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Abrupt watercourse formation in a semiarid sedimentary landscape of central Argentina: the roles of forest clearing, rainfall variability and seismic activity

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ABSTRACT

In a semiarid sedimentary catchment of central Argentina, we describe a recent process of landscape dissection, abrupt canyon and watercourse formation and soil salinization. We link these adverse hydrological and geomorphological transformations to three potentially important drivers: precipitation increase, seismic activity and deforestation. Remote sensing imagery in the last 48 years showed an exponential increase in the length of streams, with drainage density values tripling to reach 0.22 km km^2. During the same period, forest area declined from 47% to 10%, at the expense of agriculture expansion. A 3.4-fold expansion of surface water bodies and water table level raise of 0.15 m y^{-1} over the last 35 years was observed. Discharge of a new stream at the middle of the basin ranged between 0.25 and 0.45 m^3 s^{-1} accompanied by a large and stable load of salts (~0.7 g l^{-1}). Nil recharge and large vadose accumulation of salts in dry forests stands contrasted with recharge rates of ~16 mm y^{-1} and salt-leached profiles under agriculture. Although the process of landscape dissection occurred during decades of higher than average precipitation, extreme rainfall events and seismic activity were not exceptional in that period. Results suggest that the replacement of forests by annual crops played a more important role, reducing evapotranspiration, triggering the onset of groundwater recharge and favouring subsurface through piping/ sapping processes. The abrupt landscape dissection shows no signs of stabilization at the present and may only be ameliorated through changes in vegetation that restore the original non-flow condition of the forest. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS agriculture expansion; drainage density; climate variability; recharge; dryland salinity; vadose soil profiling; piping; sapping

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INTRODUCTION

The hydrology of semiarid sedimentary plains is dominated by the vertical components of the water balance, i.e. precipitation inputs and evapotranspiration and deep drainage outputs. Although many of these environments have been historically used for agriculture, they have reached widespread and more intense cultivation over the last century (Millenium Ecosystem Assessment, 2005; Scanlon *et al*., 2007). The replacement of native vegetation and perennial pastures that comes with the cultivation of annual crops can create hydrological shifts in these systems (Gordon *et al*., 2008; Jobbágy *et al*., 2008; Wilcox *et al*., 2011), often in interactions with climate variability (Leroy, 2006; Blösch *et al*., 2007; Favreau *et al*., 2009). In sedimentary landscapes, shifts in the water balance brought by land use and/or climate can influence both surface and subsurface processes, as key ecohydrological variables such as evapotranspiration, rooting depth and infiltration rates become affected. Here, we assess the role that the concurrent forces of land use change (agricultural expansion), climate variability (precipitation rise) and tectonics (seismic activity) may have played initiating an abrupt process of canyon and watercourse formation in a semiarid catchment of central Argentina over the last three decades.

The native vegetation of many semiarid sedimentary landscapes around the world, including open dry forests in Australia, South America and Africa, and grasslands in North America, make an almost exhaustive use of rainfall inputs in the long term, making deep drainage and subsurface water flow negligible (Leduc *et al*., 2001; Scanlon *et al*., 2005; Santoni *et al*., 2010). Surface water flow is also restricted in some of these systems, as low slopes and relatively coarse textured soils with high infiltration rates prevent intense rainfall-runoff events (Scanlon *et al*., 2005; Santoni *et al*., 2010; Jayawickreme *et al*., 2011). The lack of significant surface and subsurface water flow generation (hereafter 'the non-flow condition') of uncultivated semiarid sedimentary landscapes impose an important geomorphological constrain, preventing their dissection and the development of surface drainage networks (Sidley and Ochiai, 2006). This non-flow condition also leads to the accumulation of large and stagnant vadose salt pools (Clarke *et al*., 2002).

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The conversion of these forest landscapes to agriculture may strongly disrupt the non-flow condition by modifying water evacuation pathways. Deep drainage may be directly enhanced at the expense of evapotranspiration resulting in wetter soil moisture profiles and vadose salt leaching. As a result, water and salts may reach groundwater, sometimes for the first time after millennia, resulting in groundwater level rises and salinization and, eventually, in soil degradation. This process is dramatically exemplified by vast fraction of the Australian croplands that were established on semiarid forest areas (George *et al.*, 1997; Clarke *et al.*, 2002). Other regions have shown similar trends by increases in diffuse or localized recharge (Leduc *et al.*, 2001; Scanlon *et al.*, 2005; Favreau *et al.*, 2009; Santoni *et al.*, 2010). Although in theory, long term precipitation increases could also disrupt the non-flow condition of semiarid sedimentary landscapes, this possibility has not been documented in historical time scales, as far as we are aware. Beyond this direct effect, increased precipitation could promote deforestation and cultivation by creating more favourable conditions for agriculture, as documented for our study region (Viglizzo *et al.*, 1997), and interact with this process enhancing deep drainage on croplands but not on native vegetation areas.

The conversion of dry forests to agriculture can favour erosion and landscape dissection not only through its effects on the water balance (i.e. higher water flow) but also through its influence on the porosity and structural stability of soils (i.e. lower infiltration and higher soil erodibility) (Collins *et al.*, 2004; Ravi *et al.*, 2010). Rill and gully erosion at the surface and piping/sapping erosion at the subsurface levels have been described as primary drivers of sediment transport and river network formation (Laity and Malin, 1985; Dunne, 1990; Schumm *et al.*, 1995; Bryan and Jones, 1997; Valentin *et al.*, 2005; Vanwalleghem *et al.*, 2005; Viles *et al.*, 2008; Fox and Wilson, 2010). According to Laity and Malin (1985), sapping is here defined as the process leading to the undermining and collapse of valley head and side walls by weakening or removal of basal support as a result of enhanced weathering and erosion by groundwater seepage. However, piping or pipe flow erosion is commonly defined as the subsurface erosion driven by a seepage flow through a discrete soil pipe (Fox and Wilson, 2010). Because the interrelated and threshold-based nature of those erosion processes, landscape dissections resulting from their interaction commonly follow a typical non-linear dynamics that is hard to predict (Sidley and Ochiai, 2006; Zehe and Sivapalan, 2009; Fox and Wilson, 2010). The effects of surface and subsurface erosion processes on landscape instability can sometimes be fostered and amplified by tectonic factors. Depending of their magnitude and recurrence, earthquakes can induce hydrogeological shifts that lead to rising streamflows and water table levels, soil liquefaction or land subsidence (Manga *et al.*, 2003; Montgomery and Manga, 2003).

An abrupt landscape dissection process accompanied by the appearance of deep canyons and perennial watercourses has been taking place in a sector of the sedimentary plains of central Argentina, which was originally covered by semiarid forests but subject to cultivation for almost a century. In the last 25 years, this flat landscape without river networks became deeply incised (up to 15 m in depth) by streams with moderate but permanent discharges and high salt contents. This phenomenon, new to the region, is causing severe damages to infrastructures (more than $15 million in repair investments) and soil losses (~200 000 ha of fertile lands lost). Here, we describe this process and explore its potential drivers and mechanisms focusing on the interplay of decadal precipitation increases, episodes of high seismic activity and land use changes. We described trends in (1) landscape dissection, drainage density, surface water bodies and (2) land use, using satellite imagery. Trends in (3) precipitation and (4) seismic activity were characterized using existing global and regional databases. Trends in (5) water table levels were reconstructed by comparing archive and new ad hoc measurements. On the basis of (6) vadose salt and moisture profiles under different vegetation covers and (7) stream flow and salt concentration measurements, we estimate current rates of salt mobilization in the area. A conceptual model, considering all potential drivers and mechanisms, synthesizes these approaches.

MATERIAL AND METHODS

Study area

The study area is located in the western and dry edge of the flat sedimentary plains of central Argentina on the dry forest known as *Espinal* (Figure 1). The area has a temperate semiarid climate. Mean annual temperature is 15.7 °C with the coldest (July) and warmest (January) months, respectively, having an average minimum temperature of 1.0 °C and an average maximum temperature of 28.6 °C. Mean annual precipitation for the 1903–2010 period was 605 mm yr^{-1} ('INTA – Villa Mercedes' meteorological station; −33.652°, −65.420°; 525 m a.s.l.). Rainfall is concentrated in the warm season with 70% taking place between November and March, often in the form of convective storms with high spatial variability. Potential evaporation from A-type tank measurements averaged 1640 mm yr^{-1} from July 2006 to June 2009, reaching maximum values up to 11 mm d^{-1} during the summer ('INTA – Villa Mercedes' meteorological station, unpublished data). We focused our analysis on a tributary catchment in which new rivers drain into the Quinto river (San Luis province, Argentina), a perennial river draining from northwest to southeast.

Four geomorphological units have been described in the study catchment (Barbeito *et al.*, 2008): (1) the montane and surrounding piedmont area (mean slope >10%), (2) the sandy–loessic plain (mean slope ~1.5%), (3) the sandy plain (mean slopes ~1.0% and ~0.5% in the up and bottom sections, respectively), and (4) the alluvial plain associated to Quinto river (mean slope ~1.5%). The transition between the loessic–sandy and sandy plains coincides with a local tectonic depression (Barbeito *et al.*, 2008). Soils are classified as *Entic Haplustolls* in the northern sections of the catchment and *Typic Ustipsamments* and *Typic Ustorthents* in the loessic/sandy plains, respectively (Galván and Collado, 2009). The crystalline basement, which reaches the surface in the

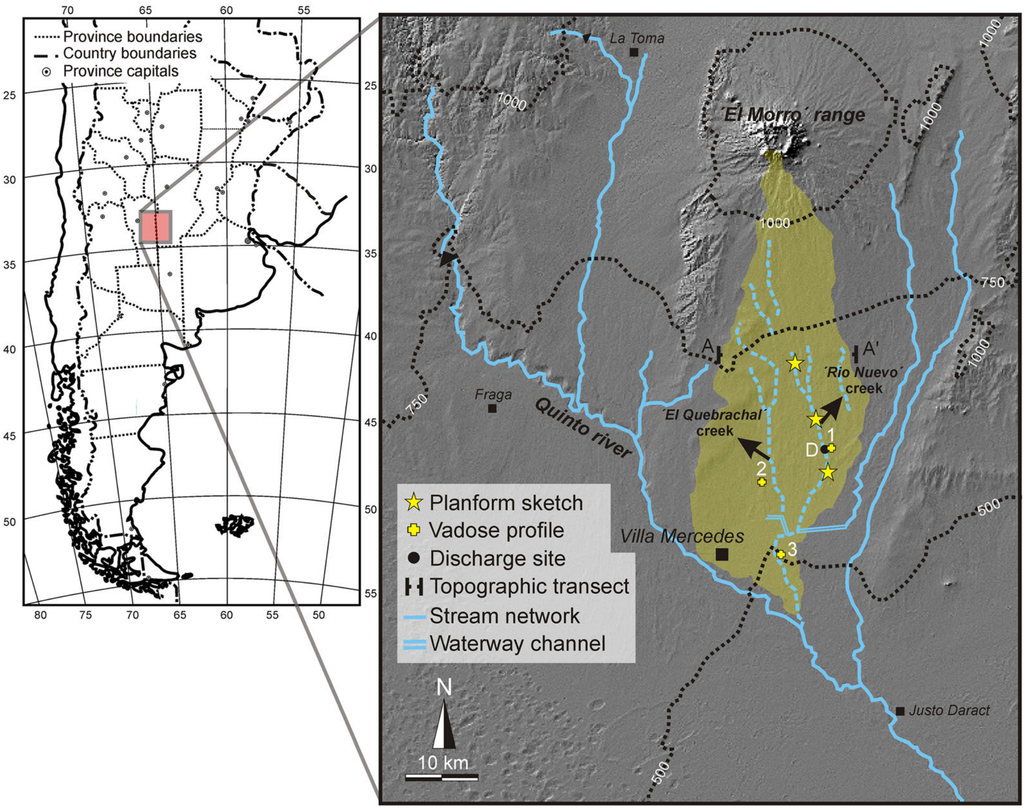

Figure 1. Location map and study catchment (green area) with measurement sites along the 'Rio Nuevo' creek. (A) Vadose profiling and recharge and (B) discharge measurements were sampled at sites 1–3 (yellow circles) and site D (black circle), respectively. Topographic level (black dotted line) and drainage network with historic (blue solid lines) and new stream channels (blue dashed lines) are shown. West–east topographic transect (A–A′) was extracted for depicting conceptual Figure 7. Channel planform sketches in Figure 8 were extracted for sites at yellow stars.

surrounding piedmont areas, is constituted by igneous and methamorphic rocks (trachyandesites and migmatic biotite schists). In both plains, the basement is covered of aeolian quaternary sediments deposited 7–9 kyr BP and is characterized by thick (up to 400 m) sandy layers with interbedded silty–loessic layers and, sometimes, thin and shallow calcareous layers that make soils low cohesive and very vulnerable to erosion processes and collapses (Barbeito *et al.*, 2008). In the lowlands where the water table is close to the surface, perennial or temporary lagoons usually appear. Several small springs emerge sparsely in the transition between the montane–piedmont and the plain geomorphological units.

The area was historically covered by open woodlands of *Prosopis caldenia, P. flexuosa* and *Geoffroea decorticans*, with a shrub stratum of *Lycium chilense*, *Condalia microphylla* and *Capparis atamisquea* and species of the genus *Cenchrus*, *Stipa*, *Sporobolus*, *Aristida*, *Poa* and *Pappophorum* dominating the herbaceous stratum. Currently, a small fraction of the native forests is left, and rainfed agriculture occupies most of the area. Coincident with rainfall increases and technological changes (no-tillage, herbicide-based fallows), annual crops have expanded at the expense of native vegetation and perennial pastures (Viglizzo *et al.*, 1997). Nowadays, summer season crops (soybean, maize and sunflower) cover most of the landscape. Rotation and dual cropping with winter crops (wheat and rye) and pastures (alfalfa) are uncommon practices. At the present, the stream network in the study catchment is comprised by two main watercourses of recent formation in most of their length ('El Quebrachal' and 'Río Nuevo', Figure 1).

Surface and groundwater changes

Change in total dry forest coverage and length of stream valleys in the catchment were measured using a time series of seven Landsat images (1976–2010, Table I) downloaded from the USGS Global Visualization Viewer website (http://glovis.usgs.gov/). Dry forest coverage in the middle section of the study region, covering 46% of the catchment area, was also obtained from aerial panchromatic photographs obtained in 1962. Scanned aerial photographs were orthorectified and combined with geometrically corrected Landsat false colour composites under the same geographic information system environment. Landsat false colour composites were derived from the spectral reflectivities of the blue, red and infrared spectral bands that were previously computed from Landsat 'raw digital numbers' by using an atmospherically correction procedure based on the dark-object subtraction method (Chavez, 1988). Polygons covering dry forest areas and lines representing the stream network were digitized, and drainage density was estimated as the ratio between the total longitude of streams and the total area of the catchment (809 km^2).

To describe regional changes in groundwater level, two sources of data were used. The first one consisted on comparisons of past and present water table depth measurements at 11 locations. Past measurements in wells covering the period 1940–1999 were collected from regional reports (BRS, 2002; Barbeito *et al.*, 2008) and records by local landholders. Present measurements were obtained for those same wells or nearby ones in the

Table I. Coverage of dry forest and total longitude of streams in the study catchment (809.1 km^2) from the aerial and satellite dataset.

Year of acquisition	Spatial data type	Path/row; spatial resol.	Dry forest coverage (ha)	Length of streams (km)
1962	Orthophoto	—/—; 1 m	~38 000*	—
1976	Landsat 2 MSS	246/83; 60 m	26 098	64.2
1985	Landsat 5 MSS	229/83; 60 m	14 498	65.0
1995	Landsat 5 TM	230/83; 30 m	12 426	67.4
2002	Landsat 7 ETM+	230/83; 30 m	10 577	96.8
2005	Landsat 5 TM	229/83; 30 m	9555	115.2
2007	Landsat 5 TM	230/83; 30 m	8876	130.7
2010	Landsat 5 TM	230/83; 30 m	8038	176.9

*Estimated from the analysis of the middle section of the catchment.

framework of this research. Finally, elevation data from the 30 m ASTER-Global Digital Elevation Model (www.gdem.aster.ersdac.or.jp/index.jsp) were extracted for all the water bodies mapped in the catchment in 1995 and 2010 by using the multispectral Landsat scenes and a unsupervised classification scheme based on the ISODATA algorithm (Jensen, 1996). To avoid potential wrong assignments, block of pixels with less than 0.36 ha (2×2 Landsat pixels) were excluded from the analysis. Remote sensing and GIS computing were developed with the aid of the Idrisi software (www.clarklabs.org).

Precipitation and seismic trends

Monthly precipitation data from 1903 to 1962 and daily data from 1962 to 2010 were collected from the 'INTA – Villa Mercedes' meteorological station. A frequency analysis based on the ranking method was performed to calculate return period for maximum monthly (since 1903) and daily rainfall (since 1962) values in the region. Differences in rainfall monthly dynamics between 1903–1960 and 1960–2010 were tested using the non-parametric Mann–Whitney U test.

To evaluate the temporal match between episodes of drainage network growth and seismic activity, earthquake data were collected from global (USGS Geological Survey Earthquakes Program, http://earthquake.usgs.gov/) and regional (INPRES, http://www.inpres.gov.ar/) databases. Values of the magnitude, and epicenter depth and distance to the study region were compiled for all records located <350 km away from the study region to evaluate the likelihood of occurrence of soil liquefaction processes and water table fluctuations according to the empirical relationships described by Galli (2000) and Montgomery and Manga (2003).

Ecohydrological measurements

Vadose soil profiles in three paired sites with neighboring plots occupied by dry forest and dryland agriculture were obtained across the catchment (sites 1–3 in Figure 1). This space-for-time approach (Peel and Blösch, 2011) was adopted to estimate differences in groundwater recharge between both land cover types. Agricultural stands were under cultivation for 5–40 years, and dry forests were subject to grazing. To avoid edge effects, paired coring positions were established along transects running parallel and 50–75 m away from the contact line of both land cover types. Bulk soil samples were collected at intervals of 50 cm in depth, with a 10-cm diameter hand auger down to 6 m of depth or the water table if it was above that level. Textural composition, gravimetric soil moisture and chloride content were measured for each soil sample. Soil texture was measured using the Bouyoucos method (Elliot *et al*., 1999). Measurements of gravimetric soil moisture were carried out by weighing subsamples before and after oven drying at 105 °C to constant weight. Chloride content was measured in soil water extracts (1:2; soil–water ratio) with a solid-state ion-selective electrode (Frankenberg *et al*., 1996). Bulk density was measured in site 1 from undisturbed soil samples collected in an open wall with exposed sediments. An average value (±SD) of 1.21 (±0.07) g cm^{-3} was obtained as reference value. Differences in chloride and soil moisture contents in vadose profiles at each site between dry forest and agriculture stands were evaluated using the non-parametric Wilcoxon matched-pairs test. Recharge rates up to 6 m in depth were estimated for forests and agriculture stands by using the residual moisture flux method (Phillips, 1994), which computes a chloride–water balance in the soil from values of rainfall depth, the atmospheric chloride deposition and the total chloride accumulated in the vadose zone. The mean annual chloride atmospheric deposition measured in the region is 0.49 mg l^{-1} (Santoni *et al*., 2010).

Average phenological trajectories for each land cover type were described using the Normalized Difference Vegetation Index (NDVI) obtained from MODIS imagery. In drylands, this index has been shown to be well correlated to vegetation activity and water use (Glenn *et al*., 2008; Contreras *et al*., 2011). We selected five representative sites covered by dry forest and agriculture in which we obtained NDVI series by using the MOD13Q1 land product of MODIS, which represents 16-day composites for a pixel size of 250 m. The data from July 2000 to June 2010 were downloaded using the 'MODIS Global Subsets: Data Subsetting and Visualization' tool at the ORNL DAAC (http://daac.ornl.gov/). Mean seasonal trajectories for dry forest and agriculture were computed as the average of the median seasonal trajectories obtained for each site. Mean annual NDVI values for each site were compared with those expected from a precipitation–NDVI model developed for the region to quantify evapotranspiration rates (Conteras *et al*., 2011).

To illustrate the current baseflow quality and seasonal dynamics of the new watercourses, discrete flow measurements were regularly taken in the middle section of the 'Río Nuevo' creek during 2010 (site D in Figure 1) with a manual flowmeter (Flo-Mate Model 2000, Flow-Tronic SA). Discharge values at site D were obtained across river sections and computed as the average value resulting from point measurements taken at 1 m intervals along a width–depth flow profile. Measurements were taken in sections with laminar water flow regime. Electrical conductivity, measured with a CONSORT C861 electrode, and chloride content, determined in laboratory following the same method described for soil samples, were also computed from water samples collected at each date. Chloride content results were linked to vadose observations, and a rough estimate of the time required to leach vadose salts out of the area drained by the outlet D (drainage catchment of 213 km^2) was obtained assuming (1) a closed surface–groundwater system, (2) no inputs of chloride other than atmospheric ones, (3) no outputs other than river discharge and (4) a temporally linear leaching process.

RESULTS

Surface and groundwater change

The length of the drainage network of the study area almost tripled since the mid-seventies (Table I). Drainage density increased from 0.08 to 0.22 km km^{-2} between 1976 and 2010, and the period of maximum growth was the most recent one (2005–2010) with an addition of 57.0 km km^{-2} of new watercourses. This expansion resulted from growth of existing watercourses and development of new ones. Although we could not infer the timing of the drainage network expansion process within each time interval, local media and settlers reported abrupt watercourse development and sediment transport episodes, always in association with intense rainfall events in April and November 1999, September 2001, May 2004, January and March 2008 and December 2009. In the last of these episodes, we documented in the field the extension of the 'Rio Nuevo' creek and the deepening of its bottom by 2.5 m over a period of less than 24 h following a rainfall event of >150 mm according to rainfall data supplied by local settlers.

Over the study period, the catchment lost more than 30 000 ha of dry forests that were converted to dryland agriculture (Table I, Figure 2). However, dry forests occupied already less than half of the watershed by 1962, reaching 10% by 2010. Deforestation achieved peak rates of 1330 ha yr^{-1} between 1976 and 1985.

Water table level rise over the last 40 years was observed along the entire catchment, being particularly intense in its middle section. In the 11 wells that we studied, all located within the middle and bottom sections of the catchment, water tables rose on average at a rate of 0.15 m yr^{-1}, with total elevation increments reaching up to 10 m in 35 years (Figure 3(A)). This regional groundwater level trend was paralleled by the expansion of water bodies between 1995 and 2010 (Figure 3(B)). The appearance of water bodies associated to shallow groundwater was clustered in local topographic depressions located at the high to middle sections of the watershed.

Precipitation and seismic trends

Following a widespread trend in central Argentina, precipitation increased in the area since the late sixties (Table II, Figure 2). The positive trend observed for annual precipitation was accompanied by a 1.5-fold increase in the frequency of large rainfall (>50 mm d^{-1}) between the 1962–1985 and 1985–2010. No changes between periods were observed for extremely large rainfall events (>100 mm d^{-1}), however, with records in 13/03/1975, 04/04/1980, 06/01/1991, and 04/03/1995, and at least in 31/03/1923 according to fragmented figures recorded

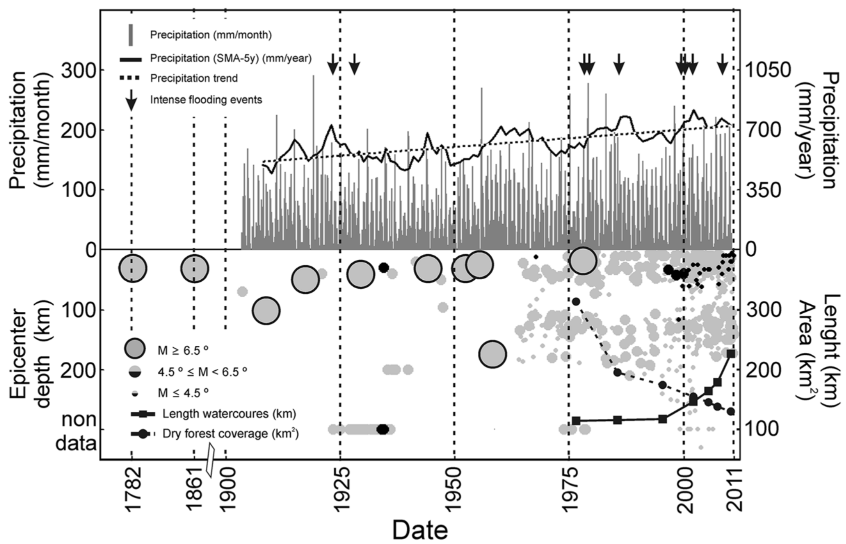

Figure 2. Historic and satellite-based data collected for the study catchment on precipitation (upper section) and earthquakes (grey/black circles), dry forest coverage (dashed line, km^2) and length of watercourses (solid line, km) (bottom section). In the upper section, monthly precipitation (grey bars, left axis), Simple Moving Average for a 5-year window (SMA-5y in mm yr^{-1}, solid black line, right axis) and 1903–2010 precipitation trend (dotted line, right axis) are shown. The occurrence of intense flooding events is marked with arrows. In the bottom section, earthquake properties are presented according to their epicenter depth, magnitude (M) and distance to the study catchment (black circles for <100 km; grey circles for 100–350 km).

before 1962 (Intendencia de Riego de Villa Mercedes, personal communication). Considering longer event integration periods of 5 days and using a baseline threshold of 100 mm, which was reached in July 1985 in coincidence with the first landscape incision in the region, we found no clear trends with the threshold being exceeded the same number of times before (12 times, 1962–1985) and after that episode (12 times, 1985–2010).

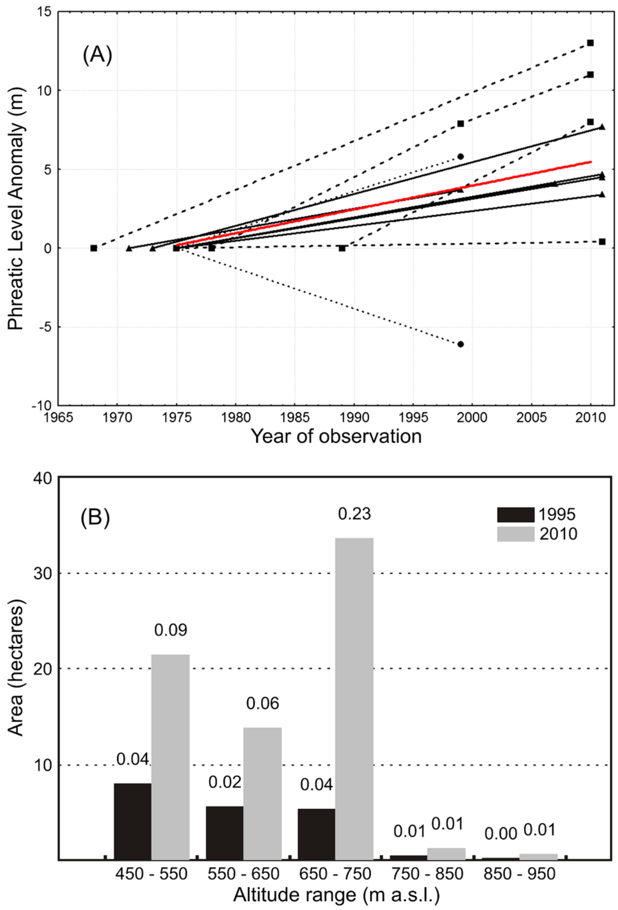

Figure 3. (A) Changes in phreatic levels (absolute anomaly values) observed in wells at sites located in the upper (thick), middle (dashed) and bottom (dotted) sections of the catchment. In red, the average linear trend observed in the middle–bottom section; (B) total area covered by water bodies at different altitude ranges at 1995 and 2010. Values of relative coverage of water bodies (×100 000) at each altitude range are shown over the bars.

Seismic activity in the region of the catchment (<100 km away) was low throughout the period of most intense watercourse development, with 29 shallow earthquakes with magnitudes >3 (Figure 2) between 1995 and the present. Strongest earthquakes in that period had magnitudes of 4.9, 4.7 and 4.5 in July 1996, May 1998 and November 1999; respectively. Those magnitudes were much lower than the strongest in modern records, which took place in Sampacho ~85 km away from the catchment in June 1934 and achieved a value of 6.0. Across the broadest region of analysis, the strongest registered earthquake took place in November 1977 in Caucete, 350 km away from the catchment, with two consecutive events of magnitudes 7.2 and 7.4 and a 2-month period of intense replicates in the 4.8–6.3 magnitude range. Earthquakes with magnitudes >6.5 were reported in 1782, 1861 and 1929 in Mendoza and in 1944, 1952, 1955 and 1958 in San Juan.

Ecohydrological measurements

Vadose soil moisture and chloride profiles indicated negligible water transport and high salt storage under dry forests. Cultivated fields, instead, showed signs of deep drainage and salt leaching (Table III), with 91% less chloride and almost two times the total water storage than their forested pairs (Figure 4, Table III). With the average chloride deposition of 0.49 mg l^{-1} measured by Santoni *et al.* (2010) in the region, estimated recharge values (±SE) were up two orders of magnitude higher in agriculture plots (16 ± 4 mm yr^{-1}) than in forest ones (<1 mm yr^{-1}).

Vegetation activity in 2000–2010 was higher in dry forest compared with agriculture, as suggested by NDVI values that were 21% higher in the former (0.56 ± 0.02 vs 0.46 ± 0.02; $n = 5$; $p < 0.05$). The NDVI value of dry forests is close to

Table II. Values of precipitation for different periods with contrasting landscape dissection rates in the last century.

	1903–1962	1962–2010			*p*-level*
			1962–1985	1985–2010	
From monthly rainfall data					
Mean precip. (mm yr^{-1})	558 (±20)	663 (±20)	636 (±28)	688 (±27)	<0.01
Max. rainfall** (mm $month^{-1}$)	138 (±6)	165 (±6)	164 (±11)	165 (±7)	<0.01
From daily rainfall data					
Avg. rainfall rate (mm d^{-1})***	n.d.		11.6 (±0.4)	11.0 (±0.3)	
Events ≥1 mm d^{-1}	n.d.		1275	1565	
Events ≥50 mm d^{-1}	n.d.		24	35	

Average annual and monthly figures for the 1903–1962 and 1962–2010 periods were computed from raw monthly and daily data, respectively. Additionally, number of rainfall events and average rainfall depth per event are shown for the 1962–2010 period. Standard errors are shown between parentheses. Differences in average annual and monthly precipitation values (*p*-level) between 1903–1962 and 1962–2010 periods were tested using the non-parametric Mann–Whitney *U* test.
*Comparing 1903–1962 and 1962–2010 periods.
**Interannual average.
***From events with rainfall depth > 1 mm d^{-1}.

those expected for the study area according to its precipitation, suggesting negligible water excess (difference between precipitation and evapotranspiration close to zero). Seasonal NDVI trajectories were highly synchronous between dry forest and agriculture, with highest relative differences taking place in spring (October–December) and the lowest in winter (August) (Figure 5).

Discharge values at the middle section of the 'Río Nuevo' creek ranged between 0.25 and 0.45 $m^3\ s^{-1}$ during 2010 (Table IV). Electrical conductivity and chloride concentration values in water were highly stable being 4.51 ± 0.04 dS m^{-1} and 689 ± 18 mg l^{-1}, respectively. Total chloride loss at this point reached 7735 Tn yr^{-1} (Table IV), which represented a net loss 36 g $m^{-2}\ y^{-1}$within the watershed. This figure is two orders of magnitude higher than the atmospheric inputs (0.3 g $m^{-2}\ y^{-1}$, Santoni *et al*., 2010) and approximately 6% of the average total soil chloride that is missing in agriculture profiles as inferred from their average difference from those under dry forests.

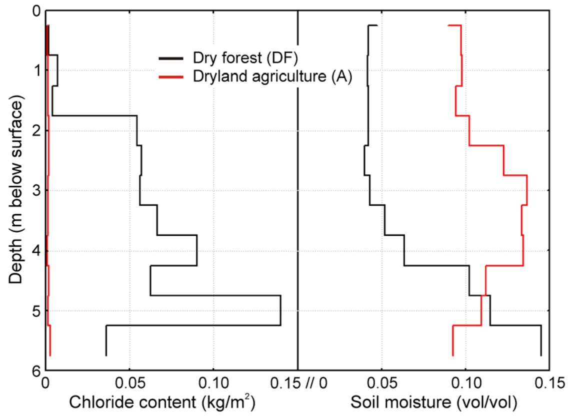

Figure 4. Chloride and soil moisture profiles observed in dry forest (DF) and dryland agriculture (A) stands (sites 1–3 in Figure 1). Median values were computed from measurements taken at three DF–A paired sites, with three replicates at each site.

DISCUSSION

Drivers of change

The exponential growth of the stream network described for the study region over the last three decades is not showing signs of stabilization. Current drainage density values are close to those reported in similar semiarid sedimentary settings in NW India (Sharma, 1987), the Russian plains (Golosov and Panin, 2006) and in South Australia (NLWRA, 2001). However, much higher values (2–3 km km^{-2}) have been reported for sapping networks on sandy substrates in the more humid situation of the panhandle of Florida (Schumm *et al*., 1995).

The abrupt formation of deep canyons and watercourses has been accompanied by a widespread water table rise, the appearance of surface water bodies in the high and middle sections of the catchment and the incipient salinization of

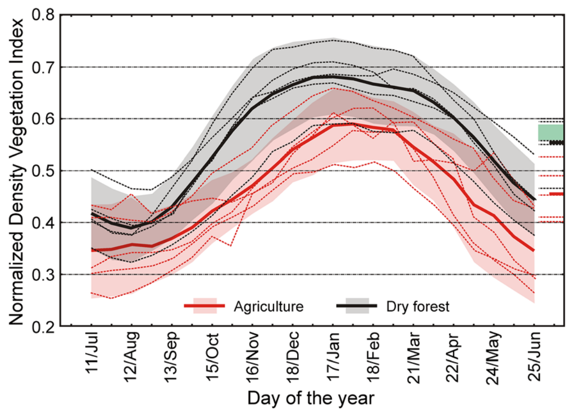

Figure 5. Average seasonal Normalized Difference Vegetation Index (NDVI) trajectories observed in dry forest and agriculture stands from July 2000 to June 2010. Average trajectories (thick lines) and 95% confidence intervals (shadow areas) for five representative sites (dashed lines) are shown. Observations (lines on the right) and precipitation-based predictions of annual NDVI (green shade on the right) are also shown.

Table III. Vadose and groundwater conditions in adjacent dry forest (DF) and agriculture (A) stands (average ± SE).

	Land cover	Site 1	Site 2	Site 3	All stands
Vadose zone (accumulated values up to 4 m below surface)					
Soil moisture (mm)	DF	346 ± 127	193 ± 34	221 ± 68	253 ± 49
	A	533 ± 43*	337 ± 27***	565 ± 61***	478 ± 42***
Chloride (g m^{-2})	DF	1050 ± 568	397 ± 291	589 ± 475	679 ± 249
	A	48 ± 30**	7 ± 2**	125 ± 107**	60 ± 37***
Groundwater					
Phreatic level (m a.s.l.)	DF	>6.0	5.5	5.0	5.5 ± 0.3
	A	3.5	5.5	3.5	4.2 ± 0.7
Chloride content (g l^{-1})	DF	11.1	2.1	2.6	5.3 ± 3.0
	A	0.03	0.02	0.95	0.34 ± 0.3
Estimated recharge (mm yr^{-1})	DF	<1	<1	<1	<1
	A	9 ± 3	18 ± 4	22 ± 7	16 ± 4

Recharge estimates were based on the Residual Moisture Flux (Phillips, 1994). Statistical differences in chloride and soil moisture content in vadose profiles (hosted by the top 4 m) were computed using the non-parametric Wilcoxon matched-pairs test. n.d., no data available
*p-level < 0.1.
**p-level < 0.05.
***p-level < 0.01.

Table IV. Seasonal dynamics of discharge, chloride content and electrical conductivity values at the middle section of the 'Rio Nuevo' creek (site D in Figure 1) during the year 2010.

Date of measurement	Period of reference	Discharge $m^3 s^{-1}$ (hm^3)	Chloride mg l^{-1} (Tn)	Electrical conductivity (dS m^{-1})
28/01/2010	01/01/2010–07/02/2010	0.38 (1.25)	724.75 (908.96)	4.55
18/02/2010	08/02/2010–09/03/2010	0.45 (1.17)	719.70 (844.90)	4.60
27/03/2010	10/03/2010–22/04/2010	0.25 (0.94)	659.47 (620.18)	4.60
18/05/2010	23/04/2010–25/05/2010	0.36 (1.02)	736.36 (752.06)	4.27
31/05/2010	26/05/2010–12/06/2010	0.41 (0.63)	630.63 (399.27)	n.d.
24/06/2010	13/06/2010–12/07/2010	0.42 (1.08)	627.01 (675.23)	4.57
29/07/2010	13/07/2010–15/08/2010	0.36 (1.06)	671.83 (712.46)	4.42
01/09/2010	16/08/2010–25/09/2010	0.31 (1.10)	717.80 (789.92)	4.52
18/10/2010	26/09/2010–29/10/2010	0.34 (1.01)	734.52 (741.61)	4.55
09/11/2010	30/10/2010–29/11/2010	0.28 (0.75)	780.31 (588.24)	4.72
18/12/2010	30/11/2010–31/12/2010	0.44 (1.21)	578.41 (702.40)	4.33
Average (total)	01/01/2010–31/12/2010	0.36 (11.47)	689.16 (7735.22)	4.51

n.d., no data available.

soils, surface and phreatic waters (Figure 6). These observations support the idea that an incipient process of dryland salinity, similar to the one reported decades earlier for cultivated dry forests of Australia (George *et al*., 1997, Clarke *et al*., 2002), may be starting to affect this region. The magnitude of this dryland salinity process is illustrated by the large rate of salt loss in baseflow, which is similar to values described for highly salinized catchments of the Murray–Darling Basin in south–east of Australia (Jolly *et al*., 1997). South of our study area, raising water tables and recent tree die-back have been reported (Bogino and Jobbagy, 2011).

Although vegetation disturbances and transformations are recognized as important drivers of hydrological and geomorphological changes in semiarid regions (Istanbulluoglu and Bras, 2005; Gordon *et al*., 2008), the complexity of their associated mechanisms may favour the selection of simpler 'abiotic' explanations rooted on climatic (e.g. precipitation extremes or long term trends) or geological forces (e.g. seismic activity) (Blöschl *et al*., 2007; Istanbulluoglu, 2009). We propose that land use changes are the ultimate driver of the rapid process of landscape dissection and water course formation that we report.

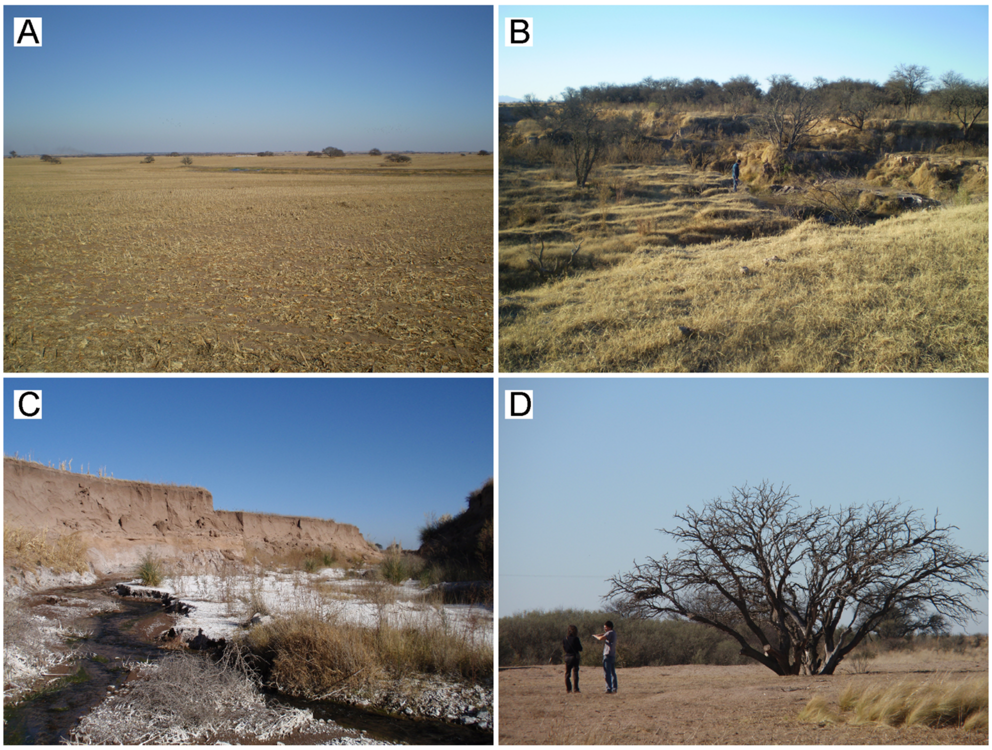

Figure 6. (A) Agriculture stands in the upper section of the catchment with a small surface water body resulting from the groundwater rise, (B) deep-seated mass failures driven by subsurface erosion processes along the new stream banks ('Río Nuevo' creek), (C) new stream channels at the upper section of the catchment ('Río Nuevo' creek) with 6 m vertical side walls and secondary salinity signals and (D) soil embankment in the middle section of the catchment (depth of the new sediments is estimated ~1.5 m).

The first source of evidence supporting this view comes from the contrasting salt storage of cultivated versus forested stands, which suggest the prevalence of a non-flow condition under forests that was disrupted by agriculture. These contrasts were in close agreement with those found by Santoni *et al*. (2010) in the proximities of the area and other worldwide cases of dry forests conversion into agriculture (e.g. George *et al*., 1997; Leduc *et al*., 2001; Scanlon *et al*., 2005). Differences between native vegetation and agriculture stands in their capacity to access (i.e. rooting depths up to 17 m in *Prosopis* stands (Villagra *et al*., 2011) and 1.8 m in annual crops (Nosetto *et al*., 2012)) and transpire water (i.e. leaf area and rugosity, as it is suggested by NDVI trajectories), combined with the common strategy of storing soil water during fallow periods followed by most annual crop farmers can explain the observed ecohydrological contrasts.

The second evidence of the outstanding role that land use changes may have had in the observed hydrological and geomorphological transformations is related to their timing both in terms of geologic and historic time scales. The aeolian sediments that hosted the new incisions and stream network have an age of approximately 9000 years, as suggested by thermoluminscence dating (Tripaldi and Forman, 2007; Santoni *et al*., 2010). Over such time span, we find reasonable to expect periods of precipitation and seismic activity than could have surpassed any extremes achieved during the last five decades (Piovano *et al*., 2009 and references therein; Sagripanti *et al*., 2011). Hence, if these abiotic drivers were sufficient to trigger the observed landscape transformation, we should have found them at the beginning of our study window. Deforestation and cultivation, instead, are a novel disturbance in this landscape.

Shorter term trends in land use, precipitation, earthquakes and landscape incisions provide additional insights. Although our temporal analyses suggest that the episodes of landscape dissection accounted in decades of relatively higher rainfall, intense rainfall events took place before and after their initiation. According to historical documentation, some of the earlier periods of intense rainfall were accompanied by floods and high discharge values in the 'Quinto' river (Figure 2), yet no incisions took place at that time. Earthquakes can affect streamflow and groundwater levels through changes in soil permeability or aquifer structure, often as a result of soil/sediment liquefaction (Rojstaczer *et al*., 1995; Montgomery and Manga, 2003). According to existing empirical relationships that relate the magnitude and distance to the epicenter of earthquakes to soil liquefaction and water table level shifts (Galli, 2000; Montgomery and Manga, 2003), none of the recorded earthquakes in our study achieved the magnitude–distance threshold required to promote soil liquefaction at our site, yet approximately 30 events could have promoted water table changes. These changes were highly intense at the footslopes of the Morro range after the 1936 earthquake (M6.0, epicenter ~180 km away from study area), which caused rock failures, spring discharge rises and hot water surges during more than a week (Barrera, personal communication). However, as noted before, no landscape incisions took place then. Noticeably, the fastest rate of watercourse formation took place in a period of relatively low seismic activity (Figure 2).

Although the timing of watercourse formation was associated to that of deforestation, observations do not suggest a linear and immediate correlation with it because the first episodes of abrupt landscape dissection occurred in 1999 when remnant forest covered 15% of the total area of the catchment. Delays between land cover change and landscape transformations may be expected if threshold responses or cumulative effects are important (Valentin *et al*., 2005; Sidley and Ochiai, 2006; Viles *et al*., 2008; Zehe and Sivapalan, 2009; Corenblit *et al*., 2011). Decadal precipitation increases may have been a more important and indirect effect on landscape transformations by favouring the expansion of agriculture (Viglizzo *et al*., 1997; Zak *et al*., 2008).

Conceptual model

Field observations and diagnostic channel morphologies collected at the stand and catchment level point to enhanced deep drainage and seepage outflows favouring subsurface erosion as the governing mechanism of landscape dissection and permanent watercourse. Although not negligible, surface erosion by runoff may act as a secondary agent of drainage network growth (Figure 7).

Subsurface erosion caused by seepage and pipe flow processes has been described as an important way for gully and canyon formation and growth (Dunne, 1990; Bryan and Jones, 1997; Derbyshire, 2001; Valentin *et al*., 2005; Vanwalleghem *et al*., 2005; Fox and Wilson, 2010) and could have been initiated at our site (Figure 6(B)). Stream bank instability and failures induced by seepage erosion can be triggered by the rapid flow of water through soil pipes and their subsequent collapse (piping) or by the removal of the basal support resulting from a constant groundwater seepage flow (sapping). Both subsurface processes are typically associated with an underlying permeability barrier that promotes lateral flow (Laity and Malin, 1985; Hagerty, 1991a, 1991b). Groundwater flow enhancement promoted by the disruption of the non-flow condition brought by cultivation could have initiated these subsurface erosion processes along sediment discontinuities or planes of weakness, particularly at landscape concavities and ancient paleo-channels (surface sediment layers buried ~9000 years ago by the aeolian sediments that are now at the surface). Subsurface erosion is supported by field diagnostic indicators that include (1) widespread isolated foci of soil collapse (Figure 6(B)), (2) moderate density of shallow (<3 m deep) pipes developed along canyon sidewalls (Figure 6(C)), (3) amphitheatre-shaped heads and sidewalls, flat channel floors, deep-seated mass failures and hanging valleys along new stream banks (Figure 6(B), Figure 8) and (4) the perennial and highly saline streams (Laity and Malin, 1985; Schumm *et al*., 1995; Fox and Wilson, 2010). The general lack of physical soil crusts and field scars of surface water erosion (rills and/or moderate gullies connected to the water bodies and large

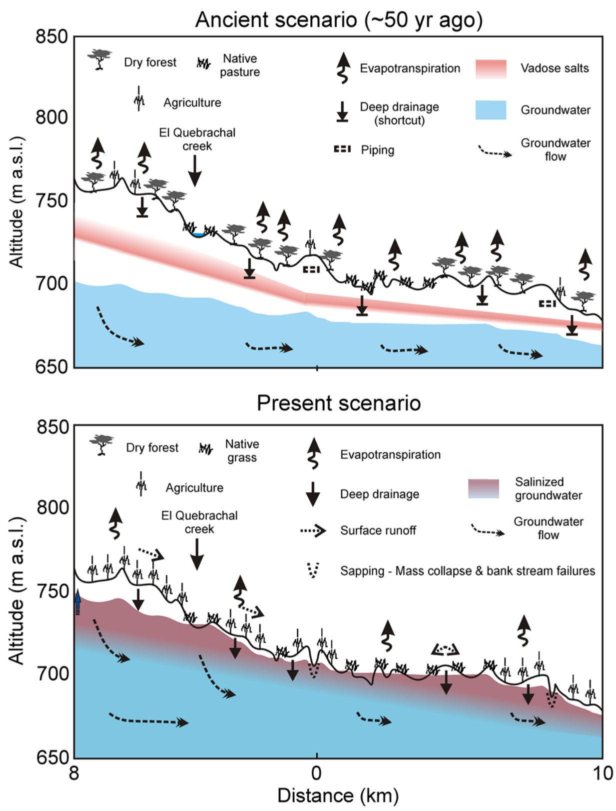

Figure 7. Conceptual model showing the processes and mechanisms involved in the hydro-geomorphologic evolution of the catchment. The profile section, located at the transition between the loessic–sandy and sandy plains, is at scale and shows the local tectonic depression where most of the new canyons and watercourses originate (transect A–A′ in Figure 1). An ancient scenario with a dense dry forest coverage was characterized by the non-flow condition with dry and salty vadose profiles, and deep groundwater levels. After the conversion of native vegetation into agriculture (present scenario), recharge was enhanced resulting in water table level rises, activation of subsurface erosion processes (piping and sapping) and abrupt appearance of lagoons and new watercourses. Once these canyons and watercourses were formed, their expansion was controlled firstly by streambank erosion and lateral mass failures led by sustain groundwater seepage inflows and secondly, by surface runoff following intense rainfall events.

streams) suggests its minor role. Once the large headcuts were formed by the collapse of the soil, growth and widening of the canyon network could have been promoted by soil saturation conditions, imposed by shallower water tables, or even by the overland flow generated in the streams after intense rainfall events.

Although the future evolution of the studied landscape is uncertain, possible pathways of change can be suggested on the basis of our observations and the trends reported in many deforested catchments in Australia (George, *et al.*, 1999; Williams, 1999). Water excesses in the study watershed (difference between precipitation and actual evapotranspiration) will likely be maintained or increased as cultivation expands, annual crops prevail over perennial pastures and salinized bottomlands prevent the development of vegetation. Whether these water excesses will translate into flooding or higher stream water flow will depend in part on the evolution of the drainage network. If it continues to grow exponentially reaching densities observed in other sapping incised landscapes, liquid water evacuation will prevail, and dissection and canyon growth will rise preventing flooding and surface salinization (i.e. spontaneous drainage of water excess and salts out of the landscape). Regarding water quality in the new streams, no changes are expected in the following decades given the large pool of salts that needs to be flushed from the vadose zone of forest areas that went into cultivation. Finally, we hypothesize that surface erosion/deposition processes will increase in the future (Figure 6(C, D)), particularly in middle and low sections of the watershed, as new watercourses funnel runoff more rapidly into those areas.

Although a full control of future landscape dissection cannot be warranted, halting forest clearance will help to prevent water excess increases. Given the current dominance of cultivation, the design of agricultural systems with higher evapotranspiration rates based on (1) perennial crops that consume water over longer periods, (1) deep rooted crops that create drier vadose zones and (3) salt tolerant species that access and consume groundwater could incline the water balance towards the original non-flow condition (Scanlon *et al.*, 2007). This condition, however, may not be fully achieved unless large proportions of the watershed are reforested as it has been shown elsewhere (Farrington and Salama, 1996; George *et al.*, 1999; Pannell and Ewing, 2006). Complementing land use actions, proper water drainage systems could help enhance current stream networks in a more predictable and planned way, avoiding the damaging effects of surprising dissection episodes. Whereas this would be particularly viable in the upper and mid watershed sections, lower slopes in low sections may require groundwater pumping infrastructure. In addition, the construction of stone bunds or rock check dams will increase the roughness of the stream channels and attenuate surface flow and sediment transport (Dogramaci, 2004; Valentin *et al.*, 2005). The effectiveness of these interventions is uncertain and requires detailed hydrological and hydrogeological assessments (Pannell and Ewing, 2006; Boix-Fayos *et al.*, 2008). Finally, water table levels appear as a critical indicator of the hydrological state of the system, and their continuous monitoring would help gauge its evolution.

Being one of the oldest cultivated section of the semiarid forests of central Argentina, the studied watershed offers an anticipated view of what may become a more common problem in vast extensions of the Espinal and Chaco regions of Argentina that are now subject to more intense deforestation (Viglizzo *et al.*, 1997; Grau *et al.*, 2005). The example of the Australian dryland salinity process and the case presented here should stimulate ecohydrological monitoring and land use innovation and regulation actions.

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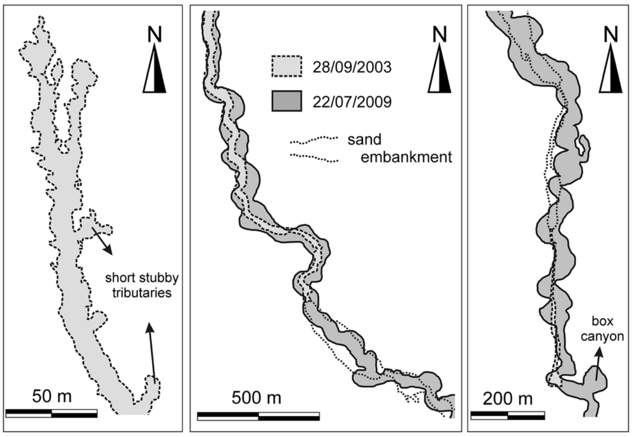

Figure 8. Channel planform changes observed in the 'Río Nuevo' creek at the upper (right), middle–up (centre) and middle–bottom (left) sections of the river canyon (Figure 1 for map location). The valley network is typical of groundwater sapping landscapes with amphitheatre-shaped heads and sidewalls cuts, short stubby tributaries, hanging small box-canyons and relatively constant valley width. Sketch planforms were obtained from high resolution remote sensing imagery (2003, dashed-light grey area and 2009, thick-dark grey area) available through Google Earth. Embankments (dotted lines) represent areas showing signs of recent sand deposition at the time of image acquisition.

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