

Seasonal Intermittent Wetlands at the Desaguadero River. Argentine. Past, Present and Future Morphodynamics

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Abstract

The Desaguadero River comprises the upper section of a major hydrological system called Desaguadero-Salado-Chadileuvú-Curacó, located in the central-western sector of Argentina, on the eastern edge of the Diagonal Árida Sudamericana climatic belt. Within this basin, extensive wetlands have developed at the confluence of two main Andean rivers, the Mendoza and San Juan rivers, and from the surface flows generated during floods associated with the mountain ice and snow melts on the catchment area. The water from these rivers was channeled along the Desaguadero river, a north-south approximately 150 km long channel.

This paper proposed the Desaguadero river wetlands as a product of co-development of ephemeral lakes and lunettes dunes, based on geomorphological surveying and field work supported by stratigraphical analyses of relict lake-shores and fluvial sedimentary deposits along with historical climatic data. The morphodynamic activity of these wetlands gradually decreased since the end of the 19th century until practically disappeared in the 20th century, due to both natural and anthropic causes.

1. Introduction

Globally, 87% of the wetland resources has been lost since 1700 CE, with an increase in loss rates in the late 20th century (Davidson 2014). The remaining wetlands are being lost three times faster than natural forests as a result of direct and indirect human impacts, including agricultural conversion, river flow regulation, groundwater abstraction, invasive species and climate change (Tooth et al. 2021).

Wetlands are determined by a particular geomorphological environment and by lithologic and edaphic features that allow their location and guarantee the constant or temporary presence of surface or subsurface water (Kandus and Minotti 2019). About 46% of those wetlands corresponds to the inland wetland areas of seasonally inundated type (Davidson 2014, Davidson and Finlayson 2018).

In Argentina, wetlands cover a large surface area and include a broad range of types. Kandus et al. (2008) has pointed out that until a few decades ago, most wetlands were undisturbed by human activities (except for those in urban areas), such as water use for irrigation, dam building, drainage for agriculture or peat extraction. One of the best known wetland system in the country is the so called "*Lagunas de Guanacache, Desaguadero y del Bebedero*". It was designated as RAMSAR site in 2007 (<https://rsis Ramsar.org/es/ris/1012>) and includes a long system of linked lakes and marshes that covers an area of approximately 962.370 ha. along the of Mendoza, San Juan and San Luis provinces. The Desaguadero River wetlands have been experiencing draining problems, similar to those worldwide. The morphodynamic activity of these wetlands, with fluvio-palustre features, has been decreasing since the end of the 19th century and all along the 20th century (Gez 1938, Vitali 1940, González Díaz 1981, Suvires 1984, Cazenave 2015, among others), due to natural and anthropogenic causes. The last biggest rise of the Desaguadero River and development of ephemeral lakes occurred at the end of the last century during

the 1987-1988 summer (Ojeda et al. 2013). Since then, scarce flows at this fluvial system have come mainly from local summer rains.

The decrease of allochthonous flows, because of ice melt, and the loss of functionality of the ephemeral lakes contributed to the valley river incision and valley deepening upstream because of headward erosion (Gez 1938, Vitali 1940, Rodríguez 1966, González Díaz 1981). This condition caused changes in the local base levels of the Desaguadero River sub-basins, favoring the development of erosive morphodynamic conditions with the development of rills and gullies in the river's banks (Ojeda et al. 2012). Ecological studies in the region have emphasized the headward erosion problem in the Lagunas de Guanacache, in the upper Desaguadero River (Sosa and Guevara 2017).

With the aim of reducing the impacts of erosive processes and partially restoring the desiccated wetlands, two small-sized dams (locally known as "azudes") were built in San Luis in 2014 by the local government, in addition to an azud made by a private individual in the Mendoza's reach of the river.

Benzaquén et al. (2017) include the wetlands of the *Desaguadero* River as being part of the wetland regions of the *Monte Central*. Sosa and Guevara (2017) have described the ecological characteristics of this region and have emphasized the headward erosion problem in the in the *Lagunas de Guanacache*.

According to Fryirs and Brierly (2013), insights from fluvial geomorphology provide an understanding of physical processes that create, maintain, enhance or destroy riverine habitat (i.e. the physical space that flora and fauna inhabit). However, as Tooth et al. (2015) affirm, despite its demonstrated relevance, the contribution of geomorphology for the study of wetlands has been limited. Then, with the intention of achieving an integral understanding of the role and relevance of wetlands, and in order to support their effective function from the environmental point of view, it is important to know their genesis and the factors controlling their development. In this regards, we present the results of the morphostratigraphic and morphodynamic studies on the wetlands of the upper-middle-reaches of the Desaguadero River. We propose a model to explain its origin and spatial and temporal development from the Late Pleistocene to the present. Also, we intend to predict the possible evolution of the system under different types of environmental pressures.

2. Study Area

The Desaguadero River is located in the arid-semiarid central-west region of Argentina. It comprises the upper reaches of a highest hydrologic system called Desaguadero-Salado-Chadileuvú-Curacó, with a basin of approximately 360,000 km² (Bereciartua et al. 2009, González 2016); and flowing into the Colorado River basin (Fig. 1). The area under study covers the upper-middle section of the Desaguadero River, from near La Tranca locality (32°21'4.12"S, 67°16'59.77"; San Juan province), a few kilometers away from the entrance of the San Juan river into the Lagunas de San Miguel or del Rosario, to the bridge on National Route N°7 and influence area of the Arroyo Jarilla (33°23'19.22"S, 67° 8'51.76"O, San Luis) (Fig 1). The main course extends with a length of about 154 km in the north-south direction following a

wide tectonic depression, located between the distal piedmont of the Andean Precordillera, on the west, and the piedmont of the *Serranías Occidentales* range on the east (San Luis province). The courses of the San Juan, Bermejo and Desaguadero rivers are controlled by a series of faults, forming a complex with N 80°W (San Juan River) to N 10°W (Bermejo and Desaguadero rivers) main directions.

The general relief of the study area (6.457,5 km²) can be described as a plain with a southward slope, with internal relief lower than 2 m, which in some sectors can reach elevations of up to 14 m in dune accumulations, and depressions of up to 6 m due to the valley deepening of the Desaguadero river.

Historically, ephemeral lakes, known as Lagunas de Guanacache (or Huanacache according to Vitali, 1940), developed in the confluence of the Mendoza and San Juan Rivers (32° 3'28.17"S, 68°22'21.13"W.), the flows from these rivers caused surface overflows flooding the low lands towards the south east, in the tripartite limit between the provinces of Mendoza, San Juan and San Luis (Gez 1938) (Fig. 1).

Climatically, the Desaguadero River is located in the eastern border of the South American Arid Diagonal (Bruniard 1982), showing in Argentina the contact between the mediterranean influences of the Pacific anticyclone and the (quasi) monsoon ones of the Atlantic ocean in the Andean belt area (Martínez Carretero 2013). A common feature in the region is the development of an allochthonous drainage network in a region with precipitations lower than 300 mm annually (Cazenave 2015). The climate conditions on the area depend on the scarce rains from the South American Monsoon System (Garreud et al. 2009), with a main allochthonous source of humidity from the westerlies, e.g. the South Pacific Anticyclone (Vera et al. 2006). Besides, in warm periods, the most intense influence of the Atlantic Anticyclone, modulated by the Low Level Jet (Antico and Berri 2004), causes rains which produce an increase in the mantiform channelized overflow, generating edaphic horizons in the plains with vegetation in expansion (Chiesa et al. 2015).

Rainfalls are generally torrential and are concentrated in the humid season between November and March (spring-summer), when about 80% of the total precipitation is recorded (Fig. 2). The average annual precipitation measured in the La Tranca meteorological station (REM 2021) was of 300 ± 92 mm for the 2020-2021 period. In the Desaguadero meteorological station (REM 2021), the last 10 years average values have been 277 ± 108 mm/year. Both stations show maximal rainfall intensities of 37 to 42 mm/h during summers (Fig 2). The average annual temperatures vary between 24,4° C for the warmest month (January) and 9,2°C for the coldest month (July) (Peña Zubiarte and d´Hiriart 2007), favoring an elevated evapotranspiration (Fig. 2). The average annual evapotranspiration varies between 256 and 293 mm, which explains the scarce availability of surface water during along the year (Trabucco and Zomer, 2009).

The aridity index of the study area varies between 0.13 and 0.20, which allows to classify the region as Arid. This classification is based UNEP aridity index, on the rainfall and evapotranspiration values corresponding to the 1970-2020 period from the Worlclim.org database (Fick & Hijmans 2017), and on

the calculus from the Global Aridity Index (Global-Aridity) of the CGIAR CSI consortium for spatial information (<https://cgiarcsi.community/>) (Zommer et al. 2007).

The wind regime is featured by average wind speeds were of $16 \pm 6,5$ km/h with maximal values of up to 52,2 km/h, 2020 to May 2021 data from La Tranca meteorological station; REM 2021). Dominant winds, with highest intensities and frequency, comes from the East and Northeast (Fig. 3).

The soils in the aluvial plains and fluvial terraces of the Desaguadero River are highly saline and calcareous, with a silty sand texture, light yellowish brown according to Munsell soil color chart. The dominating hydrological deficit, the sedimentary structures and chemical contents condition the development of soils characterized as poorly evolved, most of them classified as Entisols, with organic matter contents lower than 1% (Peña Zubiarte and d'Hiriart 2007).

The vegetation is abundant on the west piedmont of the Serranías Occidentales where the shrubs and leafless prickly low forest of the Chaqueño Domine. In the riverside, the halophytic vegetation is dominant, expanding and mixing with xerophilous vegetation, with *Atriplex* spp. (*cachiyuyos* or *zampa*) *Suaedadivaricata* (jume) and *Allenrolfeavaginata* (vidriera) as the most common plants (Peña Zubiarte et al. 1998). On the right margin of the Desaguadero River, on the province of Mendoza, the vegetation density decreases significantly, with halophilous and xerophilous forest with abundance of *Prosopis flexuosa* (algarrobo), *Atriplex lampa* (zampa), *Lycium chilense* (llaullín), *Tricomaria usillo* (usillo) and *Allenrolfeavaginata* (vidriera) (Lagos Silnik et al. 2011).

3. Geological And Geomorphological Background

The first studies on the Desaguadero River were carried out by Gez (1938) and Vitali (1940) who described the river environment and the ephemeral lake systems, and the hydrology, respectively. Paleogeographic studies indicate that in the past, the De Zonda river (nowadays Cañada de Moyano) was formed by the Mendoza and Tunuyán rivers and constituted an important component of the Desaguadero river system (Rodríguez 1966). However, both tributaries were diverted by avulsion and/or tectonic processes, and they took different courses until reaching their current position (Rodríguez 1966, Ortiz et al. 1977, Martínez et al. 2008).

The morphostructural limit of the Serranías Occidentales, known as Bermejo-Desaguadero lineament, continuous to the south as the known Giant Fault that can be identified in El Gigante, Las Quijadas and Cantantal-Guayaguas hills (Costa et al. 2001). The fault might be responsible for the basement uplifting and the deformation of the sedimentary cover by the Cenozoic tectonic inversion of the extensional basins (Gardini et al. 1996, Costa et al. 1999, Gardini et al. 2006). In the study area, this tectonic context is represented by the asymmetric Las Cabras anticline, whose western margin is constituted by the mentioned fault (Costa et al. 1995, Gardini et al. 1995, Schmidt et al. 1995, Gardini et al. 1996). González Díaz (1981) described the "Western depression and environment of the Desaguadero-Salado basin" unit, emphasizing that natural causes such as the Pleistocene climate changes and other anthropogenic changes have influenced the development of this big morphostructural element. He also pointed out the

headward erosion process which caused the deepening of the valley near the Silverio lake and the presence of two terrace levels marked by aggradation and erosion processes.

The antecedents linked to the paleoclimate and paleoenvironmental frame, in which the Quaternary deposits of the central-west of San Luis are originated, were studied by Piovano et al. (F2009) who suggest dominantly wet conditions during cold phases in regions located west and south of the AD, with a dominant Pacific source of moisture. During the same climate phase, dry conditions have been proposed across the sub-tropical lowlands east of the AD, under the influence of an Atlantic summer precipitation regime. Conversely, extensive dryness across Patagonia and wet conditions in the Pampas can be inferred during warm climate phases.

Iriondo (2010) has emphasized that the Desaguadero River was the fluvial collector of the Central Andes Rivers along the Quaternary, and constituted the main transport system of the clastic and chemical sediments of the region towards the Atlantic Ocean, although nowadays the system behaves as an endorheic basin. He has also pointed out that although the flows have currently decreased, there are sedimentary and geomorphologic elements, indicating that there were periods, especially during the Early Pleistocene, when the river flow was similar to the present flow of the Paraná River, a main river in the east of Argentina.

Considering the stratigraphic and paleoenvironmental studies on the area, it can be affirmed that the wetlands associated to the Desaguadero River have been present in the region since the Late Pleistocene (Chiesa et al. 2015). The maps elaborated by Ximenez Inguanzo in 1789 (Gez 1938) confirm their existence during that period. Archaeological studies indicate that the prehispanic populations (huarpes ethnic groups) inhabited the area at least during three main occupation periods, 1600-600, 600-400 and 200-100 years BP (Chiavazza 1999, 2001, Chiavazza and Prieto 2004, Prieto and Chiavazza 2007). Their economy was based on fishing and the use of ancient lakes in the region; fishing sites of the native people were maintained until 400 years BP (Chiavazza and Pietro 2008). Beside, an intense fishing activity during the first half of the 20th century can be recorded from conversations with local people while carrying out the present study. The presence of goat manure in the surface of old farmyards, nowadays covered by dunes, is also a sign of a considerable dry trend in the second half of the century.

The oldest deposits in the banks of the Desaguadero River were included into the Arco del Desaguadero Formation by Rodríguez and Barton (1993), suggesting a Lujanense mammal age (Late Pleistocene) and Platense age (Holocene). Chiesa et al. (2015) determined through an absolute dating the Pleistocene-Holocene limit in the deposits of the Desaguadero River (9580 ± 120 14C 11091-10687 Calibrated Age). After that and considering the lithological characteristics and altitude of the Desaguadero River and the Bebedero saline lake depression, Chiesa et al. (2015) proposed the division of the Arco del Desaguadero Formation into three units of lower stratigraphic category (Members).

4. Materials And Methods

The geomorphological units, including details of lakes and dunes, were delimited based on the interpretation of satellite imagery of high spatial resolution provided by GoogleEarth ©, and hillshade images generated from Digital Elevation Models (DEM), and on screen digitized trough QGIS GIS. The DEMs used (MDE-Ar v2.0), with 30 m of spatial resolution and -2 ± 4 m of vertical resolution, were provided by the Instituto Geográfico Nacional online database (IGN 2019). This MDE was also used to obtain morphometric data such as slope and relative heights. The digitizing and general processing of imagery data were processed by means of the Geographic Information System QGIS 3.4©.

The lithology of geomorphological units was characterized by means of stratigraphic profiles performed during the field work on the walls of incised alluvial deposit by the ephemeral streams carried out in numerous campaigns since 2010. The rock and sediment samples collected at field were described and processed in the laboratory of Universidad Nacional de San Luis in order to determine their granulometric characteristics by means of mechanical dry granulometric separation and the Bouyoucos hydrometer method for the finest particles. These mesh apertures correspond to the boundary of the Udden Wentworth scale.

5. Lithostratigraphic Units And Palaeoenvironments And Of The Desaguadero River

The wide tectonic depression developed between the Serranías Occidentales of San Luis and the distal foothills of the Andean Precordillera, constituted a fluvial depositional environment during the Neogene. This generated the relatively impermeable substrate characterized by ripples that have been recognized in the current riverbed, which are preliminarily attributed to paleo mega-undulations with a wavelength of 50 cm and an amplitude of 20-30 cm (Fig. 4). Overlay the Quaternary fluvial and lake sediments (Arco del Desaguadero Formation) and the layer associated with the Holocene aeolian deposits rest. In the study area, the most outstanding paleoenvironmental features are observed in the outcrops found in the Desaguadero banks, where sediments of moderate to low intensity are observed, associated with fluvial flows and decanting processes in lake bodies, for a time span comprising the last ca. 25,000 years (Chiesa et al. 2015).

In both works, the authors detail the development of the lake deposits considering their stratigraphy and presence of paleobiota, and refer the basal strata to the Lujanense mammalian age (Upper Pleistocene) and the overlying strata to the Platense (Holocene) (Pascual and Bondesio 1981). They also point out that the strata exposed in the banks of the Desaguadero River show the great development reached by the lake bodies from the north of the Desaguadero town and whose deposits cover the Pleistocene strata linked to the distal piedmont of the *Serranías Occidentales*.

Chiesa et al. (2015) propose to extend the area of the outcrops and divide the Arco del Desaguadero Formation into three units, the lower one called Salina del Bebedero Member with fluvial sand deposits in the Desaguadero River and sandy conglomerates of the paleocoast of the Bebedero Lake, assigning the

succession to the Upper Pleistocene and highlighting the strong presence of gastropods and bivalves in the lake body (Font et al. 2014).

In the valley of the Desaguadero River, the deposits of the Desaguadero River Member predominate, which partly integrate the cut and fill profile with fluvial and lake deposits associated with the Desaguadero paleo-river and associated lakes. It consists of silty sandstones and sandy siltstones, with a laminated and massive structure, thin layers of settling and linked to an environment of low-intensity fluvial interaction and expansion of lake bodies. In this unit, Rojo et al. (2012) identified an important palynological and gastropod association linked to the Hypsithermal stage or Climatic Anomaly of the mid-Holocene (Font and Chiesa 2015).

The dates and biological records allow us to assign the lower and middle Holocene to this stratigraphic unit and indicate that they correspond to a maximum of flows and lake expansion (ca. 12,000 years), from which point it begins to decrease until the limit with the upper Holocene. At the base of this unit there is a white, laminated stratum of carbonate and gypsum, indicative of sedimentation under ephemeral lake conditions (Fig. 5). Also, in different sectors, sediments interbedding is identified from light green and reddish brown colors, denoting the variability of the water level in the lake bodies, as well as its fluvial contribution. Generally, the entire sequence has a high saline content and the presence of laminae, rosettes and concretions of gypsum can be recognized.

Field data, particularly from the stratigraphic relationships observed in the Arroyo Jarilla banks, a tributary of the Desaguadero River, allow us to estimate that the predecessor course to the current Desaguadero River was approximately 3 km wide.

The cuspidal sedimentary record corresponds to the Dos Anclas Member, assigned to the upper Holocene and in which shallow river, lake and saline deposits are identified, as well as eolian deposits of the floodplain. In this unit, the reduction of the lake bodies stands out, in particular the decrease in the flow of the Desaguadero river that caused the transformation of the Bebedero lake into the current saline body, where a salt production company is established; likewise, the retraction of the lakes in the valley of the river course is evident where the lake floors are exposed and which appear as sandy salt mudstones (Chiesa et al. 2010).

6. Current Geomorphological Features At The Desaguadero River

In the piedmont and alluvial plain areas that make up the study area, 5 main sub-environments were identified (Fig. 6): Distal Andean Piedmont (DAP), Desaguadero River Valley and associated lake systems (DRV), Western Piedmont of the Serranías Occidentales (PSO), San Juan River spill zone (SRD) and Dune fields of the old Bermejo River alluvial plain (DBF). The units of mountains corresponding to the Serranías Occidentales (SO) range present in the study area, are identified in the map in Figure 6 but are not described in this contribution.

A notable general feature of the area of interest is the great difference between the western sector (DAP) and eastern sector (PSO) with respect to the Desaguadero River Valley (DRV), both in drainage density, vegetation, and in the dominant geoforms and/or geomorphological associations.

The marginal subunits of the Desaguadero River Valley and the associated lake systems are first briefly described in order to be further described later for the Desaguadero River system.

Distal Andean Piedmont (DAP)

This subunit is part of an extensive morphological unit that Polanski (1952) called "*Gran Llanura de la Travesía*" and which forms a wide sedimentation basin along the orographic blocks parallel to the Precordillera, the Cordillera Frontal and the Macizo de San Rafael, in the west, and the Sierras de San Luis (*Sierras Pampeanas Occidentales*), in the east (Abraham and Prieto 1981).

In the analyzed area the most outstanding geomorphological features are the dune fields, the sand beds and the deflation and temporary waterlogging surfaces, all of them associated with the old spills of the Tunuyán and Mendoza rivers (Ojeda et al. 2013). The latter suffered the displacement of their main course associated with avulsion and/or tectonism processes (Ortíz et al. 1977, Martínez et al. 2008) until they reached their current position.

The relief is characterized by a very gentle slope to the east, variable between 0.02 and 0.05 %, with internal slopes that generally do not exceed 3 m in height, associated with the presence of lunettes and longitudinal dunes. Surrounding the dunes and the temporary deflation and waterlogging surfaces, there are also medianous accumulations (sandy geoforms with no defined shape) and thin sandy layers that, in general, do not exceed 1m in thickness. Except for localized sectors, the dune geoforms are highly immobilized due to the fixation of the deposit by plant colonization.

The temporary deflation and waterlogging surfaces form units with a flat bottom and a slight slope against the regional slope, developed on reddish sandy siltstones. They are completely devoid of vegetation so they are often informally referred to as "peladales" and are easily distinguishable in satellite images due to their light shades. González Díaz and Fauqué (1993) pointed out that these areas are locally referred to as "*ramblones*", whereas, due to their occasional flooding by rainwater or river overflows, they are also known as "*bañados*" or "*barreales*" (Costa et al. 2001).

Western Piedmont of the Serranías Occidentales (PSO)

It comprises a foothill strip with variable widths between 5 and 20 km, located at the foot of the elevations of the *Serranías Occidentales* (González Díaz 1981) whose elevations include, from south to north, the *Cerrillada de las Cabras* (768 m.a.s.l.), the *Sierra de El Gigante* (1140.8 m.a.s.l.), the *Sierra de las Quijadas* (1069.8 m.a.s.l.) and the *sierras of Guayaguas* (830 m.a.s.l.), *Cantantal* (892.7 m.a.s.l.) and *Alto Pencoso* (670 m.a.s.l.) (Fig. 6).

This piedmont unit is made up of different aggradation levels that, from its middle and distal sectors, form a gentle piedmont descent with slopes of 4% in the proximal sectors and 0.24% in the distal ones. These are overlain by large alluvial fans, such as the one on Cerro Cantantal (43 km²), Sierra de las Quijadas (21 km²), Agua Amarga (104 km²), Sierra de El Gigante (209 km²), Represa del Carmen (107 km²) and Arroyo Jarilla (97.6 km²).

Other prominent geomorphs include streams associated with current surface runoff, which can develop wide flood plains, with values between 200 and 1200 m wide and encasement smaller than 5 m. These ephemeral courses discharge the sediments transported after the great rains as lobes in the distal foothill zone and in some sectors invade the environment of the old dried lakes associated with the Desaguadero River.

Unlike what occurs on the right bank of the Desaguadero River, aeolian geomorphs are very scarce, except in those sectors where recent runoff from foothill streams and alluvial systems that remain dry most of the time, are remobilized by wind action. In the distal sectors the fluvio-aeolic rework of the foothill deposits themselves develops sandy layers with thicknesses of 60 cm to 1 m.

Dune Fields of the old Bermejo River alluvial plain (DBF)

The Bermejo River valley has been defined as an extensive sandy intermountain desert (Suvires 1984) where the Bermejo river converges with the San Juan River in La Tranquita, 7 km north of the town of La Tranca (Gez 1938). Its waters are turbid, slightly reddish and hardly mixed with the clear waters of the confluent river. In the sector covered by this study, there are large areas of deflation and temporary waterlogging, limited on the leeward side by sandy accumulations of the lunette type and with partially saline floors. In the leeward sectors there are also longitudinal dunes, product of the remobilization of the sands of the old flooding plain.

The geomorphological pattern is similar to that described for the distal Andean piedmont sub-environment, where lunettes and longitudinal dunes indicate winds from the E-SE quadrant. The course of the Bermejo River can be followed in satellite images up to about 30 km north of the spills of the San Juan River, then it is lost due to the sandy remobilizations of the old alluvial plain.

San Juan River spill Zone (SRD)

It comprises the final reaches of the San Juan River on the tripartite boundary of Mendoza, San Juan and San Luis provinces. Due to the decrease in river energy because of the low slope, morphologies of spills and ephemeral lake bodies are developed, locally referred to as Lagunas del Rosario, which integrate the Guanacache Lake system. Vitale (1940) also referred to them as Bañados de San Miguel and La Tranca.

In its south-southeast limits, the transition from non-incised to incised channels can be observed. The latter are taken as the boundary of the Desaguadero River basin. Satellite images records indicate recent activity in this subunit until 2017, although with a clear decrease in the surface area involved compared to that of 1998.

Desaguadero river valley and associated lake systems (DRV)

González Díaz (1981) characterized the environment of the Desaguadero River as a “ponded river” constituted by extensive and shallow lakes to the north and with a lower section with salt marshes and circumstantial ponds.

Due to the practically null contributions of flows from the San Juan River, currently the Desaguadero River can be classified as a non-permanent course, with a local feeding by seasonal rains that in the last 5 years averaged a value of 250 mm/year, according to the information provided by La Tranca meteorology station (REM 2021). Likewise, data from the Km 47.3 station (SNIH 2021), located more than 150 km from the study area in the mountain area on the San Juan River, clearly show how at the beginning of the twentieth century, maximum flows of 745,000 m³/s were recorded, to then decrease to maximum values of approximately 400,000 m³/s and finally at 100-200 m³/s towards the end of the century, with a last outstanding record of 150 m³/s in the year 2008. Finally, the capacity data of the N° 1219 "El Encón" Station (SNIH 2021), located about 20 km upstream of the current terminal spills of the San Juan River, indicate values that since 2015 oscillate between only 4 and 8 m³/s (Fig. 7).

In addition to the decrease in ice-snow melting flows from the cordillera, there are water restrictions associated with the construction of 4 dams (Ullum, Los Caracoles, Punta Negra and Cuesta del Viento) along the San Juan and Jachal rivers, on San Juan province, of which Punta Negra and Los Caracoles are for consumptive use (González 2016).

Based on the detailed hydrological mapping using Google Earth © images, the headwater of the Desaguadero River can be located at the convergence point of a series of incised-channel tributaries which generate a subdentritic to subrectangular network, located between 1 and 2 km south-southeast of the terminal sector of the Guanacache complex system of channels and ephemeral lakes.

From the morphological point of view, the Desaguadero River corresponds to a mostly rectilinear course for the 142 km section included in the study area, with a sinuosity index of 1.28 and a very low longitudinal slope with frequent values between 0.03 and 0.06%. These characteristics are attributed to the main control exercised by regional tectonic structures and their location parallel to the direction of the main landscape geofoms.

The current channel has a variable width of 36±15 m, commonly between 2 and 5 m above the levels of its former floodplain, including the floor of the former temporary ponds, although in some sectors it can

reach 6 to 8 m deep (Fig. 8). The channel bed is represented by thin thicknesses of sandy-loamy sediments, which partly expose sedimentary rocks referred to the Desaguadero River Member (Chiesa et al. 2015) of the Arco del Desaguadero Formation (Rodríguez and Barton 1993).

The incision of the main current channel of the Desaguadero River in its former floodplain was pointed out by Gez (1938) who indicated its main receding headwaters at Salto de Acevedo, about 50 km south of Laguna Silverio (L3.1), approximately, in the Laguna El Tapón (L8) (Table 1, Fig. 10a). Vitali (1940) points out that the drying up of the ponds had already been foreseen in 1883; and in 1928 as date of the incision, they had observed a 2 m drop in the riverbed, in the place where a metal bridge was being built over the Desaguadero River. Rodríguez (1966) and Chiesa et al. (2010) also suggested a relatively recent incision of the current channel; the latter are based on radiocarbon dating and the evolution of the Bebedero paleolake, the local base level of the entire river system (González 1981).

Currently, the headwater associated with the current incised channels is located near La Tranca locality (San Juan), about 80 km north of the location mentioned by Gez (1938). According to the local residents, this position was reached after erosive processes temporarily associated with the huge earthquake of Cauce (San Juan) in 1977. This allows us to approximate an average backward erosion speed of the main slope of 2 km / year.

From the intersection of the Desaguadero River with the Arroyo Jarilla to the north, there are notoriously horizontal surfaces, constituted by silt-sandy sediments, by sectors covered with saline precipitates, corresponding to the floors of the old ephemeral lakes.

The ephemeral lakes are characterized by soils like El Ramblón series (Peña Zubiarte y d' Hiriart 2009), with little genetic development (A1-ACk-Ck), of dark brown coloration (7.5YR3/4 to 4/4 according to Munsell Color System), sandy loam texture with abundant calcium carbonate, and belonging to the Order of Entisols.

The origin of the ephemeral lakes of the Desaguadero River is interpreted as a combination of factors such as important flood flows during the ice melting season, the low longitudinal gradient of the riverbed and its floodplain and an impermeable bed (González Díaz 1981; Ojeda et al. 2013). During its active period, its character was of dominant clastic sedimentation and associated with foothill periglacial river systems. Even after the important incision of its main riverbed, the seasonal flood flows inundated the ancient plains and the hydro-aeolian depressions excavated. The last major event was recorded in the summer of 1987-1988 (Ojeda et al. 2013).

The combination of erosion-wind accumulation processes with the formation of lunettes in the leeward margins, developed the flood depressions and together with the periodic floods, they shaped their morphological characteristics and traits.

The floods of Desaguadero River developed systems of chained ephemeral laked, which occupied large but shallow areas. According to Gez (1938), with the exception of Las Quijadas and Silverio ephemeral

lakes, all other low lands that are covered by floods are shallow embalsmed where large masses of cattail grow.

The dimensions of the bodies decrease noticeably from the headwaters of the river to the south and also have a variable degree of internal geomorphological complexity. In some areas there were differentiations in a multiple set of smaller lakes, called here Ephemeral Lake Complexes (ELC), while in others, the internal complexity is much lower or there is a single body categorized as Ephemeral Lake (LE) (Table 1). In both cases, the lakes or complexes of ephemeral lakes are limited to the west by lunettes of variable dimensions, whose maximum heights are reached to the south, such as those associated with Gualén-El Tapón lake, with maximum slopes of up to 14.7 m (Fig. 9).

In the north of the study area, near La Tranca the so-called "Guanacache Lakes Complex" (L2) begins, shared by the provinces of Mendoza and San Juan and associated with the dynamics of the San Juan river. From the sources of Desaguadero River to approximately 50 km downstream and with a maximum width of 16 km, L3, a complex of ephemeral lakes develops, that contains two main lakes registered as such in historical maps called Silverio Lake (L3.1) and El Porvenir Lake (L3.2).

Continuing to the south there are smaller lake complexes such as L4 and L5, without specific names so far. L6 corresponds to El Ramblón, which is characterized by a very saline floor, which some authors call "*Gran Bajo Salitroso*" (Peña Zubiarte y d' Hiriart 2009). To the east and southeast of the above is El Quebrachito (L7), one of the best defined ELC in terms of its internal structure and which will be used as an example to analyze its evolutionary development. Then, El Gualén - El Tapón (L8), Corral de Tierra (L9) and South Azud Lake (L10). The latter three have an elongated structure in a north-south direction, large lunettes on their eastern edges, and a relatively simple internal structure.

Table 1

Ephemeral lakes of the of Desaguadero River (CLE= Ephemeral Lake Complexes; LE= Ephemeral Lake)

	Name	Other names	Surface. (ha)
L1	ELC Guanacache Lakes	Rosario Lake (Province. Of Mendoza and San Juan)	No data
L2	ELC Guanacache Lakes	Basin of lakes and reservoirs - Rincón Lake	35393.0
L3	ELC Las Quijadas Lakes	Silverio Lake (L3.1) El Porvenir Lake (L3. 2)	57035.2
L4	ELC Arroyito	-	7787.9
L5	ELC unnamed	-	1423.3
L6	LE El Ramblón	La Masa Cruz and Los Chosmes Lakes	5672.2
L7	ELC El Quebrachito	Quebrachito Lakes	5815.0
L8	LE Gualén - El Tapón	Santiago or Salto Lake	5655.2
L9	LE Corral de Tierra	-	464.0
L10	LE South Azud Lake	-	1962.7

7. Discussion

Framework of the studied system

The development of ephemeral lakes in arid zones has been widely studied. Lees and Cook (1991) have proposed a conceptual model for the co-development of lakes and lunettes for the coastal environment on northeast Australia based on field observations and supported by stratigraphical investigation of relict lake-shore barriers. This model has been applied to shallow lakes (initially 1-2 m deep) subject to strong uni-directional winds.

According to Shaw and Bryant (2011), the majority of arid and semi-arid regions are characterized by endorheic (internal) drainage or, in extreme cases, may lack integrated surface drainage altogether. Under these circumstances, surface depressions become important local and regional foci for the accumulation of water in episodic (termed here ephemeral) lakes. Furthermore, in some cases, the lakes have lost their closed status and overflowed at times, as in the Bonneville and Lahontan Lakes of the Great Basin (Benson et al. 1990)

For smaller ephemeral lakes, lineaments controlling factors as in the Texas High Plain (Osterkamp and Wood 1987) or linear depressions between longitudinal dunes, as in parts of the Kalahari (Mallick et al. 1981), have been proposed. Erosional processes, such as deflation, are especially important in the genesis of smaller local or subregional-scale features (Shaw and Bryant 2011). These authors also point

out that deflation has often been cited as an originator or contributor in pan development, e.g. Egypt (Haynes 1980), the Kalahari (Lancaster 1978a), Australia (Hills 1940; Bowler 1973), Texas (Reeves 1960), the Argentine Pampas (Tricart 1969) and Zaire (de Ploey 1965).

In relation to the morphology of ephemeral lakes, we can refer to the pan surface morphology as proposed by Shaw and Bryant (2011). They determined that the shape of the pans are the product of periodic flooding and desiccation, including: (a) rainfall effects, (b) groundwater depth, brine concentration and associated crystal growth and dissolution at or near the sediment surface and (c) aeolian deflation. These authors also reported that given the potential dynamism of these three factors, surface features themselves are among the most ephemeral of geomorphological phenomena, some lasting no longer than the interval between one rainfall event and the next.

Koch (2016) has studied the geomorphological characteristics of Lake Torrens and has emphasized the importance of the studies carried out about the paleoclimates in Australia, particularly on a wide range of lakes in arid-semiarid climates of the centre-south and centre-south-western areas, such as those of Lake Frome (Bowler 1986), Lake Gregory (Veth et al. 2009), Lake Mungo (Bowler et al. 2003; Bowler & Price 1998) and Lake Eyre (Magge et al. 2004). However, he has pointed out that there are still questions to be answered on this subject.

Goudi et al. (2016) have stated the existence of worldwide sites with the presence of big pans, highlighting that the pans have morphological similarities to those observed in areas like the High Plains of the USA, South Africa, the Pampas of Argentina and Australia.

The development of dunes derived from the fluvial courses (Source-bordering Aeolian dune formation along the Scheldt River, Netherlands) during the Younger Dryas has also been studied (Kasse et al. 2020). One of the most prominent geomorphological elements associated to the ancient ephemeral lakes are the lunettes. Lunettes are arcuate aeolian landforms (Hills 1940) which occur on the downwind side of many ephemeral lakes, e.g. in Australia's lakes (Lees and Cook 1991). These morphologies can be used as key climatic indicators offering insight into wet and dry phases experienced by the lake (Bowler 1981). Price and Korniker (1961), Holliday (1997), Price (1963) and Bowler (1973) described these deposits in Texas, USA, where they identified the source of sediments in the disintegration processes of the fine sediments of the dry lakes due to the formation of desiccation cracks and the pressure of growth of evaporite crystals (Arche y Vilas 2001).

The lunettes have been widely recognized in the world, and their importance as a paleoclimate indicator has been emphasized, such as in Lake Victoria Australia (Chen 1995), Lake Malata-Lake Greenly complex in Australia (Dutkiewicz and Prescott 1997), High Plains of Texas and New Mexico (Holliday 1997), Kalahari desert (Lawson and Thomas 1997) and northeast Cape (Marker and Holmes 1995) South Africa.

Morphologically, they are characterized by their half-moon shape and asymmetric transversal topographic profiles, with the highest slope front towards the wind. Their dimensions are directly related to the dimensions of the beach or ephemeral lake to which they are associated (Thomas 1988, Holliday

1997), and correspond to position dunes with a shape that allows to determine the direction of the wind that originated them (Pye and Tsoar 2009).

Some of them usually contain high quantities of silt and clay, transported as pellets from the adjacent beaches during the low water level period. Other dunes are composed almost completely by sand according to regional hydrologic conditions (Lancaster 1978b, Bowler 1983, Goudie y Thomas 1986). Bowler (1973) pointed out that they have been attributed to deflation of lake beaches during high lake-levels, producing quartz sands, and lake-floor deflation during low stands, producing sand composed of pellets formed by aggregation of silt and clay.

Lees and Cook (1991) have reported the importance or recognizing that the types of lakes under consideration are very shallow and initially have extremely flat-bed profiles. According to this model, the lunette formation starts with an initial stage with a persistent uni-directional wind that transfers sufficient energy to the water surface to generate waves large enough to interact with the lake bed sediments. If there is a persistent dominant wind, ripples and later sand waves with climbing ripples, will form and migrate under the action of the wind waves. Tabular cross stratification and bedding typical of combined-flow ripples will dominate this zone.

In Argentina, the lunette dunes have been described as silt-clay deposits of Pleistocene age in the loessic-pampean region, and they have been related to the paleo-lentic environments of the Salado Basin in the province of Buenos Aires (Dangavs 1979; Dangavs y Blasi 1994; Blasi et al. 2010; Fucks et al. 2012). Archi and Vilas (2001) have identified these geoforms in Tierra del Fuego province; and Mazzoni and Vázquez (2009) have described limo-clay lunette dunes in the south of Patagonia. Blasi et al. (2010) have emphasized the salt role as fundamental for the development of saline efflorescence, the absence of vegetation on the dry platforms, and in the pellets formation. They also highlight the importance of the hygroscopic character of the resulting pellets, which favor the lunettes stability since they take humidity from the air and/or the rain (Price 1963).

At the local level, Ojeda et al. (2013) have distinguished lunette dunes related to the paleocosts of ephemeral lakes associated to the Desaguadero River and developed from the south westerly paleo wind direction. These geoforms of great magnitude extend for several kilometers, following the undulating morphology of the lake paleoborders. Their dimensions reach between 60 and 150 m wide, between 3 and 6 m high and a maximum of 14 m in relation to the desiccated floor of the El Tapón ephemeral lake (33° 5'24.26"S, 67°11'57.21" W).

As regards wetlands, there is still no consensus on a universal definition about them (Brinson 2004; Kandus 2008). Nevertheless, we follow the definition given by Tooth et al. (2015), who holds that wetlands are areas that are periodically or continuously flooded by shallow water or have saturated soils, and where plants grow and other biological activities are adapted to humid conditions.

In relation to the wetlands characteristics, Cowardin et al. (1979) have reported that wetlands are lands where saturation with water is the dominant factor determining the nature of soil development and the

types of plant and animal communities living in the soil and on its surface. The single feature that most wetlands share is soil or substrate that is at least periodically saturated with or covered by water. These authors have also stated that the upland limit of wetland is designated as (1) the boundary between land with predominantly hydrophytic cover and land with predominantly mesophytic or xerophytic cover; (2) the boundary between soil that is predominantly hydric and soil that is predominantly nonhydric; or (3) in the case of wetlands without vegetation or soil, the boundary between land that is flooded or saturated at some time during the growing season each year and land that is not.

The Ramsar Convention on Wetlands of International Importance (Ramsar 1971) classified the wetlands in three types: Marine/coastal wetlands; Inland wetlands (with 20 categories) and Human-made wetlands. Following this proposal, according to Sosa and Vallvé (2004) the Guanacache wetland system belongs to the Inland wetlands, and because of its characteristics it was included in the categories codified as: P N T s W U R Y.

The Class Streambed, according to Cowardin et al. (1979), includes all wetlands contained within the Intermittent Subsystem of the Riverine System. Water regimes are restricted to irregularly exposed, regularly flooded, irregularly flooded, seasonally flooded, temporarily flooded, and intermittently flooded. These authors stated that in most cases streambeds are not vegetated because of the scouring effect of moving water, but, like Unconsolidated Shores, they may be colonized by "pioneering" annuals or perennials during periods of low flow or they may have perennial emergents and shrubs that are too scattered to qualify the area for classification as Emergent.

Historically, wetlands have been associated with hydromorphic, alluvial and halomorphic soils (Shaw and Fredine 1956). Although the term hydromorphic is used in a wide sense, these soils are usually associated with temporary or permanent waterlogging or flooding marshes, swamps, peatlands and generally with gley soils. The alluvial soils correspond with floodplains (Tiner 1999).

Soils featuring these properties reflected in their taxonomy and in cartographic units can be considered adequate substitutes (proxy data) for delimiting and qualifying the distribution of wetlands over a territory (Kandus 2008). In general, wetlands are considered azonal systems due to their dependence on the hydrologic regime and local geomorphological setting, but in Argentina they show marked regional variations. In the framework of the Project Evaluation of Wetlands in South America, Canevari et al. (1998) identified six wetland regions (Kandus 2008).

Morphostratigraphics and regional paleoclimate

The morphostratigraphic and regional paleoclimate information allows inferring that the Desaguadero River and the associated ephemeral lake systems would have constituted a wetland area since the Neogene, favored by the important flood flows coming from the ice melt in the Cordillera and local conditions of low regional slope on an impermeable hydrological substrate.

The development of the Desaguadero River as a streambed wetland according to the proposal of Cowardin et al. (1979), would be characterized by an intermittent riverine system water regimes restricted to seasonally flooded.

Although the general geomorphological characteristics and relationships allow us to determine a depressed area within a semi-arid to arid region, with water deficit and saline soils, the presence in the past of ephemeral lakes does not correspond to the typical pan or salt lakes associated with endorheic depressions, because its upper Cordillera river basin (300 km to the west) during the Pleistocene fed lake complexes that eventually developed an exorheic system with an outlet to the sea through the Salado-Chadileuvú-Curacó-Colorado system.

A hydro-wind model is suggested that allows differentiating three main stages in the evolution of a lake that is intermittently flooded from the river, as well as affected by the wind. Stage 1 comprises the flooding process and the silt-sand sedimentation of a wide flood plain, during the ice melting period. Then, stage 2 proceeds with the excavation of deflation depressions related to the strong winds coming from the E-ENE in the sediments of the floodplain during the dry period, in conjunction with the leeward formation of lunettes. Stage 3 involves a new seasonal flood, but wind depressions or basins and lunettes control the floodable areas, resulting in a subdivision of the lake system into smaller ponds (Fig. 11).

During the flood period, the waves on the leeward side of the beach softened the western edge of the lakes, while the eastern shore was reworked by the wind with the mobilization of sands, occasionally as longitudinal dunes that generate a festooned design.

While some ELC continued with reduced activity until the end of the last century, other sectors, such as the El Ramblón lake (L6), the surface was disconnected by avulsion processes and in an over-elevated position in relation to the already incised bed of the Desaguadero River, thus preventing its new flooding, making it difficult for it to become a wetland again, even considering flows of the magnitude of the last great flood or even greater.

Different concurrent factors produce the modification of the relief in the river and lake system; in the latter, a prominent feature is the desertification causing an intense erosive activity on the edges of the old lakes. Also, the incision of the riverbed due to the decrease of the local base level, with low flow and exposing the floodplains for long periods. While, on the eastern edge of the basin, the deposition of fine sediments occurs by terminal spills of the foothill streams in the former levels of lake and floodplain floors.

8. Conclusions

The wetlands associated with the Desaguadero River have existed since historical times, favored by regional climatic and local geological conditions. This period of fluvial and lake activity reduced until its almost total paralysis, during the end of the last century. The main causes of this fluvial system and

wetlands condition are natural (global warming) and anthropic (construction of dams for irrigation) impacts in the basin.

The morphodynamic and geomorphological features of the wetland areas correspond to ephemeral lakes (LE) and ephemeral lake complexes (ELC), where wind activity plays a major role in the process of subdivision and geomorphological modeling of the area, representing a hydro-eolian process in a purely continental environment, with the concomitant development of ephemeral lakes and lunettes during flooding stages and strong bi-directional winds from E and ENE.

Desertification associated with the loss of the wetland dynamics, feed by allochthonous water sources, of the Desaguadero river reach analyzed is considered irreversible in the medium and short term according to the global warming trends established as per IPCC (2014), and even in a possible reversion if we consider the use of water for irrigation in the upper basin by means of the dams.

The incision of the main channel of the Desaguadero River deactivated topographically floodable areas, so that even in the event of high flow conditions, it seems very unlikely that they would return to their former condition of ephemeral lakes. Taking into account the establishment of water reservoirs in the upper basin of San Juan River, this condition will not be feasible in the near future for the entire area analyzed.

Since 2014 some of the old wetlands are being partially recovered based on two azudes , the lower or south azud is located upstream of the mouth of the Arroyo Jarilla in the Desaguadero River, reaching a reduced depth in an area parallel to the riverbed, while, the upper or northern azud is located upstream of El Tapón lake (L8 in Fig. 10a) that only seems to be leveling the depression of the current Desaguadero river channel , without flooding the neighboring lake areas.

The construction of small lakes or azudes allows the partial reactivation of old wetlands, locally reducing the activity of erosive processes; however, it should be noted that these constructions establish different ecosystem conditions with permanent lakes, or temporary ones, in case of long droughts.

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Figures

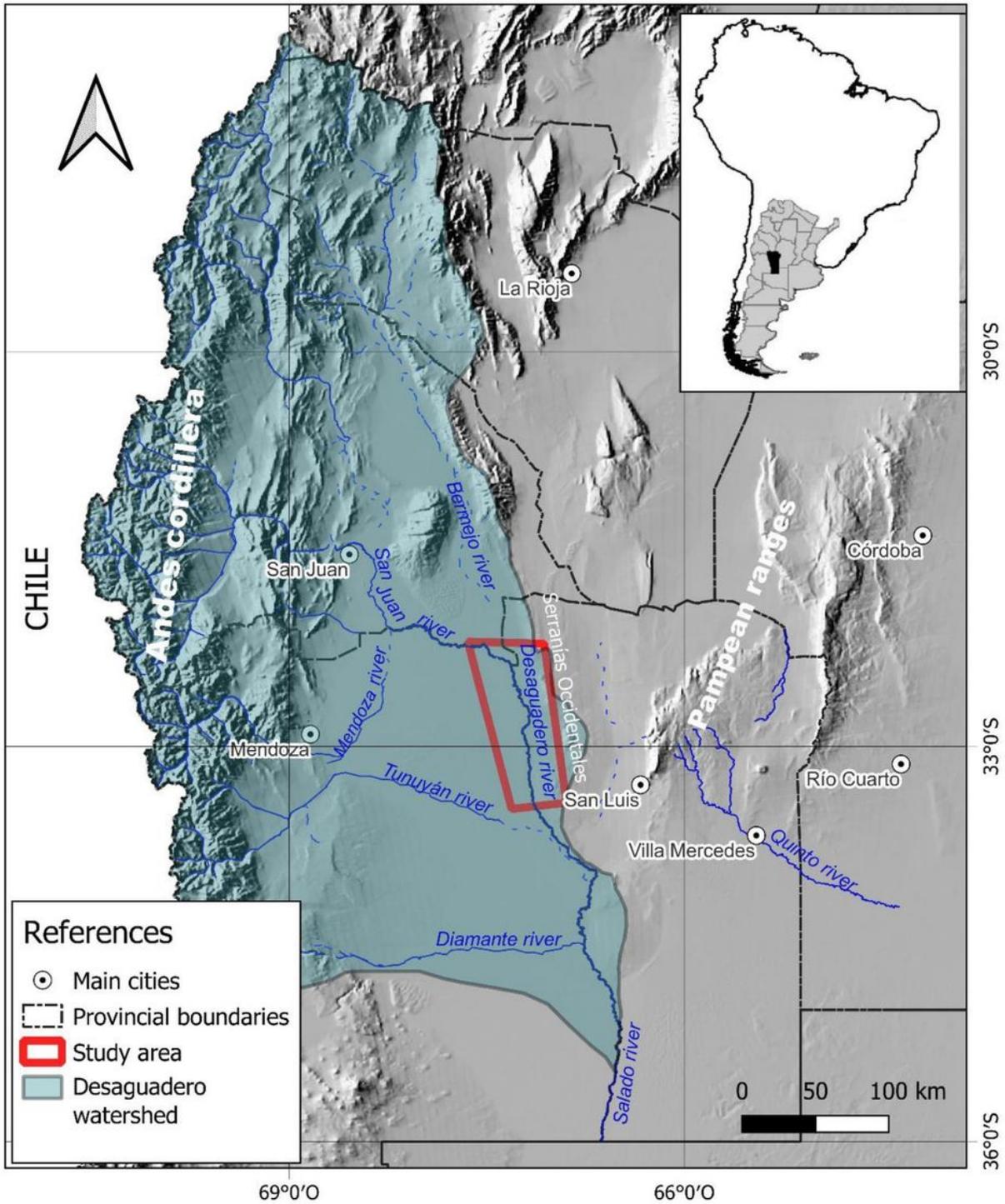


Figure 1

Location of the study area in the arid-semiarid central-west Argentina (Desaguadero river basin to downstream of the Diamante river)

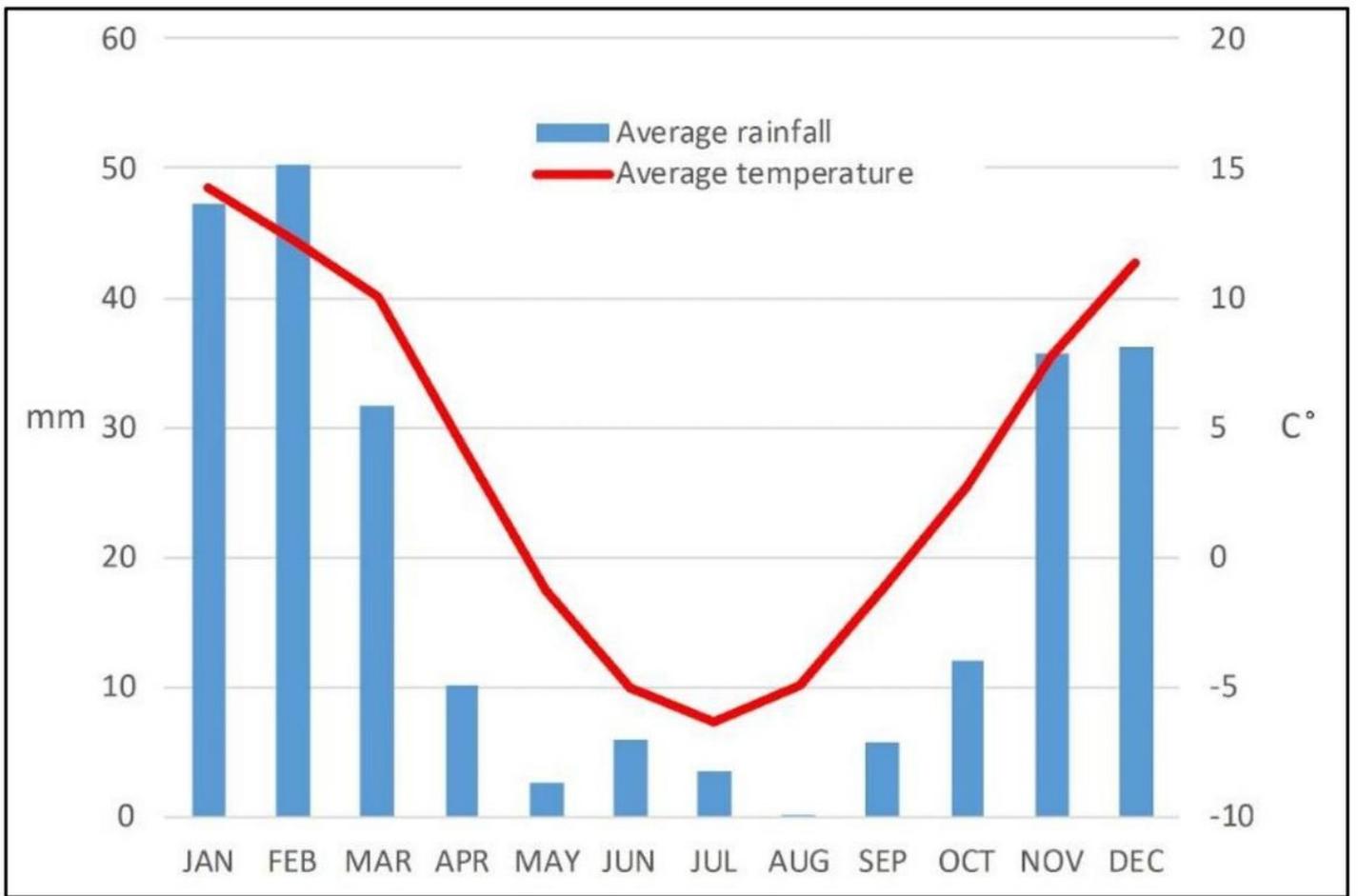


Figure 2

Climograph based on data from La Tranca meteorological station (REM 2021) for the period 2008-2020.

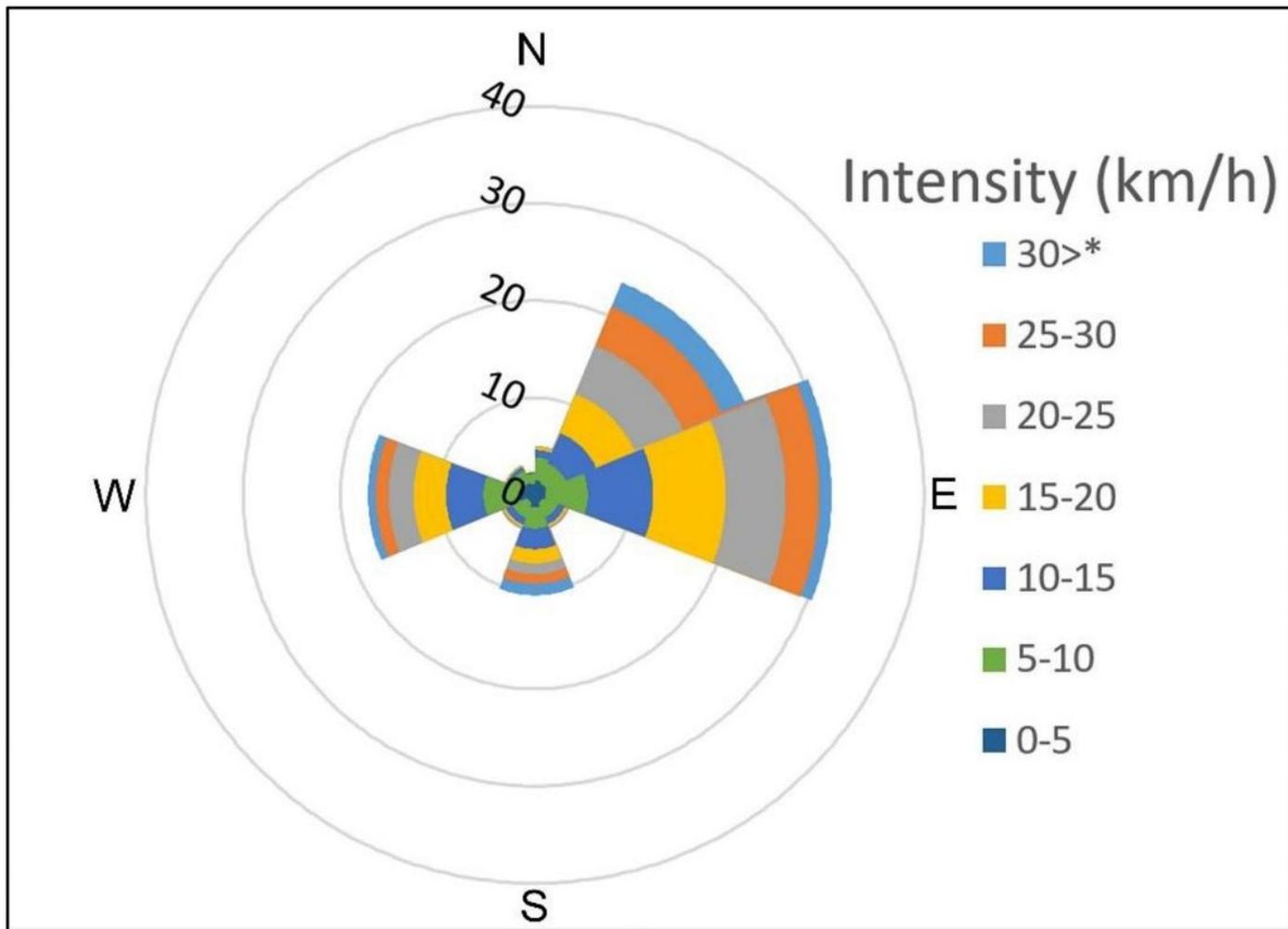


Figure 3

Rose wind diagram generated from the database of the meteorological station La Tranca (REM 2021) for the period 2019-May 2020.



Figure 4

Photograph of the Desaguadero River bed showing paleo-megaondules.



Figure 5

Photograph of the ravines of Arroyo Jarilla at the confluence with the Desaguadero River. Sedimentary exposures corresponds to the paleo lake of the Desaguadero river.

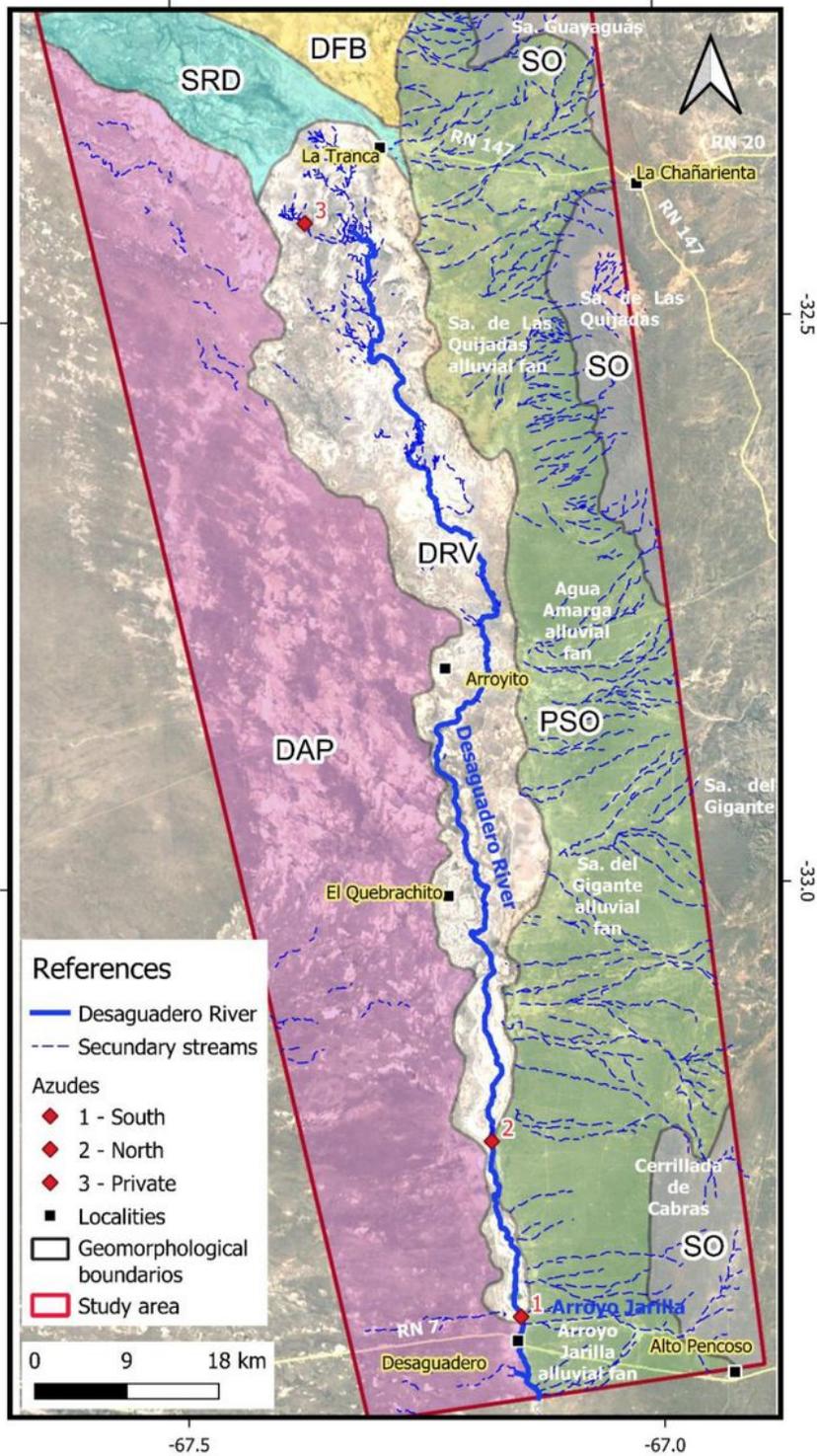


Figure 6

Geomorphological sub-environments delimited on Google Earth © satellite image: Distal Andean Piedmont (DAP), Desaguadero River Valley and associated lake systems (DRV), Western Piedmont of the Serranías Occidentales (PSO), San Juan River spill Zone (SRD) and Dune fields of the old Bermejo River alluvial plain (DFB), Serranías Occidentales (SO)

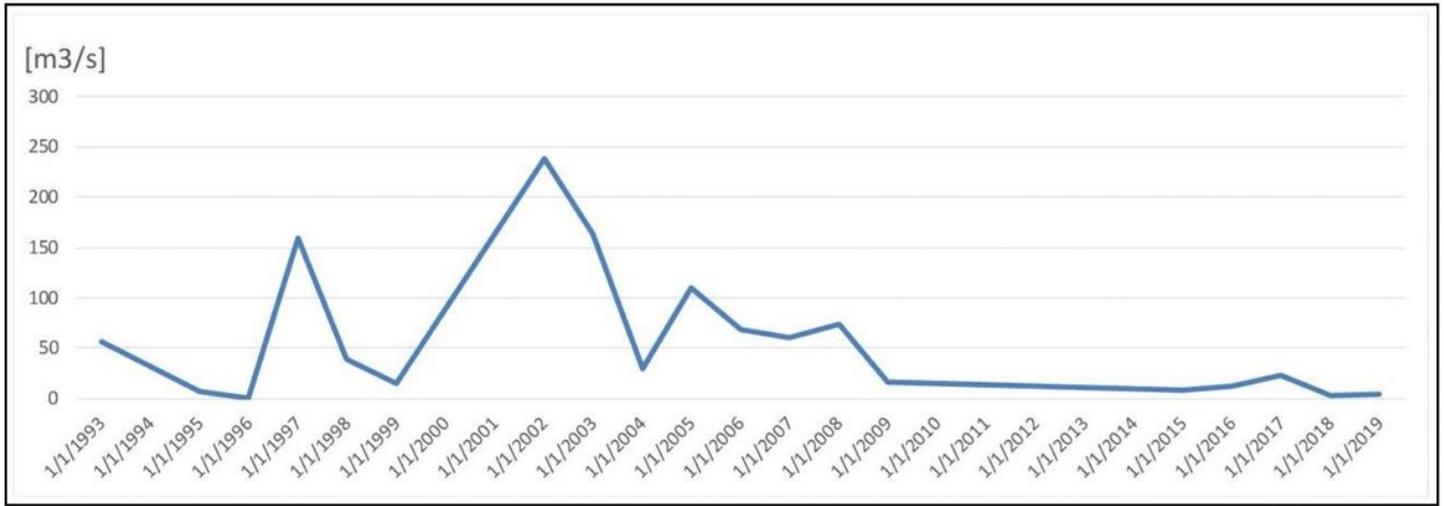


Figure 7

Maximum Daily Average Flow Rates (m³/s) from the Encon station (SNIH 2021)



Figure 8

Panoramic view to the north near La Tranca locality. The Desaguadero River valley with its terrace levels, obtained in 2008.



Figure 9

Panoramic view to the north taken from the lunette of El Tapón ephemeral lake. Its saline floor is observed to the right.

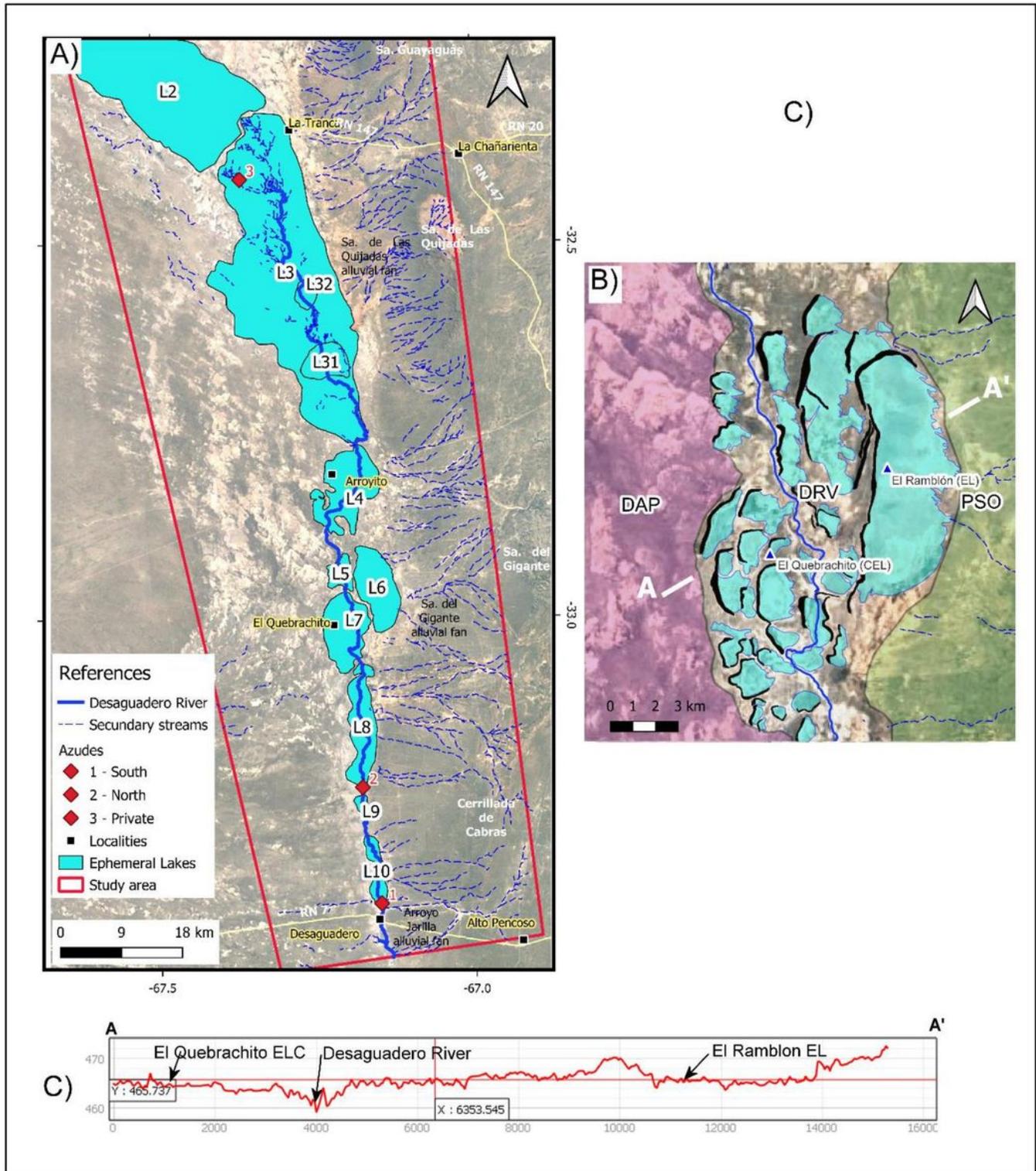


Figure 10

a) Ephemeral lakes (see Table 1) and drainage network b) detail of El Quebrachito (ELC) and El Ramblón (EL) c) topographic profile A-A' (exaggerated)

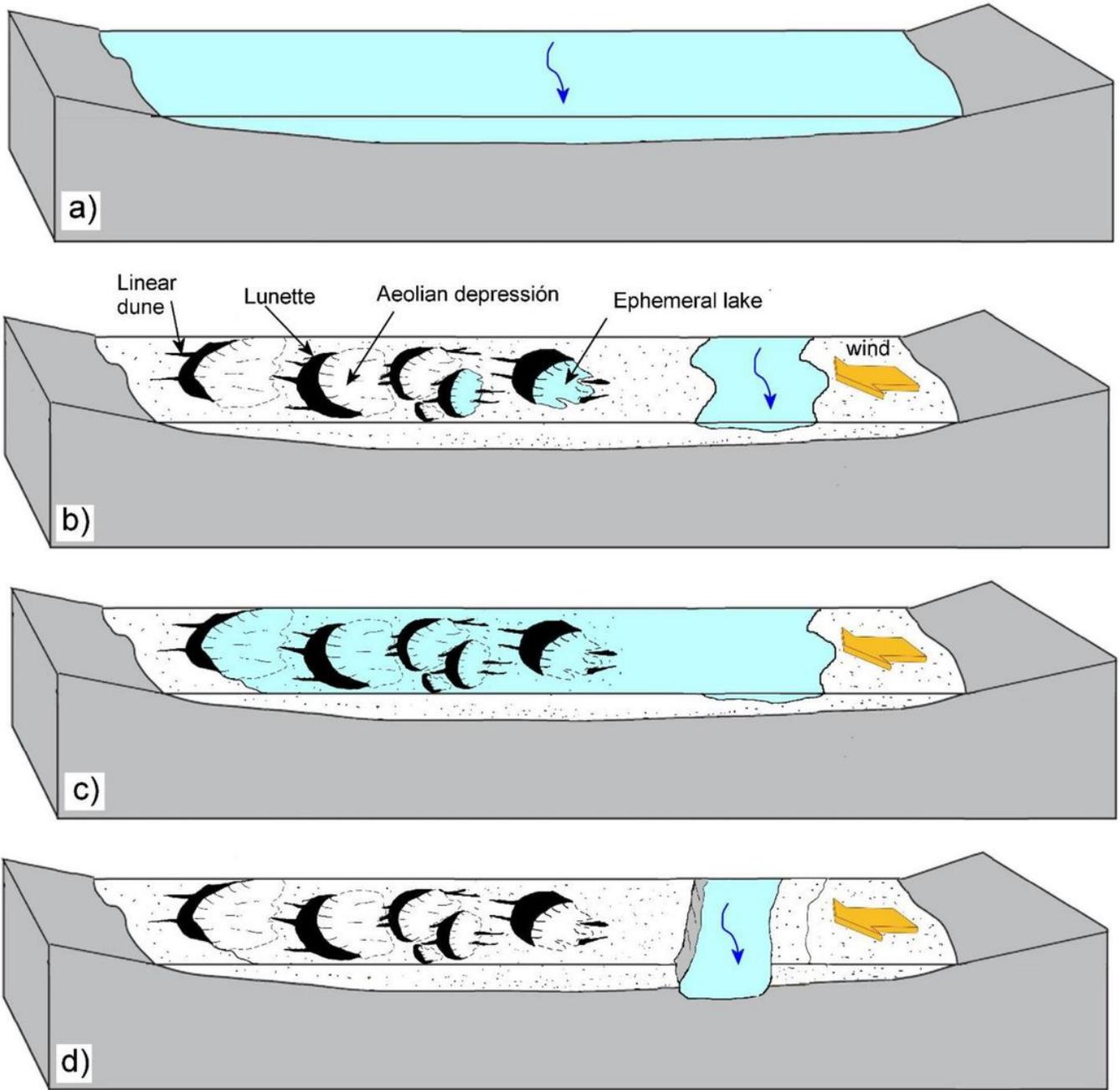


Figure 11

Proposed evolutive model to ephemeral lakes and lunettes