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GULLY EROSION AND STREAMS DEVELOPMENT IN THE RÍO QUINTO BASIN, MIDWEST ARGENTINA

Desarrollo de cárcavas y cursos de agua en la cuenca del Río Quinto, centro-oeste de Argentina

Adrian H. Gallardo[1,2*], Aldo Giaccardi[1], David Aguilera[1], Yesica N. Battistino[1] and Amancay Martinez[1]

[1]*San Luis National University, FCFMyN, Department of Geology, Ejercito de los Andes 950, San Luis 5700, Argentina*
[2]*CONICET (Argentina National Scientific and Technical Research Council), CCT San Luis, Argentina*
[*]*Corresponding author: adgallardo@geowater.com.au*

Abstract: *The last decades have seen a dramatic increase in gully erosion and the development of watercourses in the Río Quinto basin, within the San Luis province of Argentina. The phenomenon is causing severe damage to existing infrastructure, as well as making large areas of agricultural land unproductive. This paper analyses the key factors that contribute to soil denudation and the formation of new channels in the region. The nature of the debris deposition is also explored. The interconnection between sediment types, physiography, climate change, and land cover has created unique conditions that make the area susceptible to a loss of soil cohesion and erosion. An increase in precipitation would have contributed to gully initiation over time, while overland flow exploited older stream channels which led to the reactivation of the drainage system. Piping is another mechanism controlling the removal of sediments in the subsurface. Fine-grained materials, high levels of sodium, and elevated alkalinity facilitate dispersion processes that render the soil structure unstable. Carbonate dissolution also appears to be significant in calcareous layers. Fluvial development has recently accelerated due to a wetter climate and land clearing, and is likely to worsen in coming years. Lobate deposits are present at the downslope end of major streams, and these sediments would represent the episodic deposition of debris torrents and hyperconcentrated flows as the system energy dissipates. Results of the study constitute a useful reference both for prevention and for the implementation of mitigation measures in the region.*

Key-words: *streams, gully erosion, piping, hydrology, climate change, Argentina.*

Resumen: *A lo largo de las últimas décadas se ha visto una aparición notable de cárcavas y cursos de agua en la cuenca del Río Quinto, provincia de San Luis, Argentina. El fenómeno causa severos daños a la infraestructura existente, y convierte importantes parcelas agrícolas en tierras improductivas. El presente manuscrito analiza los factores principales que contribuyen a la erosión de suelos y la formación de nuevos cursos en la región. También se investiga la naturaleza de los depósitos de detrito en el área. La relación entre sedimentos, fisiografía, cambio climático, y uso de la tierra ha creado condiciones particulares que favorecerían la perdida de cohesión y la erosión de los suelos. El aumento de las precipitaciones habría también contribuido con el desarrollo de cárcavas, mientras que la escorrentía superficial sobre antiguos cauces podría haber reactivado el sistema de drenaje regional. El sifonamiento constituiría un mecanismo adicional para la remoción de sedimentos. La presencia de materiales finos, altos niveles de sodio, y una elevada alcalinidad facilitarían los procesos de dispersión y la inestabilidad de los suelos. La disolución de carbonatos sería importante en horizontes calcáreos. El desarrollo de cursos fluviales se aceleró durante los últimos años como resultado de un clima más húmedo y la deforestación. Es de esperar que el problema se intensifique en años venideros. Se observa una serie de depósitos lobulados en el margen distal de los arroyos, que serían el resultado de la sedimentación esporádica de torrentes de barro y flujos hiperconcentrados cuando la energía del sistema se disipa. Los resultados de la investigación proveen un material de referencia útil para la prevención y la implementación de medidas de control en la región.*

Palabras clave: *arroyos, carcavamiento, sifonamiento, hidrología, cambio climático, Argentina.*

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The abrupt formation of gullies and surface watercourses has become a recurrent problem in the Río Quinto basin, in the Midwest region of Argentina. In particular, the morphology and hydrological characteristics of the San Luis province are rapidly changing due to the emergence of erosional channels on relatively gentle slopes. Examples of such a dynamic environment are seen in the *Quebrachal Creek* and the *Río Nuevo* (“New River”), streams that suddenly developed across the farming plains of northeast San Luis.

The generation of watercourses is a natural process associated with the landscape evolution, and could even be beneficial to the ecosystem in the catchment. In the short-term however, these changes impact on existing infrastructure such as housing, roads and railways, and jeopardise the availability of land for agricultural practices. In particular, changes in the runoff regime, variations in soil salinity, and fluctuations in phreatic levels are all cause of deep concern for the rural communities of San Luis. Concomitant with the erosion, the creeks also provide pathways for the rapid deposition of debris downstream. As stated by Blair (1999), many gullies, as in Death Valley of California, are the source of lobate-shaped alluvial deposits. The formation of creeks and the aggradation caused by transient debris flows is a common process long recognised by earth scientists (Kuenen 1950; Kurdin, 1973; Takahashi 2014; etc.).

To present, the vast majority of the research dealing with soil erosion and deposition processes have been undertaken in the Northern Hemisphere, where conditions (especially climate) are often specific for the region of study. Even when the principles driving erosion-deposition show commonalities worldwide, assessing the hydrological behaviour at a singular location requires an understanding of unique characteristics such as the local geology, land use, and meteorological conditions. The significance of the morphology changes in San Luis has recently drawn the attention of local authorities and the scientific community, resulting in a number of publications aimed at gaining a better understanding of the phenomena. In this context, changes in the hydrological conditions of the *Río Nuevo* were recently explored by Sanchez *et al.* (2013), as a way to establish mitigation measures in its area of influence. Precipitation, seismic activity, and deforestation were also assessed by Contreras *et al.* (2012) as potential drivers for landscape dissection. According to these authors, higher than average precipitation, along with the replacement of forests by annual crops, played an important role in initiating an abrupt process of watercourse formation. An increase in precipitation in San Luis has been previously mentioned by Berton and Echeverria (1999), who noted a shift from semiarid to subhumid conditions. Recently, Nosetto *et al.* (2015) have postulated that rather than slope runoff, formation of gullies would be triggered by hydrological processes in the subsurface. These authors made recommendations to focus future works on the groundwater characteristics and its response to surface events.

Despite the recent studies reported in the literature, we still know relatively little about the processes that generate new watercourses in San Luis. The main purpose of this study is to provide new insights into the possible mechanisms that trigger soil denudation and gully erosion in the Río Quinto basin of eastern San Luis, and to explore the nature of the saturated mass typically mobilised downslope within the incised channels. The study complements other investigations carried out in the area in recent times (*e.g.*, Cabanes, 2015; Galvan *et al.*, 2015; Martinez Diez, 2015), and contributes to the development of a conceptual model that predicts the overall impacts of climate change on the region. Finally, this paper will be of interest not only to earth scientists but also to local authorities seeking to mitigate the environmental impacts and economic losses caused by the new morphology of the terrain.

Study area

Physiography

The study site is part of the El Morro catchment, within the Río Quinto basin, approximately 100 km east of the city of San Luis in the Midwest region of Argentina. The *Cerro el Morro* (“El Morro Hill”) and the flanks of the *Sierra de Yulto* (“Yulto Ridge”) constitute the natural boundaries of the catchment, to the north and west respectively. To the south, a major river, the *Río Quinto*, discharges into an endorheic basin several kilometres to the east, outside of the San Luis province (Fig. 1). The area is part of a large sedimentary landscape typically used for cattle grazing and intensive agriculture. The land cover is dominated by pastures and forests to the north and by open woodlands and scrublands further south. Morphologically, the site can be divided into three major units of distinctive topography: a) the northern region mainly defined by hillslopes of steep to moderate gradient (15 to 2 %) in a hilly landscape of sharp contrasts; b) the central region of undulating terrain, gentle slopes, and both sand dunes and eolian depressions; and c) the south characterised by wavy to flat lands that transition to the alluvial plains of the *Río Quinto* (Sanchez *et al.*, 2013). The headwaters of the catchment are found at the foothills of the *Cerro el Morro*, where multiple and intermittent streams meander in a discontinuous pattern until they disappear into the sand dunes and loess prairies of the south. Towards the middle basin however, soil incisions and gullies are more recurrent and shape the morphology of the new streams such as the *Río Nuevo*, which drains approximately 30 km to the south in a valley up to 35 m wide and 12 m in depth. The soils of the region have been classified as mollisols with subordinated entisols (Peña Zubiate *et al.*, 1998). The mollisols are ubiquitous in foothills and they form the valley floor of the intermountain valleys of the basin. They are typically characterised by an organic matter content of 1 to 2 % in the top 25 cm of the soil profile. The parent material is mainly loess and very fine to fine sands, often of calcareous composition. The entisols are unconsolidated and poorly developed soils, commonly found in the plains and depressions of the area. These soils are young, with limited horizons and a general composition of 70 % sands, 20 % silts, and 10 % clays. The content of organic matter is usually above 1 % (Battistino, 2012).

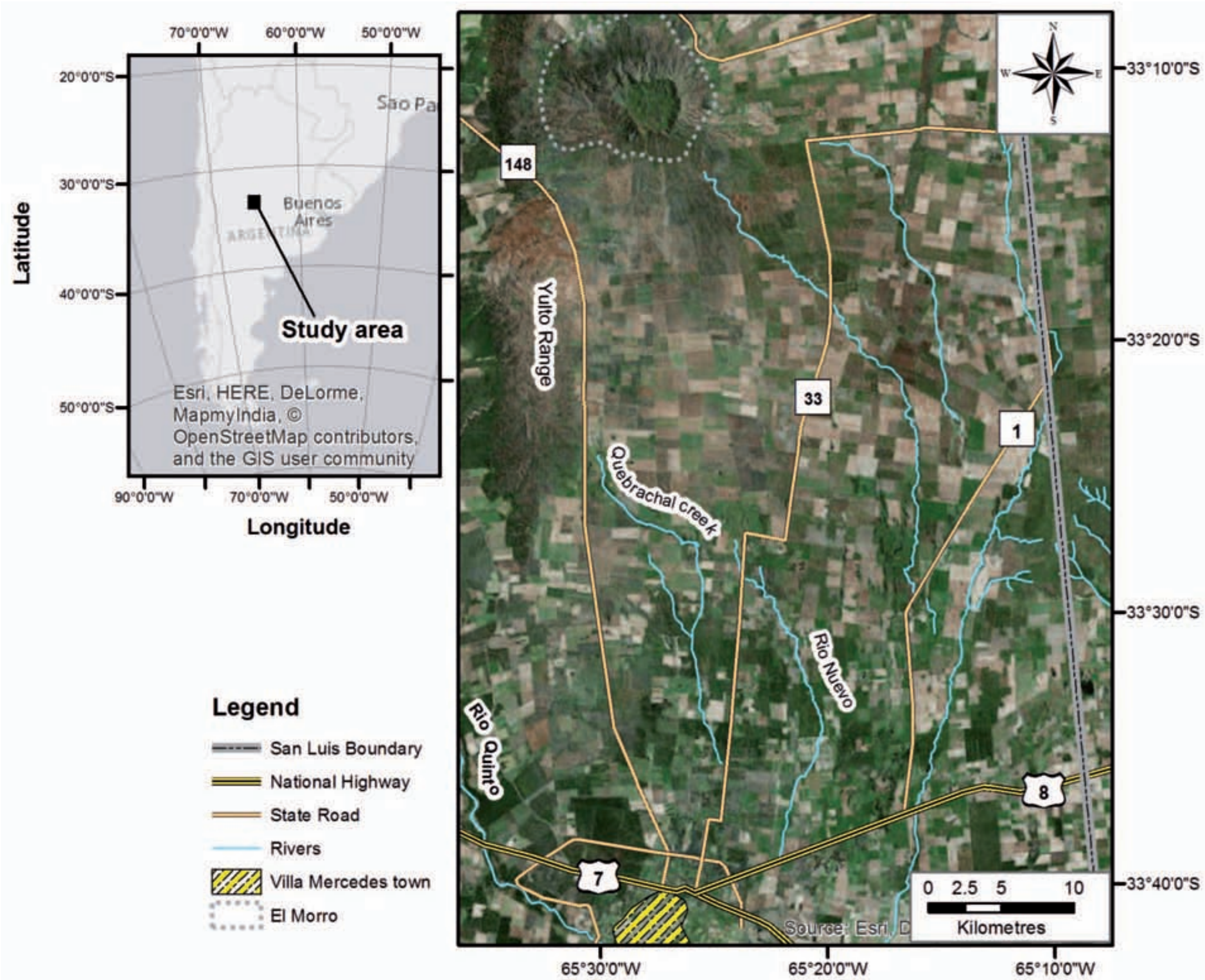

Fig. 1.- Location map and aerial view of the El Morro catchment.

The climate of the area is classified as dry continental. Long-term data from the INTA (National Agricultural Technology Institute) – *Villa Mercedes* weather station (33.65º; 65.42º) indicates that rainfall is irregularly distributed, with most of the precipitation occurring in spring and summer (September to March), and less than 20% of the rains in the “dry” season of autumn/winter (Ojeda, 2005). It is worth noting that the rainfall regime increased from an average of 547 mm/year in the first half of the 20th century, to 655 mm/year for the period 1952 - 2014 (Fig. 2). This is consistent with the trends observed by Veneciano *et al.* (2000), and Jofre (2011), who recognised an increase of more than 200 mm in the mean annual rainfall of the region after 1950.

Average annual temperatures at *Villa Mercedes* range approximately between 16º and 17º, with the highest records in January (up to 42º) and minimums close to -10º in July (REM, 2015).

Geological Context

At the regional level, the area of interest is part of the Pampean Ranges, a system of isolated mountains rising abruptly from the surrounding plain of central Argentina (Riccardi, 1988). The ranges are formed by a series of Precambrian fault blocks that produced restricted longitudinal basins filled with continental sediments of variable age, from Palaeozoic to Mesozoic. The crystalline basement of the area is composed of granitoids and metamorphic rocks that reach their maximum expression in mountains such as *Yulto* and *El Morro*, after emerging from the Cainozoic cover of the lowlands. The Quaternary sediments are made up of Pleistocene and Holocene deposits of various terrestrial origins. Colluvium and abundant loose debris are commonly found on the foothills of the *Cerro El Morro*, as a result of avalanches and landslides mobilised in steep slopes. These materials produce a landscape of small hills

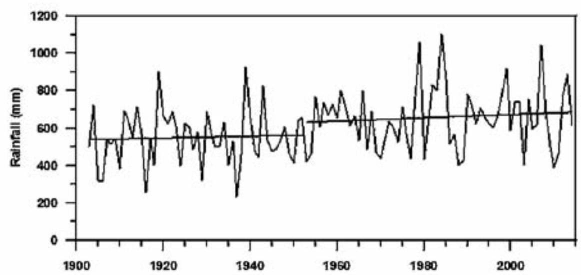

Fig. 2.-Annual precipitations and trend for the period 1903 – 2014 in *Villa Mercedes*, San Luis.

slightly dissected by ephemeral streams. The debris is mainly composed of boulders and gravels, with a composition derived from both the underlying basement and a bed of vulcanites from the Pliocene (Costa *et al.*, 2002).

The rest of the catchment is characterised by loess mantles of variable thickness (3 – 15 m), largely covered by sand dunes up to 6 m high that generate a gently undulating landscape. The loess lacks a defined stratification and is better observed on the banks of the creeks and ravines that dissect the area. Additionally, a large field of sand dunes developed on the land surface over time. This system has been referred as the Pampean Sand Sea (Iriondo, 1999). The dunes are typically elongated in the northeast – southwest direction, with a composition mostly in the range of very fine to fine sands. The mineralogy is dominated by subrounded to subangular quartz, along with feldspars, muscovite, and subordinated ferromagnesian minerals (Costa *et al.*, 2002). Today, the dunes are considerably stabilised by vegetation and not easily recognised on the ground, due to their subdued topography. According to Kröhling (1999), the loess and sand dunes formation indicate a relatively dry period for the Pampas region in the late Holocene. The eolian activity was also responsible for the deflation processes that led to the formation of depressions and lakes in the region. These features are primarily semi-circular, often extended north-south. Deflation was strongly dominant during all glacial events, with a depth limited by the piezometric levels at the time. As the erosion progressed, the ground surface approximated the groundwater static level, which in turn consolidated the soil aggregates and favoured the vegetation growth, with the consequent halt to the soil denudation.

Methods

Field and laboratory work were undertaken to establish the causes of the formation of watercourses in the *Cerro El Morro* catchment, south of the *Cerro El Morro* hill. The analysis was largely centred on the *Río Nuevo* and *El Quebrachal Creek*, although the processes accounted for in the assessment can be extrapolated to other areas of the catchment. Field mapping and satellite images were first used to construct a geomorphological base map. In addition, aerial photos were employed to monitor the dynamics of erosion-deposition events within the area of interest. Meteorological records from the nearby station at *Villa Mercedes* were extracted from the database of the INTA and the University of La Punta, San Luis. Site visits were conducted to ground-truth the geomorphic features identified in the images and to map the geology of the area.

Soil samples were collected in gullies and hillslopes of the *Río Nuevo* and *El Quebrachal*. The procedure consisted of taking samples in a random pattern across the field, which is suited to uniform sites where it is difficult to identify a single dominant type that would represent most of the area. Testing of the samples was subsequently performed at the laboratories of the Department of Geology, San Luis University, to determine the physical and chemical properties of the soils in the region. Grain-size analyses were carried out on mechanical sieves to determine the particles distribution. Soils were first dried to 105ºC to eliminate any moisture and then shaken for disaggregation. The weight retained in each sieve was recorded and the soil distribution curve obtained. The sieves measured the soil fraction between 53 and 2,000 µm. The distribution of fines was determined by the hydrometer method, which involves the sedimentation of a solution mixture in a cylinder. The cation composition of the sediments was measured by wavelength dispersive X-ray fluorescence (WD-XRF). The system utilises a series of crystals to diffract the X-rays of particular wavelengths in different directions. Crystal materials used for the analysis included lithium fluoride 200 and 220 (LiF), germanium (Ge), and PET film. Spectra interpretation and determination of elements was performed by the use of the software SuperQ and associated modules (PANnalytical, 2015).

Two samples were also analysed by flame emission spectroscopy (FES) to determine the salt content of the soils. The specimens were diluted in distilled water and filtered after 24 hours. Liquid samples were then nebulised and placed in the flame of a Metrolab 315 instrument. Finally, the emitted radiation passed through the monochromator and the specific wavelength of each of the elements was measured.

Results

The *Quebrachal Creek* is an endoreic drainage system that flows in a predominantly north-south direction. It is located approximately 4 to 7 km west of the *Río Nuevo*. The creek is rather unique, as it is the sole channel of the region that can be identified in aerial images from the early 60's (Fig. 3a). The waterway appears continuous, with a narrow channel that dissipates into the underlying sediments further south. The absence of alcoves or evidence of slope recession indicates that erosion at the time was limited. Nevertheless, vague incision lines observed in the photos suggest the presence of possible paleochannels under the soil blanket, near the main watercourse. These seepage zones can be identified by their wide area and darker colour, likely due the presence of wet vegetation. Examination of more recent images shows that by 2003, the channel had widened due to physical erosion, which led to the development of an anastomosing network within the creek (Fig. 3b). The enlargement of ponds and minor lakes is also evidence of a general rise of the water table, frequently to levels above the natural surface in the vicinity of the creek.

The Caucete earthquake has also been considered to be a potential trigger for the formation of gullies and soil depressions in the Río Quinto basin. On November 1977, an earthquake of intensity 7.4 on the Mercalli scale took place in the region of Caucete, approximately 300 km northwest of the study site. The phenomenon was accompanied by soil liquefaction and a vertical displacement of 30 cm (Moreiras and Paez, 2014).

Once gullies develop, they often trigger other soil degradation processes such as piping, soil fall or soil topple

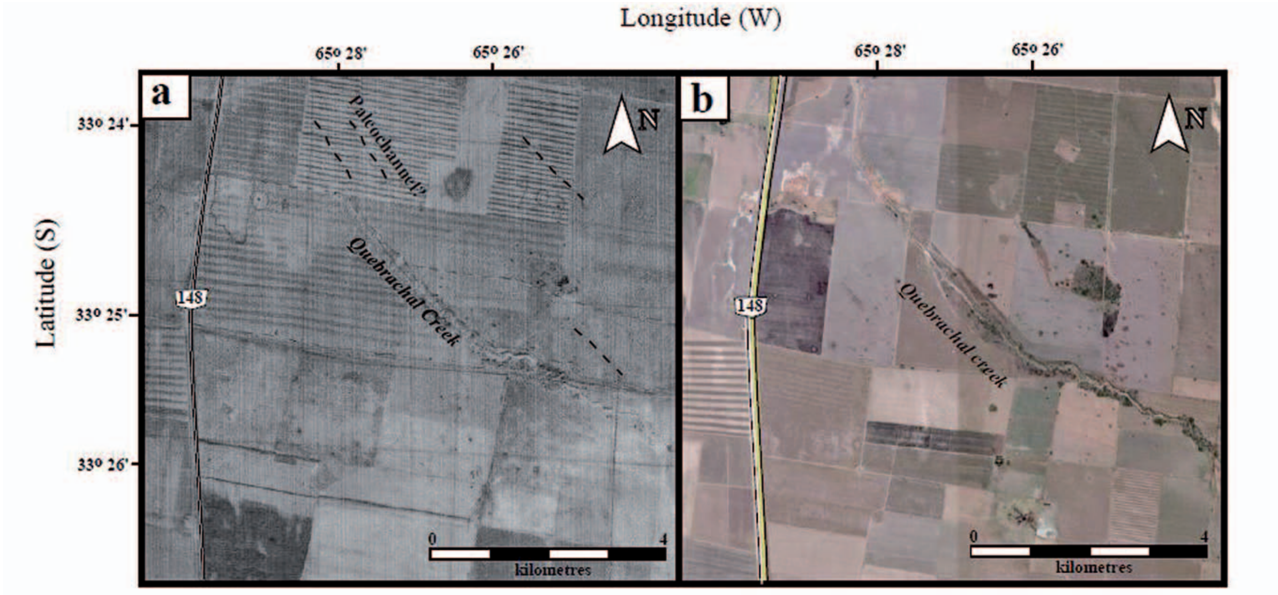

Fig. 3.- Aerial image showing the headwaters of the Quebrachal Creek and its evolution in time. a) image from 1962 (modified from Barbeito *et al.*, 2008); b) image from 2003.

after tension cracks develop and undercutting occurs (Poesen *et al.*, 2003). As noted by Gunn (2000), pipes may range from a few centimetres in diameter to those that are large enough to crawl into. Similarly, conduits between a few cm up to ~1 m in diameter were observed in the surroundings of the *Río Nuevo*. The pipes are not simple linear structures, but often sinuous and without a defined direction. These features develop in the shallow substratum, to a depth not exceeding 3 m below ground level (Battistino, 2012). The enlargement of these conduits is frequently associated to a loss of material strength and cohesion, ultimately leading to the collapse of the roof and the formation of additional cavities.

Patchy outcrops of calcrete were observed at a number of locations near gullies and streams. The main feature observed in the calcrete is a near-surface sinkhole of about 20 cm^2 which acts as a preferential pathway for overland flow into the underlying substratum (Fig. 4). The extent of the pipe network is still unclear as more detailed mapping is required to define the geometry and boundaries of the calcareous sediments. It is anticipated however, that the density and size of the pipes could be much larger than what has been established so far.

Discussion

Rainfall

Gully erosion begins when runoff concentrates into channels and rills develop, which may later enlarge into deep trenches in the land surface over time (Luffman *et al.*, 2015). Similarly, channel development in the *Quebrachal Creek* might have been initially influenced by hillslope runoff after intense rainfalls. This is supported by the increase in precipitation registered in *Villa Mercedes* during the 20^{th} century, with average rainfall rates steadily above 600 mm/year after 1950 (Veneciano *et al.*, 2000). Paleochannels and pre-existing drainage lines would have acted as preferential pathways for overland flows, evolving from incipient gullies to an ephemeral stream and ultimately into a permanent watercourse. Nevertheless, it is argued that until about 2005, climatic factors would have played only a secondary role in the formation of watercourses. Effectively, even though long-term records show a general increase of precipitations throughout San Luis, the appearance of streams is mostly restricted to areas south of *Cerro el Morro*. This is in agreement with Contreras *et al.* (2012), who indicated that early periods of intense rainfall were not accompanied by the formation of watercourses around the *Río Quinto*. This suggests that rainfall alone is not enough to explain gully formation in the area, at least until the last decade. As it will be discussed in the following sections,

Fig. 4.- Sinkhole developed in calcrete near the *Río Nuevo*.

the contribution of rainfall-runoff to stream development might have intensified at the beginning of the 21st century, when a new wet cycle led to a major reactivation of the drainage system.

Earthquakes

The potential for correlation between seismicity and liquefaction is well known (Ishihara, 2006; Unjoh *et al.*, 2012; Wang and Manga, 2010; etc.). Nonetheless, there is no evidence to back the idea of subsurface disruptions at such a distance from the epicentre of the Caucete earthquake. Furthermore, it is likely that many of the destructive earthquakes have been characterised by deformations distributed in folds and secondary faults, without surficial ruptures (Perucca *et al.*, 2006). Again, this agrees with Contreras *et al.* (2012), who postulated that none of the earthquakes that they studied achieved the magnitude-distance threshold required to promote soil liquefaction within the Río Quinto basin.

Seismic waves may induce changes in permeability due to the opening or unclogging of fractures, whilst piezometric heads can also fluctuate in response to crustal deformation (Ohno *et al.*, 1999). The seismic waves could cause an expansion and/or contraction of the aquifer, with consequent effects on the strength of the sediments. Variations in groundwater levels also result in changes of the pore-fluid pressure, which are accompanied by a shift in the aquifer's granular structure. These mechanisms increase the permeability of the rock formation but are more likely to occur near the earthquake epicentre, particularly in confined units, which are more sensitive to permanent deformation. Rock failure and fracturing due to large but remote earthquakes are harder to explain, as the intensity of seismic waves fade with distance. Therefore, it is reasonable to infer that waves from the Caucete event could have distressed the shallow crust in the near-field of the earthquake, but would be too small to induce gully erosion far beyond.

Piping

It is considered that the physical and chemical characteristics of soils in the catchment would be susceptible to piping and the associated erosion. Soil texture and grain-size distribution indicates that sediments are predominantly very fine sands, with subordinate loams and traces of clay (Fig. 5). As recognized by Sherard *et al.* (1967), uniform and fine cohesionless sands have the least piping resistance, which intensify seepage and erosive forces. The removal of soil particles would be further accentuated along cracks, shear zones, or in more permeable horizons where water flow and velocities increase. In addition, the soils show elevated pH and high levels of Na^+, which are critical for the development of pipes. In effect, the Na^+ content (7.48 %) exceeds the combined concentration of Ca^{2+} (6.7 %) and K^+ (0.06 %), whilst pH values are normally above 8. High levels of Na^+ deflocculate the clay fraction of the material and render it extremely vulnerable to erosion (Romero Diaz *et al.*, 2007). High pH also promotes the clay/loam fraction to disperse and enhances surface cracking and the initiation of piping.

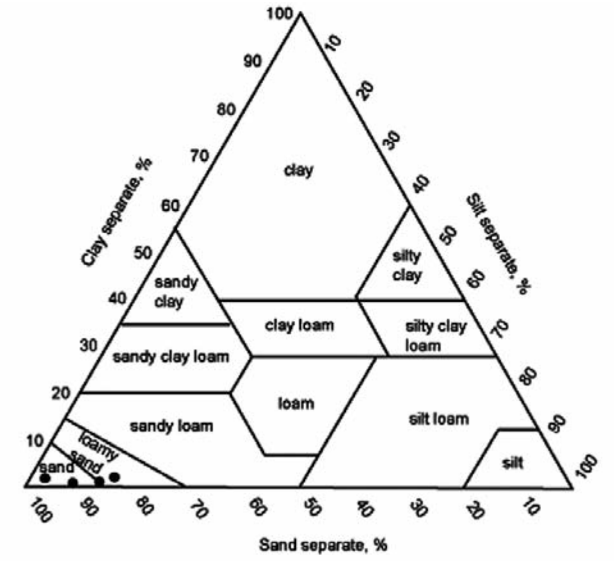

Fig. 5.- Soil texture classification for soils in the studied area.

Isolated outcrops of calcrete indicate that calcite weathering might promote the formation of cavities at specific locations. On the whole, carbonate dissolution appears to be a subordinate process however, the mechanism is still expected to accentuate the instability of the soils at a local scale.

Biological activity

Wildlife burrows would be an additional factor reducing the cohesion of the sediments, although it is also considered a minor process. Biological activity would be dependent on the habitat characteristics, mostly vegetation availability and the degree of sediments' compaction. In this context, the greatest effects of animal burrows are expected along riverbanks. Tunnels can compromise banks stability and create the conditions for slope failure. Furthermore, burrows can collapse and enhance the formation of sinkholes. Burrowing vertebrates like rabbits churn the upper regolith and bring fresh rocks to the surface, where they can be weathered more quickly (Lech and Trewin, 2013).

Interaction between streams formation and hydrological processes

As previously discussed, a major reactivation of the *Quebrachal Creek* and the *Río Nuevo* occurred after 2005. What were the critical factors that led to such a resurgence of the streams? It is likely that a general shift to a wetter climate could be the primary mechanism. During the period 2000 - 2010 average rainfall continued rising, with precipitations near historical maximums (*e.g.,* 2007). An increase in precipitation would translate into higher overland flows and enhanced erosion.

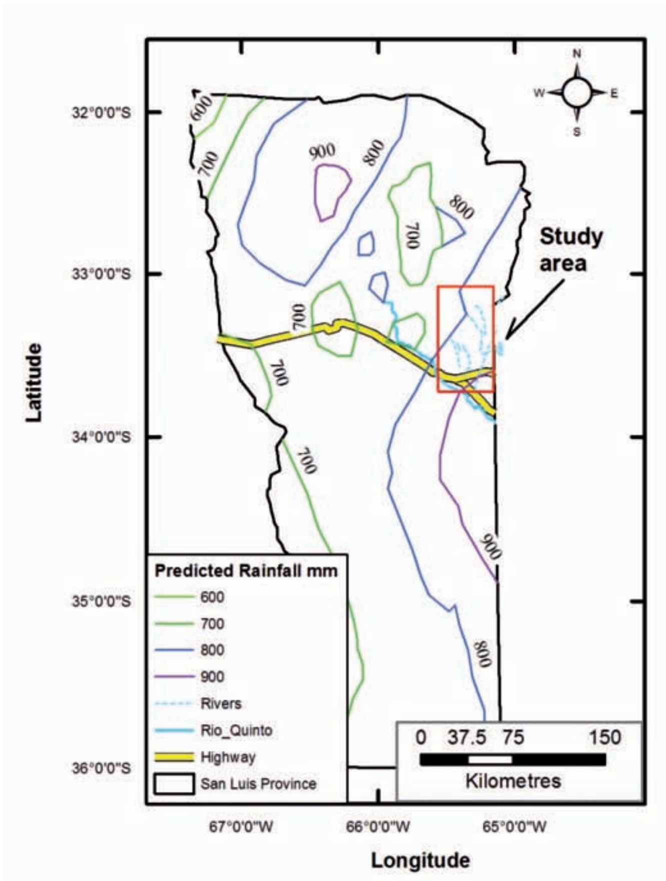

Fig. 6.- Predicted average precipitations in San Luis for the year 2020 (after Berton and Echeverria, 1999).

Numerical simulations by Berton and Echeverria (1999) indicate that precipitation in the province of San Luis is projected to further increase to an annual average of 500 - 900 mm by 2020, with most of this increase to take place in the east of the province, where the study site is located (Fig. 6). Erosion would increase as rainfall progresses in intensity and duration, and stream formation is expected to accelerate if the vegetation cover is further degraded.

Erosion rates up to 1 m/year were reported by Shellberg *et al.* (2010) for alluvial soils that had undergone changes from traditional aboriginal practices to widespread cattle grazing. More recently, Nosetto *et al.* (2012) noted that the replacement of grasslands by crops, or less obvious changes such as cultivating two crops in a year, could lead to significant hydrological alterations. In this regard, the Midwest of Argentina has experienced a dramatic shift from native woodlands to soybean cultivation, mainly to meet the high demand from Asian markets in recent years. This increase in the demand has in turn stimulated the land replacement and led to larger plantations, and more intensive agricultural practices.

Another question arises: how do the recently formed watercourses terminate? Gullies usually end where the transporting capacity of the concentrated runoff drops and/or where the erosion resistance of the topsoil increases sharply (Poesen *et al.*, 2003). More rainfall also reduces the water absorption capacity of the soils and consequently, favours the mobilisation of a saturated mass of soil at the surface. Thus, runoff will be preferentially diverted towards existing drainage pathways leading to a "cut and fill", in which sediments from the channel are eroded but redeposited downstream in successive events (Luffman *et al.*, 2015). This theory is supported by aerial images that reveal lobe-like landforms in the lower parts of major watercourses. These features are distinguished by more than one zone, suggesting the progressive accumulation of sediments downstream during multiple depositional events. For instance, at least two deposition events can be seen in the *Quebrachal Creek* (Fig. 7), with up-gradient proximal lobes of more reduced dimensions, typically about 500 m by 150 m, and larger distal deposits up to 2,000 m by 700 m by side.

Younger deposits have a rugged topography and are only slightly affected by eolian rework, whilst the older sediments are distinguished by a ubiquitous vegetation cover and clusters of mature trees. In general, the stratigraphy of the deposits is relatively simple, predominantly massive to slightly banded, mainly due to the presence of thin layers enriched in organic matter. Furthermore, the sediments are poorly sorted and lacking coherence or any other distinguishable pattern. This raises the question about the nature of the mass movement. Debris flows are distinguished by the fact that sediments are well-mixed, poorly sorted, and show no preservation of primary stratigraphy or bedding (Coussot and Meunier, 1996). These characteristics are similar to the deposits observed in the studied site, meaning they are unlikely to have been deposited by any dry depositional process. On the other hand, sediment mobilisation is influenced by the water content of the mass, typically sub-saturated in the actual debris flow, but increasingly hyperconcentrated upon the addition of substantial volumes of water (*i.e.*, water content greater than debris flows, but less than muddy streamflows). In this regard, the particle distribution of the observed deposits is

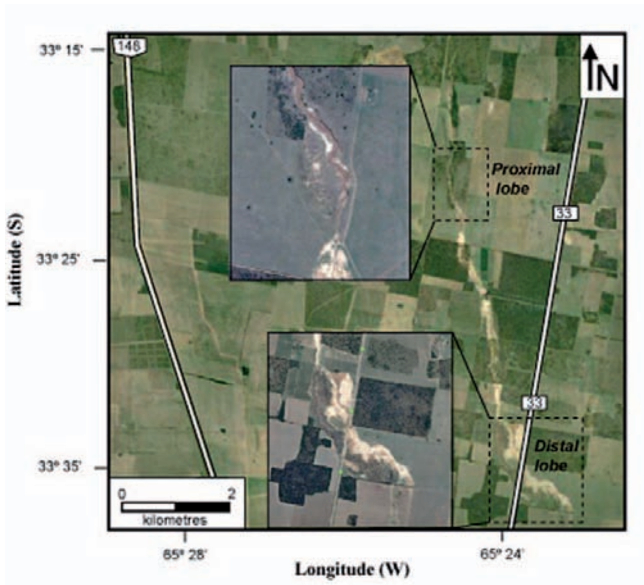

Fig. 7.- Aerial image showing the spatial distribution and accumulations of lobate de.posits along the downstream section of the *Quebrachal Creek*.

suggestive of water-rich hyperconcentrated flows. As stated by Xu (1998), hyperconcentrated flows reach their maximum transport capacity when sediment particles > 0.05 mm are more than 40 %, and grains < 0.01 mm do not exceed 20 % of the total mass. Furthermore, the relative shallow slopes and smooth boundaries of the lobes resemble a mixture of water and sediment that was probably mobilised as a plastic mass. This is consistent with Levy *et al.* (2010), who stated that low-angle slopes on which the flow terminates (~14º) are strongly suggestive of water-lubricated flows. In consequence, it is argued that lobe deposits in the El Morro catchment are derived from the stream's valley floor, in which sediments and water were mobilised as a single-phase debris flow in proximities to the headwaters, followed by low-viscosity, water-rich hyperconcentrated flows travelling longer distances downstream. The episodic deposition of short-run debris evolving to more mobile hyperconcentrated flows would cause frequent transformations of the stream profile and may explain the current distribution of lobe fans along the channel (Fig. 8).

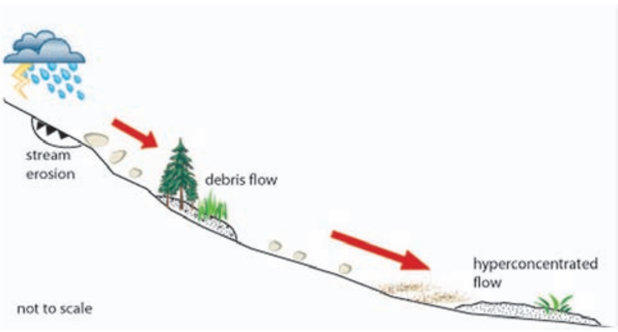

Fig. 8.- Conceptual model to explain the mass flow occurrence in stream channels of the El Morro catchment. Based on Tichavsky and Silhan (2015).

Conclusions

This study explored the key factors that contribute to the emergence and expansion of watercourses in the Midwest of Argentina. Incipient streams were first identified in aerial images of the early 60's, as they appear to have developed over the unconsolidated sediments that filled a pre-existing drainage network. The sediments dissection might have been influenced by a climatic shift that commenced in the second half of the 20th century. Under wetter conditions, the soil profile becomes largely saturated and infiltration is restricted. As a result, there is an increase of overland flows making the landscape more vulnerable to gully erosion. Following a trigger event, runoff water leads up to intermittent streams which in turn evolve into permanent courses.

Climate alone would not explain the appearance of watercourses in the basin, as the phenomena is not widespread in other watersheds of San Luis. A major earthquake measuring 7.4 on the Mercalli scale has long been attributed to be the cause for the early development of channels in the region. The event would have triggered liquefaction and a permanent ground deformation throughout the localities that surround the epicentre of the phenomena. However, there is no evidence suggesting significant seismic effects spreading into the Río Quinto basin, more than 300 km away from the focus of the earthquake. Our study suggests that natural pipes might play an important role in soil degradation and the formation of surface courses. In particular, the physical properties, high pH, and significant Na^+ content of the soils make them vulnerable to dispersion processes and to the development of pipes in the subsurface. Carbonate dissolution from calcrete accumulations is another process that can influence the formation of cavities underground. Additionally, wildlife burrows enhance the sediments permeability and further promote the passage of water in discrete sections of the shallow substrate. This mechanism may be also conducive to piping, although it would be greater in vicinities of riverbanks and areas of abundant vegetation, which provide a natural habitat for burrowing fauna.

More recently, further precipitation increases would have contributed to reactivate the drainage network in the basin. More rainfall translates into higher runoff and streamflow discharges, with the consequent acceleration of soil erosion. Predicted wetter conditions in combination with land clearing for agriculture are likely to exacerbate the problem in the future.

Soil denudation is concomitant with sediment transport and deposition. These depositional zones are distinguished by lobate features identified in the downstream part of the channels. The sediments would have accumulated over successive events from the mobilisation of a mass of debris that evolved into hyperconcentrated flows further downslope.

Results of the study are important for a wider understanding of the hydrological behaviour of the Río Quinto basin. In a time of environmental changes, and with a vast area of agricultural land under threat, further work to understand and control the abrupt development of streams should be taken as a priority for research in San Luis.

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