavily exploited through dams, weirs, canals, and other structures (Davies et al., 1994). Although most dams in drylands are multipurpose dams, with hydropower and flood control as common primary functions, many of them operate as water-conservation structures to support irrigation and/or drinking water supply. Water- conservation dams maintain the reservoir as full as possible and impound the entire runoff volume in periods of reservoir filling (Petts, 1984). Thus, the disparity between natural and regulated flow regimes may be particularly striking in drylands (Walker et al., 1995). One particular concern is that dryland fluvial processes (and therefore the fluvial response to impoundment) may be very different from those generally accepted in more humid regions (Tooth, 2000b, 2013; Nanson et al., 2002). Dryland rivers are characterized by extreme variability in flow and sediment transport (Davies et al., 1994; Bunn et al., 2006; Young and Kingsford, 2006). Long periods of little or no flow are interspersed with floods of high, sometimes extreme magnitude (Tooth and Nanson, 2000), short duration (Graf, 1988), and low predictability (Poff and Ward, 1989). Floods control erosion, transport, and deposition processes (Bull and Kirkby, 2002) and therefore constitute the major determinant of dryland channel shape and size (Tooth, 2000b). As morphogenetic floods exhibit highly skewed frequency (Tooth, 2000b), complete adjustment of dryland channel form to process is sometimes inhibited (Bull and Kirkby, 2002). Feedback mechanisms between channel form and process are rarely found in drylands (Tooth, 2000a), and therefore researchers have a tendency to presume that dryland rivers are in an unstable, nonequilibrium state (Tooth and Nanson, 2000).

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

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

2. Materials and methods

2.1. Study site

The Sauce Grande River collects its waters on the eastern slope of the Sierra de la Ventana Range and flows down into the Atlantic Ocean draining a basin area of ~4600 km^2 (Fig. 1). The climate in the majority of the river basin is dry-subhumid. Mean annual rainfall decreases from 800 mm in the uplands to 640 mm in the lowlands, and mean annual potential evapotranspiration is 1030 mm (Paoloni et al., 1972). Interannual rainfall variability is marked and linked primarily to alternating phases of ENSO (Scian, 2000), inducing episodes of drier- and wetter-than-normal climate (Campo et al., 2009; Bohn et al., 2011). Recurrence of drought and increasing water demand owing to population growth very seriously impact on local water resources (Andrés et al., 2009).

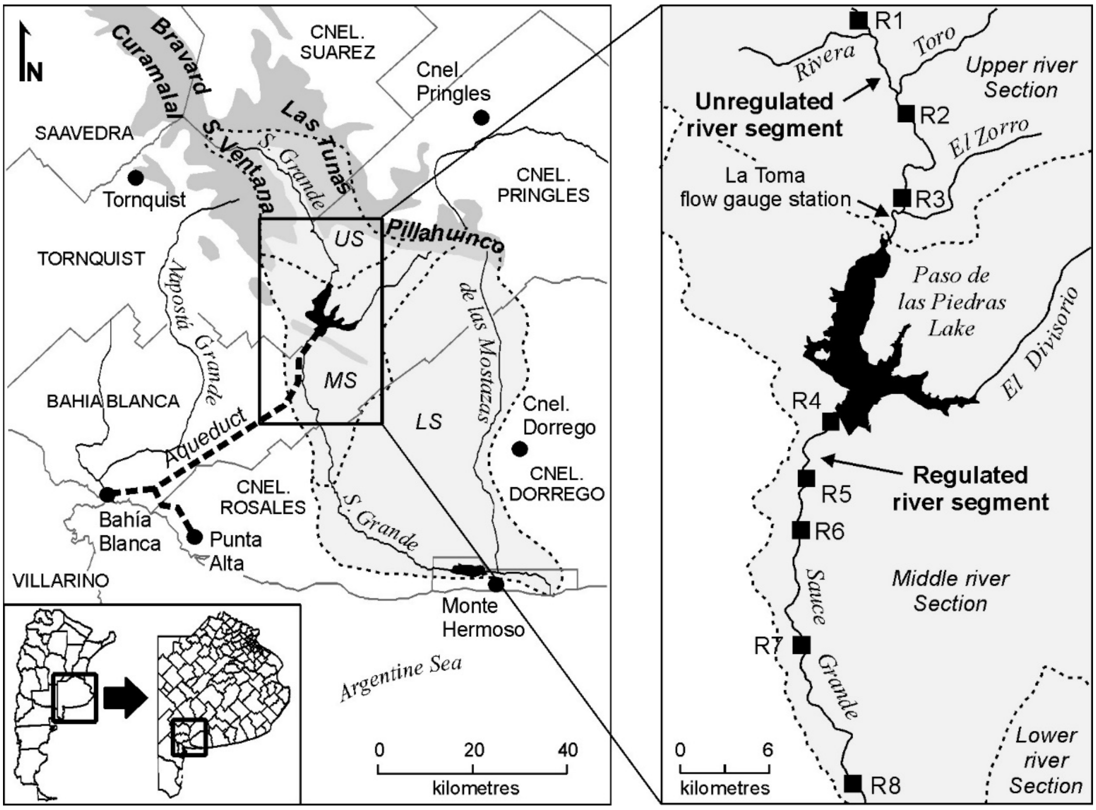


Fig. 1. Map of the Sauce Grande River basin showing main regional features (left) and the river segments selected for analysis (right). The location of reference river reaches (R) along each river segment is also illustrated. US, MS and LS in the left map designate the upper, middle, and lower river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

2.1.1. Hydrological context

The natural river flow regime is perennial flashy (rainfed) and event-driven. Mean daily flow (1910-1947) is 3.4 m^3 s^{-1}, but floods may reach more than 1000 m^3 s^{-1} in a few hours (Schefer, 2004). The Paso de las Piedras Dam (initiated in 1972 and completed in 1978) impounds the middle river section for water supply to the cities of Bahía Blanca and Punta Alta (Fig. 1). Its reservoir has a surface area of 36 km^2 and a maximum storage capacity of 328 m^3 10^{-6} for 25 m depth (Schefer, 2004). Annual yield to meet water demand is 65 m^3 10^{-6}; this is about 60% of the mean annual inflow volume (107.2 m^3 10^{-6}). The remaining volume is conserved within the reservoir to assure water supply in periods of drought; flow release downstream occurs only in periods of full storage. Water is conducted either through the bottom gate (controlled flow releases) or through the overflow spill weir (uncontrolled release).

Figure 2 illustrates monthly runoff volumes at La Toma (Fig. 1) and monthly volumes of reservoir discharge as a surrogate of flow magnitude upstream and downstream from the dam. Gauged and estimated reservoir discharges indicate that the reservoir has absorbed the full range of inflow volumes over 19 years of record (48%). In years recording reservoir discharges, annual runoff volumes were reduced by 54%, annual maxima were reduced by 42%, and annual minima were reduced by 86%. The reservoir history registers only two episodes of overflow spills (1984 and 2002), during which the flood wave was attenuated by 31 and 34%, respectively. In the absence of flow release, downstream flow averages 0.26 m^{3}s^{-1} and originates from reservoir seepage below the dam structure. Except for some ephemeral tributaries, the Sauce Grande River receives no permanent flow inputs until its confluence with de las Mostazas Creek (lower river section; Fig. 1) about 110 river km downstream from the dam closure.

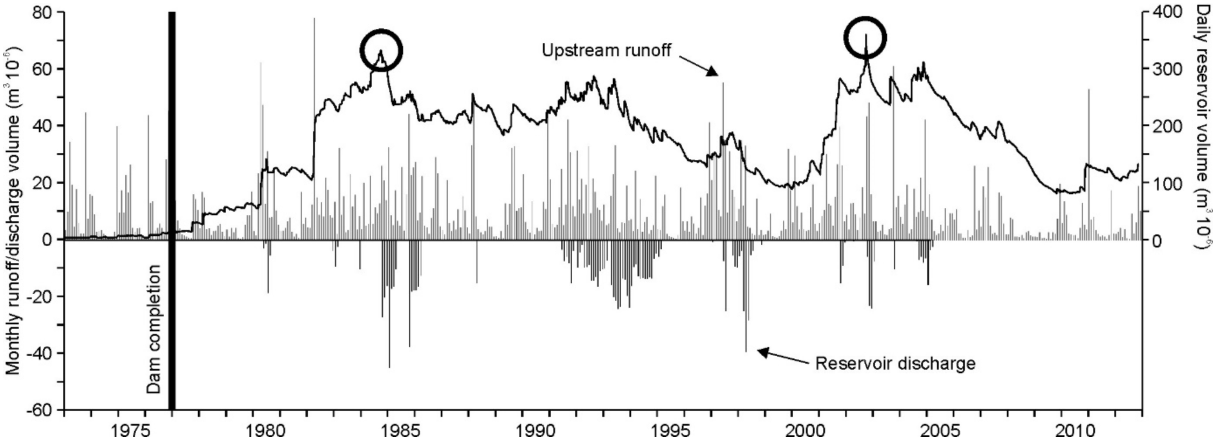


Fig. 2. Monthly runoff volume upstream from the dam and monthly volumes of reservoir discharge over the period 1973-2012. Upstream runoff volumes were estimated from rainfall using the GR2M model (Makhlouf and Michel, 1994). Monthly volumes of reservoir discharge over the period 1973-1988 were calculated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

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

2.1.2. Geomorphic context

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

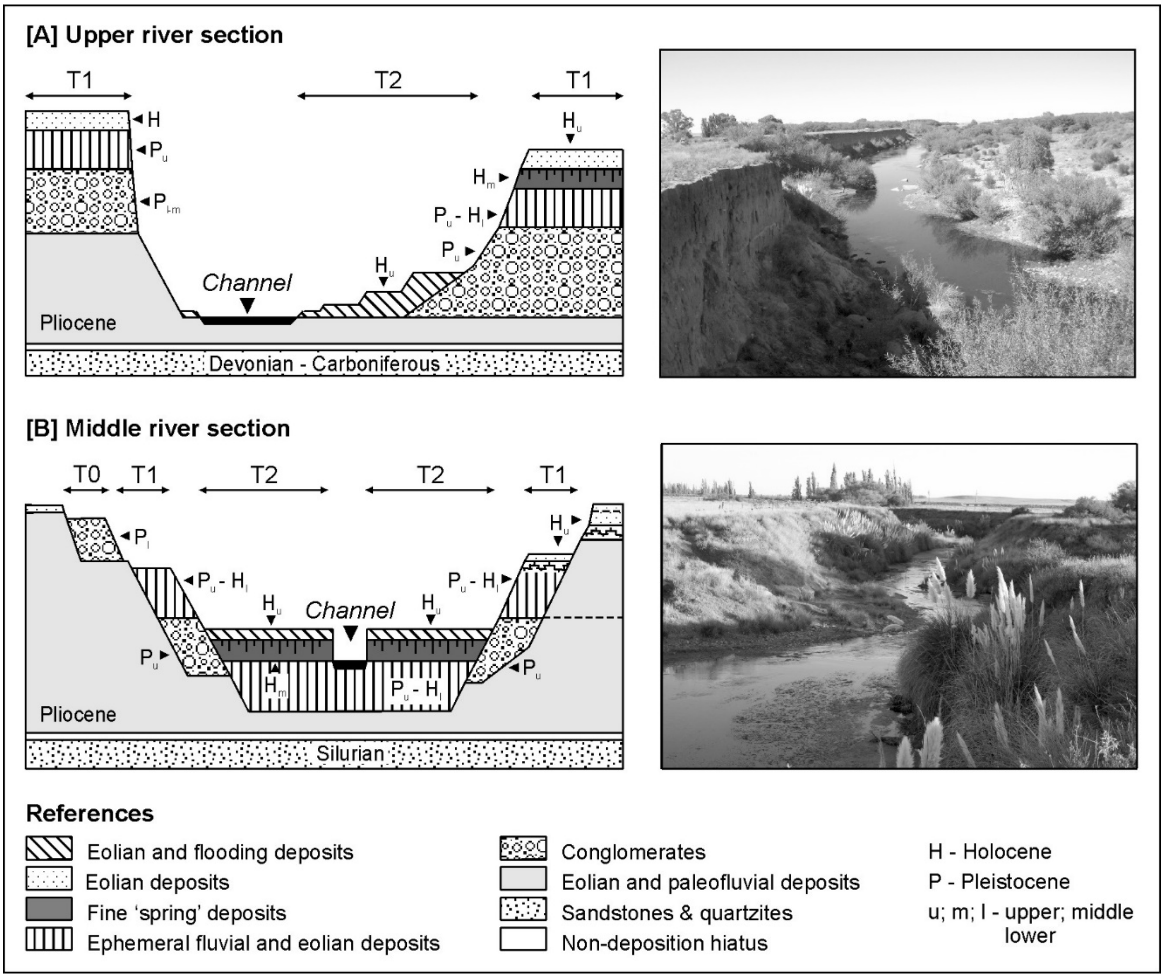


Fig. 3. Schematic cross sections of the Sauce Grande River showing typical geomorphic and

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

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

2.2. Scales of analysis

This paper quantifies post-dam geomorphic and vegetation changes across multiple scales (Fig. 4). Changes with time were inspected using a chronological sequence of historical aerial photographs (1961, 1981) and high-resolution imagery (Ikonos, 2004) defining two comparative periods. The first period (1961-1981) spans a pre-disturbance phase, characterized by unregulated flow conditions, and a phase of early disturbance linked to dam completion in 1978 and initial filling of the reservoir (Fig. 2). The second period (1981-2004) spans the post-disturbance phase where the dam controls the magnitude, frequency, duration, and variability of downstream flows. Changes from unregulated to regulated river conditions for a given time step were inspected by contrasting two river segments located above and below the dam (~26- and 41-km length, respectively). In addition, field-based descriptions of present channel conditions (2011-2012) were performed for eight reference reaches of 1-km length located above (3 reaches) and below (5 reaches) the dam (Fig. 1).

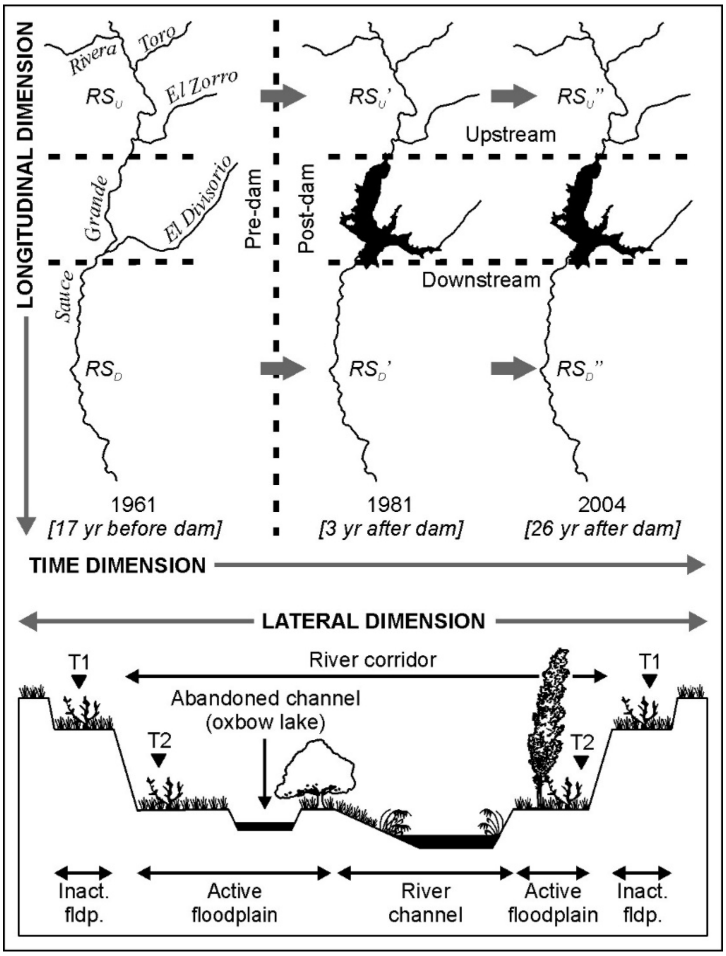


Fig. 4. Spatial and temporal scales used in geomorphic and vegetation analysis. Quantification of change within the regulated river segment (RS_D) is performed with time ($RS_D \rightarrow RS_D$”) and with respect to the unregulated river segment upstream (RS_U). Upstream and downstream river segments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

2.3. GIS- and field-based analyses

We have mapped fluvial forms and land cover types within each river segment and for each time step used in analysis using ArcGIS (ESRI©). Mapped fluvial forms included the river channel and major floodplain features such as abandoned meanders, oxbow lakes, and terraces (Fig. 4). In this paper, the term ‘river corridor’ encompasses the river channel (delimited by the top portions of cutbanks and point bars) and the active floodplain, i.e., *the alluvial surface next to the channel, separated from the channel by banks, and built on materials transported and deposited by the present regime of the river* (Graf, 1988, p. 214). Mapped land cover types include: (i) surfaces with none or little vegetation (bare surfaces); (ii) surfaces covered by water; (iii) agricultural lands, including crops and pastures; (iv) grasslands, dominated by graminoid species of *Stipa* and important associations of pampas grasses (*Cortaderia seollana*); and (v) woodlands, clearly dominated by native species of willow (*Salix humbodltiana*). In vegetation analysis, the term 'riparian vegetation' refers explicitly to grasses and woods developing within the river corridor. Field-based analysis of present channel conditions in the reference reaches used the stream reconnaissance scheme devised by Thorne (1993) and included: (i) survey of the channel geometry (slope, planform, and cross section); (ii) description of channel forms and materials, and (iii) interpretation of vertical and lateral relations of channel to floodplain.

2.4. Quantification of geomorphic and vegetation changes

2.4.1. Geomorphic changes

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

[T_2 - T_1]. To determine rates of stream lateral migration in terms of length per unit time (Shields et al., 2000), we measured the area enclosed by successive stream centrelines (active migration area, A_m). Rates of stream lateral migration were then calculated as the ratio of A_m to the stream centreline length in T_1, divided by the time interval length [T_2 - T_1]. Quantification of width change used series of transects splitting the channel every 200 m of channel length. This provided two types of measure: absolute channel width, given by the length of each transect, and relative channel width, calculated as the area enclosed between consecutive transects divided by channel length. Differences in width [w] between consecutive time steps [w_{T2} - w_{T1}] provided a net measure of channel narrowing (negative differences) or widening (positive differences) along each river segment.

2.4.2. Vegetation changes

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

2.5. Error analysis

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

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

3. Results

3.1. Geomorphic change

3.1.1. Planform change

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

Table 1

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

		Unregulated river segment		Regulated river segment	
Channel migration ($m^2 10^{-2}$)		1961-1981	1981-2004	1961-1981	1981-2004
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
Stream lateral migration (m^{-1})		0.31	0.26	0.02	0.06

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

3.1.2. Width change

Upstream from the dam, coupled channel widening and narrowing occurred during both comparative periods with a tendency to narrowing during the second comparative period (Fig. 6). Width changes occurred most likely in river sections exhibiting active lateral migration. Thus, many channel sections narrowed owing to lateral accretion and outward migration of meander bends (up to 50% during 1961-1981, and up to 60% during 1981-2004), and river sections dominated by cut bank erosion increased in width by up to 62% (1961-1981) and 55% (1981-2004). Below the dam, the channel revealed a tendency to narrowing during both comparative periods (Fig. 6). The period 1961-1981 was characterized by marked contraction of the channel width (12 to 33%) owing to deviation and artificial straightening of the river course in the vicinity of the impoundment. During the period 1981-2004, the channel width contracted in 31 sites (15% of cases). The percentage of channel narrowing decreased in the downstream direction from 44 to 4% and responded to two distinct, localized processes. Immediately below the dam and over ~4 river km, the channel narrowed by between 9 and 44% owing to artificial meander cutoff, building of artificial levees, and other dam-related waterworks. Downstream from river km 4, the position of bank lines remained relatively unchanged. However, contraction of the channel width (6 to 30%) was inferred by vegetation encroachment over former bare channel surfaces.

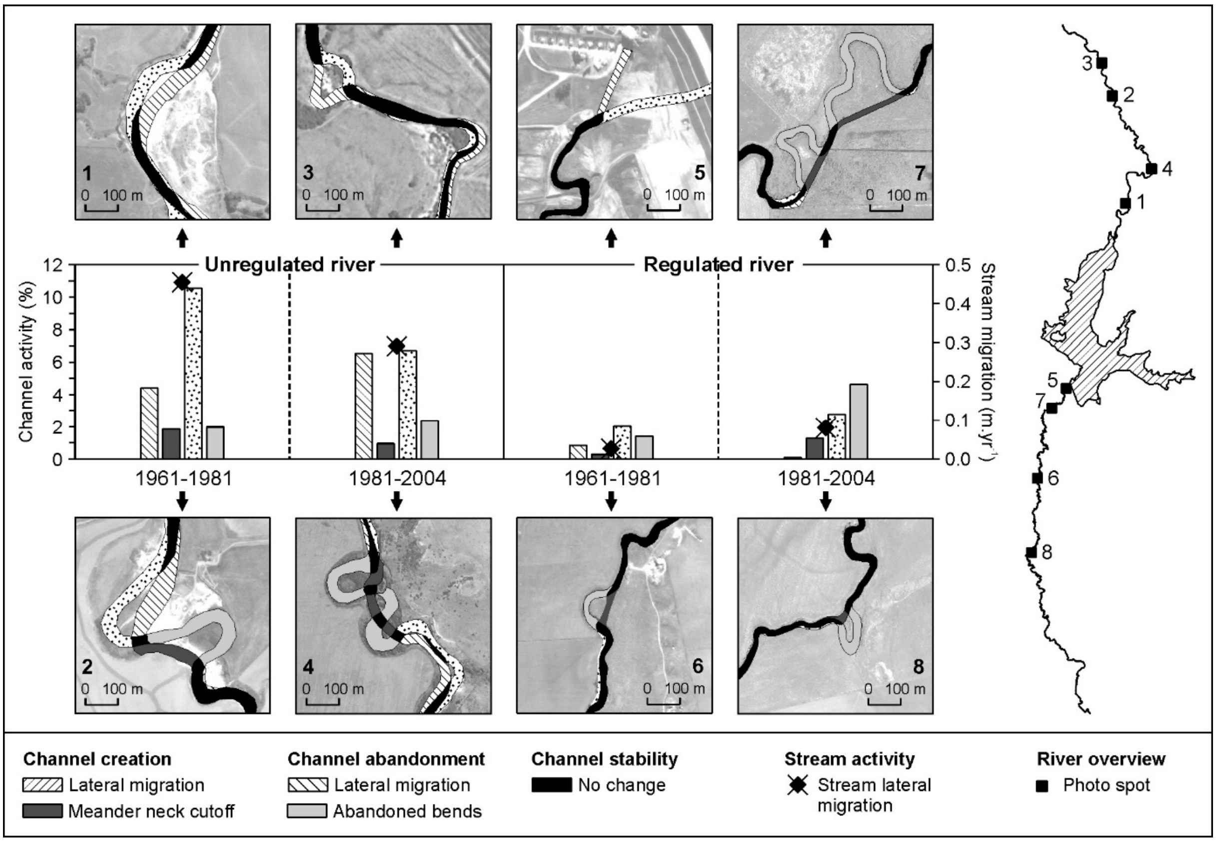


Fig. 5. Channel and stream activity within the unregulated and regulated river segments by

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

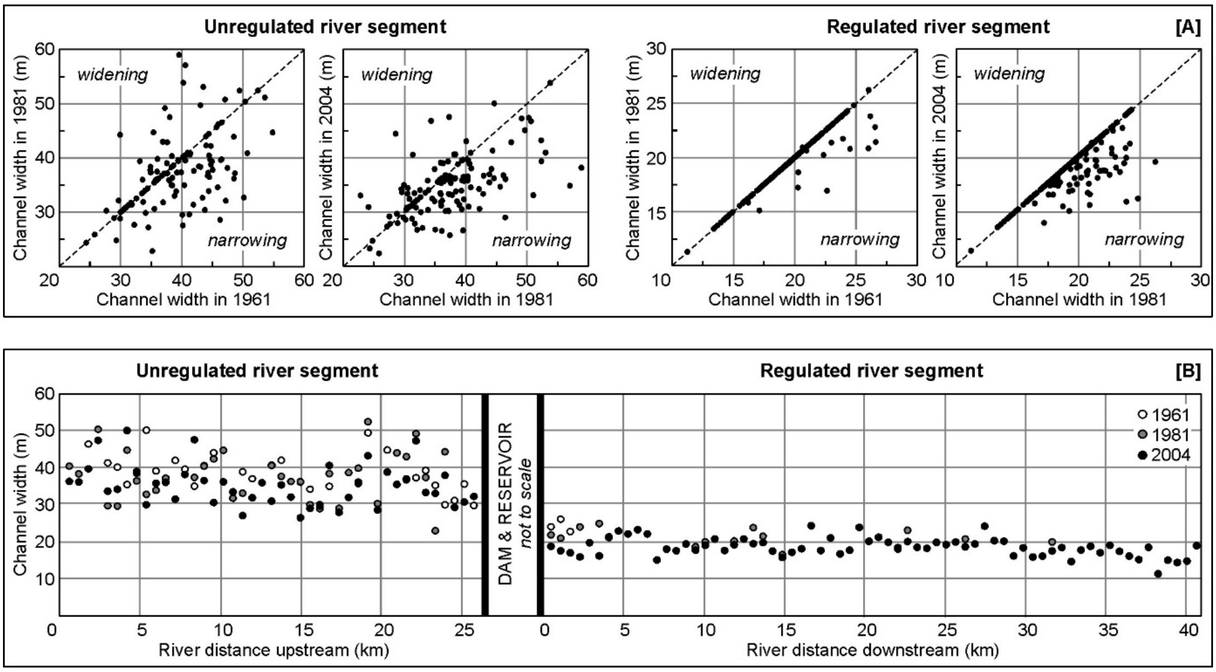


Fig. 6. [A] Scatterplots comparing the river channel width between consecutive time steps, and [B] river channel width as a function of time and distance downstream. Channel width was calculated as a function of channel area divided by 200-m length along each river segment. The hashed central line in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

3.2. Vegetation changes

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

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

Table 2

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

	Surface area (ha)			Difference (ha)		Rate of change (%)	
Cover type	1961	1981	2004	1961-81	1981-04	1961-81	1981-04
Unregulated river segment upstream from the dam							
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**
Regulated river segment downstream from the dam							
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**

Second, the river corridors upstream and downstream from the dam revealed contrasting trends in vegetation dynamics (Fig. 7). Other than the expansion of agricultural lands over grasslands (583% between 1961 and 2004; Table 2), the most important transitions downstream occurred from water surfaces to woodlands (38%). This suggests a tendency for woody vegetation establishment within the river channel, near to the water surface. A moderated tendency for woody vegetation growth over former bare banks (18%) and grasslands (16%) was also identified. Yet the expansion of woodlands over these landscape units was notably less significant than that observed within the river corridor upstream from the dam (Fig.7). Upstream, woodlands expanded within the river channel and the floodplain, covering 33% of former grasslands and 57% of former bare banks.

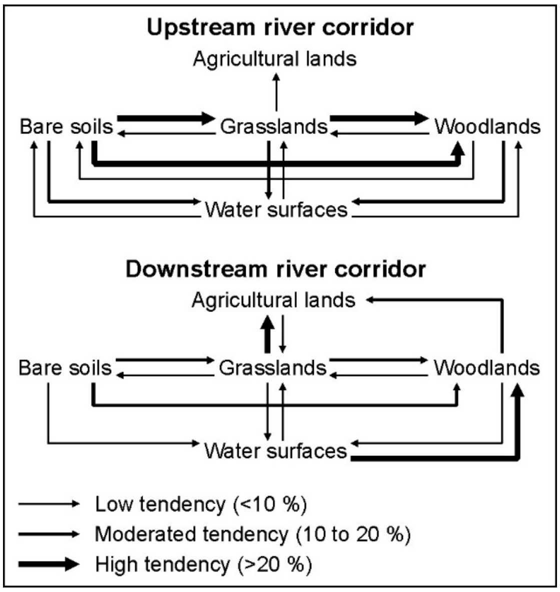


Fig. 7. Trends in vegetation dynamics within the river corridors upstream and downstream from the Paso de las Piedras Dam. Trends were calculated from transitional diagrams of landscape units by comparative period.

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

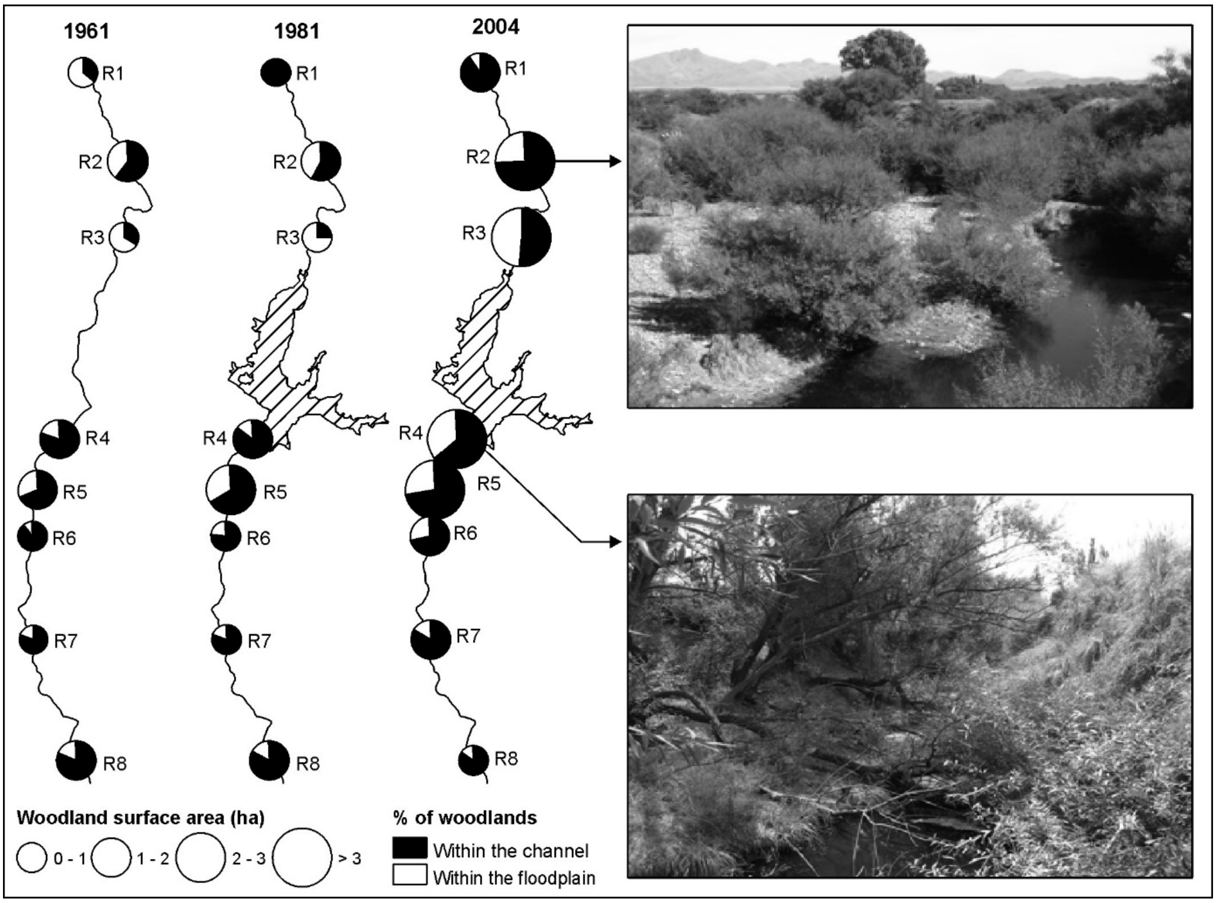


Fig. 8. Surface area occupied by woodlands by river reach (R) and time step. Pie charts differentiate percentages of woody vegetation developing within the river channel and the floodplain. Photos provide an example of vegetation encroachment within the channel upstream and downstream from the dam.

3.3. Present channel conditions

Present channel forms clearly differentiate river reaches located above and below the dam. The river channel above the dam (Fig. 9) is broad and shallow ($27 < w{:}d < 37$), and the floodplain is well developed for much of the river course. Channel width averages 53 m (±16 m), and floodplain width averages 135 m with high variation (±94 m). The channel morphology is clearly meandering for all reaches; variations in sinuosity ($1.1 < 1.5$), meander wavelength (150 m < 600 m), and meander width (20 m < 200 m) are probably linked to local variations in slope and degree of confinement within the incised valley. Bed material is coarse in riffles (cobbles and coarse gravel) and finer in pools (small gravels, sand and silt); banks are composed of noncohesive deposits in point bars (sand and gravel) and of layered, cohesive paleofluvial and aeolian deposits in cut banks (fine sand, silt and clay). Bank profiles reveal active cut bank erosion including bank undercut and toe scour (especially in R3; Fig. 9); channel sections exhibiting vertical banks display coupled toe accumulation by mass wasting. Lateral accretion in point bars is a more dominant process. Outward migration of the meanders led to formation of terrace steps contained within the valley, and hence topographically lower than the preincision surface.

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

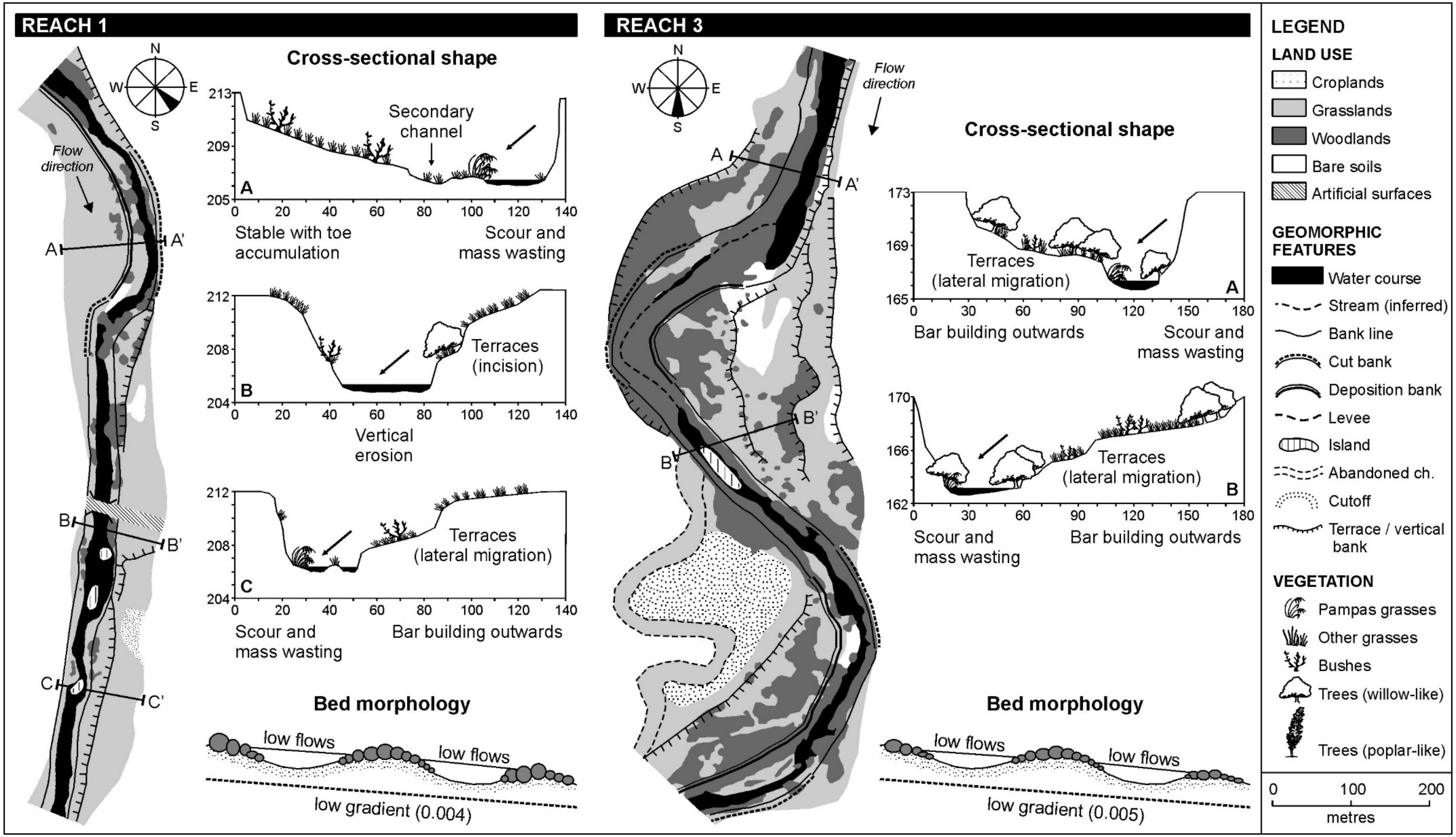


Fig. 9. Geomorphic features, land cover types, and representative cross sections for two reference reaches located upstream from the Paso de las Piedras Dam. The locations of the reference reaches along the unregulated river segment upstream are shown in Fig. 1.

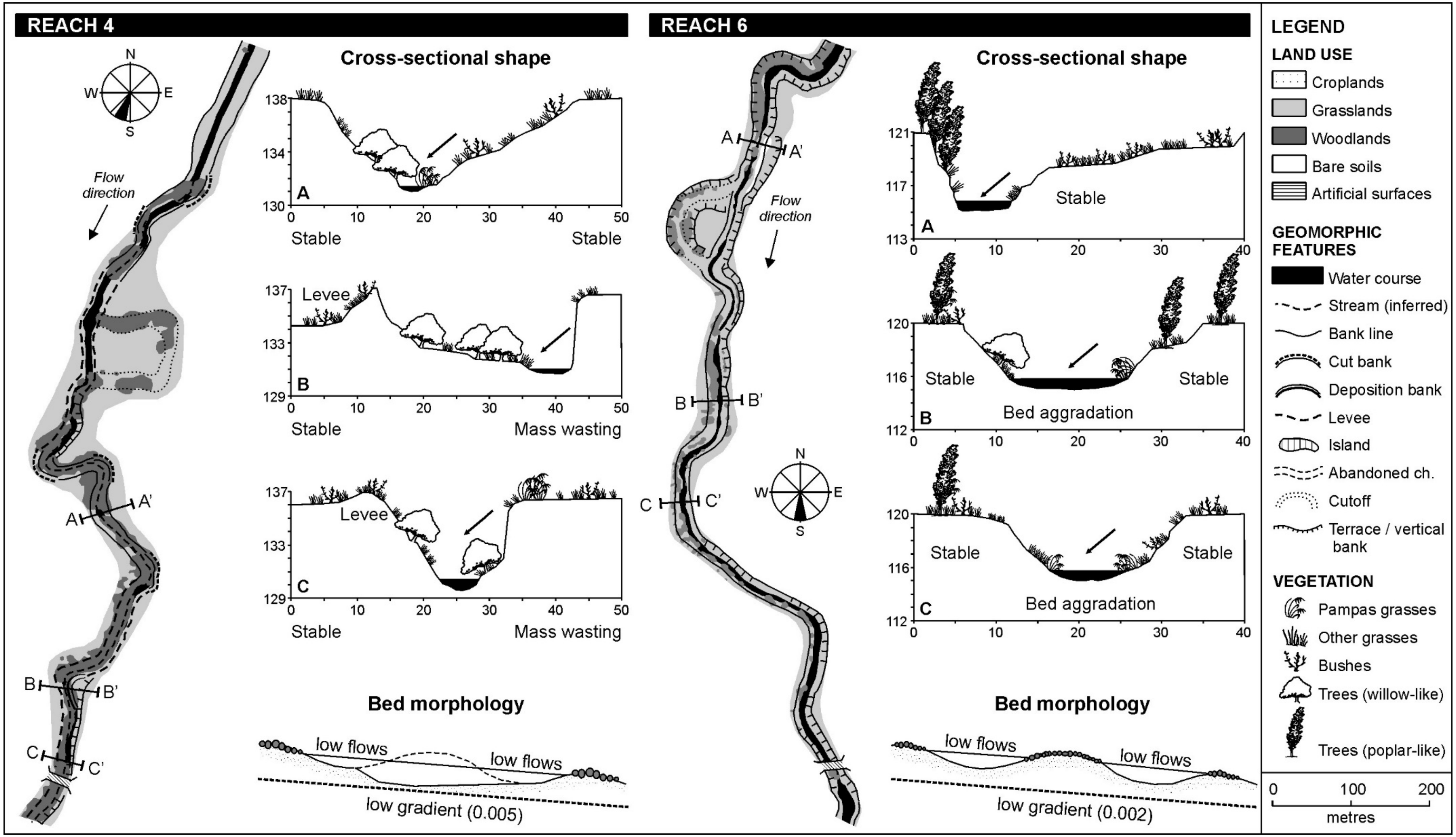


Fig. 10. Geomorphic features, land cover types, and representative cross sections for two reference reaches located downstream from the Paso de las Piedras Dam. The locations of the reference reaches along the regulated river segment downstream are shown in Fig.1.

4. Discussion

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

The construction and operation of the Paso de las Piedras Dam led to substantial changes in the hydrology of the Sauce Grande River downstream. The frequency and magnitude of floods were dramatically reduced, and the permanence of low flows increased significantly. Although the sediment trapping efficiency of the reservoir may be assumed as near 100% (Petts, 1984; Williams and Wolman, 1984), this study postulates that under conditions of extreme reduction in flow discharge, the impacts of the dam on the sediment transport capacity of the stream were more significant than those on the sediment load.

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

4.1.1. Channel stability

One of the most common consequences of impoundment of meandering rivers in drylands is the reduction of lateral migration rates (e.g., the upper Missouri and many other meandering rivers within the American Great Plains; Table 3). Within the regulated Sauce Grande, however, lateral channel migration was not reduced but inhibited. Any evidence of lateral channel activity constrained to the phase of pre- and early disturbance and major planform changes observed during the post-disturbance phase — such as meander cutoff and abandonment of meander bends — revealed a human-related origin in 80% of cases. Planform stability has been reported for very few meandering rivers (e.g., the lower Murray; Table 3) and appears to be a more common consequence within regulated braided rivers (e.g., Orange and Durance rivers; Table 3).

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

Table 3

Examples of geomorphic changes of regulated dryland rivers by world region

River	Impoundment	Purpose	Channel adjustments*	Citation
North America				
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 unstability$^+$, 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)
Mediterranean Basin				
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)
Central Asia				
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, $w^{-/o}$, 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	$d^{+/-}$, $w^{-/+}$, $s^{\circ/+/-}$, planform stability	Thoms and Walker (1993)
South Africa				
Orange	Vanderkloof & Gariep (1970’s)	Hydropower; irrigation	Main channel planform stability, filling of secondary braids, n^{+} (vegetation encroachment)	Blanchon and Bravard (2007)
South America				
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)

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

Two interrelated processes explain marked planform and cross section stability in the river section below the dam. First, the morphology of the unregulated Sauce Grande is driven by floods of high relative magnitude and low frequency common to most dryland rivers (Graf, 1988; Tooth, 2000b; Nanson et al., 2002; Tooth, 2013). Since the Paso de las Piedras Dam retains nearly the full range of floods, the processes promoting migration of meanders bends and adjustments of the channel cross section downstream were heavily truncated. As a result, the broad morphology of the regulated Sauce Grande remained unchanged since dam closure and is likely to exhibit stable conditions until a geomorphically significant flow event occurs. Second, reduction of the magnitude and frequency of morphogenetic flows should promote channel aggradation. However, and as reported by Petts (1979), channel aggradation below dams requires introduction of sediment from tributaries and/or redistribution of sediment within the channel. Within the regulated Sauce Grande both processes are unlikely. The river below the dam flows for the majority of its course without influence of tributaries and, in the absence of reservoir discharges, sources for water and sediment are limited to (i) reservoir seepage, (ii) groundwater inflows, and (iii) overland flow along the river course. Combined with the endogenous production of organic matter, these processes could explain bed deposition of very fine materials. On the other hand, redistribution of sediment within the regulated river channel is unlikely because the regulated flow is incompetent to rework the pre-dam channel forms.

4.1.2. Vegetation dynamics

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

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

Irrespective of climate and land use changes influencing vegetation dynamics at the scale of the river basin, vegetation structure and successions along the river corridor are primarily driven by a combination of hydrologic and geomorphic factors (Hupp and Osterkamp, 1996; Hughes, 1997; Corenblit et al., 2007). Accordingly, altered hydrology and morphology within the regulated Sauce Grande explain upstream-downstream differences in the spatial extent of vegetation growth, in the nature of vegetation transitions, and in patterns of vegetation establishment with distance downstream. .

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

Geomorphic factors. Downstream differences in patterns of vegetation establishment clearly reflect (and influence) channel planform stability. Channel migration promotes establishment of riparian pioneers by providing new bare and moist surfaces suitable for vegetation establishment and growth (Hupp and Osterkamp, 1996; Friedman et al., 1998; Tockner et al., 2010). Within the river upstream, this aspect was evidenced by landscape transitions from bare bank surfaces to woodlands (57%). Downstream from the dam, lateral channel stability prevented formation of new channel surfaces suitable for vegetation establishment, and therefore vegetation development was constrained to the pre-dam channel shape. Immediately below the dam, the valley-like channel forms permitted proliferation of willows over riparian surfaces that are no longer subject to flood disturbance. Farther downstream, the channel is narrower and deeper, which makes the area available for vegetation establishment relatively small. Hence, willows develop discontinuously near the water surface where the bank slope decreases and the soil moisture is high. This aspect explains the high percentage of transitions from water surfaces to woodlands (38%) within the river corridor downstream.

4.1.3. Reduced channel capacity

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

4.2. Present geomorphic state

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

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

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

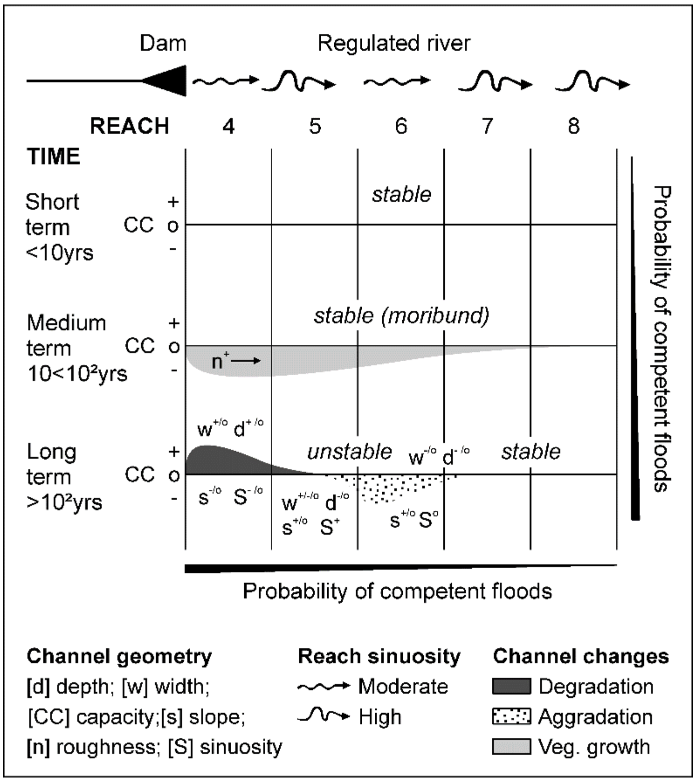
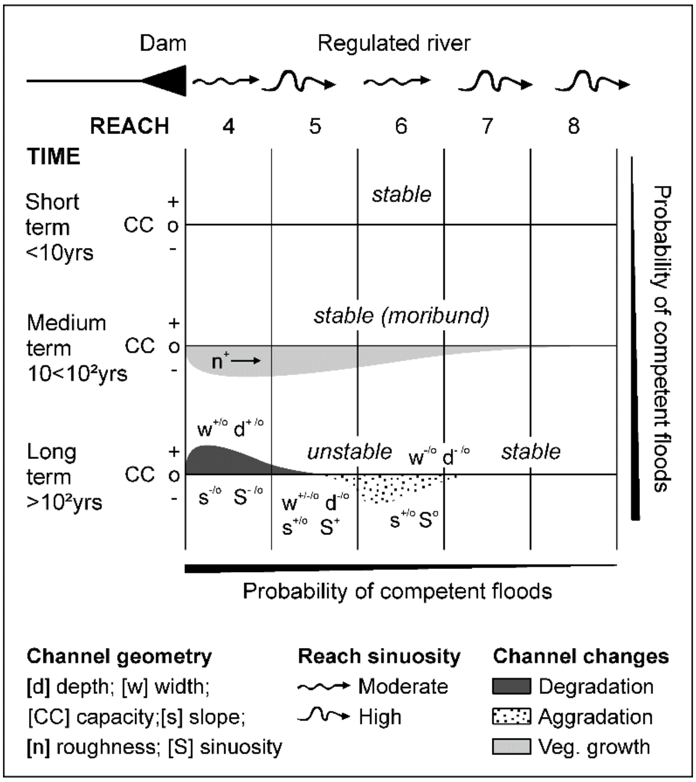


Fig. 11. Adjustment of the channel morphology to extreme flow regulation below water-storage reservoirs in drylands. The model of adjustment (modified from Petts, 1979) considers

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

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



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

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

Yet a geomorphically significant flood is likely to occur with time (Fig. 11). If so, degradation may occur immediately below the dam (reach 4) increasing channel depth and width. Differential erosion by meander migration may produce localised changes of the channel width in reach 5. Given the low energy of the river section below the dam, the eroded material will be deposited in reach 6 and, within the distal reaches, the channel morphology will not change. Tooth (2000a) reported that in dry, lowland zones with absence of tributaries, channels were stable because of the effects of flow transmission losses and attenuation of flood hydrographs. Although the most obvious spatial comparison contrasts river reaches upstream and downstream from a dam (Braatne et al., 2008), channel stability in this low-gradient lowland river section probably existed prior to dam closure and will remain unless a high-magnitude, low-frequency flood event occurs.

5. Conclusions

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

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

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