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Determination of droughts and high floods of the Bermejo River (Argentina) based on documentary evidence (17th to 20th century)

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SUMMARY

This study reconstructs a series of droughts and high flow volumes of the Bermejo River from the 17th to 20th century based on a content analysis of historic documentary evidence, which is calibrated with instrumental climate data. The historic data series shows an increase in the frequency of extraordinarily high waters beginning in the 19th century and a significant decrease in extreme droughts beginning in 1890. The data are compared to variations in the Mendoza River for the same period, which show that there was a long-standing lack of correlation between the rivers.

"*Upon news of the Bermejo River in January 1568, I sent Captain Juan Gregorio Bazán, who hurried toward the rising sun for more than fifty leagues... approaching the mountains from which the river flowed, there was such flooding that they all were nearly lost.*"
[(Diego Pacheco, 1566, the earliest report of the flood.)]

1. Introduction

Documentary sources can be used to create detailed chronologies and reconstruct river flow volumes and climate (Metalcalfe et al., 2002; Pfister et al., 2009; Ogilvie, 2010). Most research on the reconstruction of river flow volumes from historic records is concentrated in Europe (Brázdil et al., 2005a, 2006; Thorndycraft et al., 2003; Barriendos and Martín-Vide, 1998; Benito et al., 2003; Brázdil et al., 2005b; Pfister et al., 2002; Williams and Archer, 2002). This topic has also been worked on in North America, but to a lesser extent (Endfield and O'Hara, 1997; Florescano and Swan, 1995; O'Hara and Metcalfe, 1995; Mendoza et al., 2006; Jones, 2003; Saint-Laurent et al., 2009). In South America, archival evidence, although it has not been fully exploited, has been used since 1991 to extend instrumental records of river flows in central and northern Argentina, such as the those of the Salí-Dulce and Salado River Basins (Prieto et al., 1996; Prieto, 2009; Dussel and Herrera, 1999; Herrera et al., 2003; Herrera et al., 2011), the Del Plata River Basin (Prieto and Richard Jorba, 1991), the Paraná River (Prieto, 2007, 2009), and the Mendoza River (Prieto et al., 1999, 2001; Prieto and Rojas, 2012).

This paper presents a detailed reconstruction of the flow of the Bermejo River from the year 1600 to the present, based on published and unpublished data from historic documents. The Bermejo River flows through Bolivia and Argentina. Its headwaters are in the subtropical Andes (northwestern Argentina and southern Bolivia). Its principal tributaries are the Grande River of Tarija, in Bolivia, as well as the Iruya and San Francisco Rivers in Argentina. As the Bermejo River leaves the mountains and heads east into the Gran Chaco region, it flows into a large sedimentary plain with vast flooded areas, typical of a lowland river. The high waters created by rains and snowmelt in the upper basin are concentrated from November to April, with a maximum in February. The low period is from May to November.

2. Materials and methods

2.1. Data source

2.1.1. Archives and collections

The Spanish colony in the Americas was extremely bureaucratic. The crown ordered that all official documents be done in triplicate. One copy was archived in the city where it was produced, the second sent to the governing body or viceroyalty, and the third sent to the crown in Spain. This led to an enormous accumulation of documents, especially in the imperial capital (Prieto and García-Herrera, 2009).

The principal repository is the *Archivo General de las Indias* (General Archive of the Indies or AGI) in Seville, which includes documents from the earliest part of the Spanish colonization of

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the Americas. For the current study, the most relevant sections of the archive were the *Audiencia de Charcas*, *Audiencia de Buenos Aires*, and *Indiferente General*. Until 1776 the Bermejo River region depended on the Viceroyalty of Peru. For this period, the most notable documents are the earliest conquistadors' 16th-century accounts and reports by the governors and military officials on the fight against the natives. They informed the king about the advances made into indigenous territory in the 17th and 18th centuries. Around the end of the 19th century, Argentine and Chilean historians transcribed AGI reports from these countries, in particular reports and letters from royal officials. From Argentina, Levillier (1922) is notable for this. There are also relevant documents archived in Madrid such as the *Archivo de la Real Academia de la Historia* (Archives of the Royal Academy of History) which includes significant Jesuit documents and the *Colección Mata Linares*. In the *Archivo de la Biblioteca Nacional* (Archive of the National Library) in Buenos Aires, there are a number of manuscripts written by priests as well as their travel journals that predominantly cover the Chaco region, which includes modern Argentina, Paraguay, and Bolivia. Another relevant collection is the *Cartas Anuas* (Annual Letters) of the Jesuits, which spans the early 1600s to 1767, when they were expelled from Spanish America. The letters were originally in Latin and are located in the Vatican Library. Those from Argentina and Paraguay were translated and published in *Documentos para la Historia Argentina* (1927). Other letters from the Jesuit Order have been found in the *Biblioteca Nacional de Chile* (National Library of Chile). There is valuable information in the archives of the orders of San Ignacio, San Francisco, and Seráfica and their local and regional administrative offices.

The most important political and administrative unit in Hispanic America was the viceroyalty. At the beginning of 1544, the Viceroyalty of Peru was created in Lima, which included the study region for two centuries. In 1776 the Viceroyalty of Río de la Plata was created and its capital was in Buenos Aires. Its jurisdiction included Bolivia, Paraguay, Uruguay, Argentina, and northern Chile.

Most of the information since 1776, including records from Bolivia, is preserved at the *Archivo General de la Nación* (General National Archive) in Buenos Aires (in the *Alto Perú* section). In Argentina, provincial archives are located in the provincial capitals. We were especially interested in those from the provinces of Tucumán, Salta, Santiago del Estero, Jujuy, and some records from Santa Fe. In all of these, information goes back to the earliest part of the conquest and continues until the 20th century, including significant hydrological data. The most relevant documentation for Bolivia is located in the *Archivo Nacional de Bolivia* (National Archive of Bolivia) in Sucre as well as some provincial archives such as the *Centro de Documentación Eclesiástica* (Eclesiastical Documentation Center) at the Franciscan Convent, in Tarija.

In addition, there is information on the Gran Chaco region and the Bermejo River from accounts and diaries of soldiers, travelers (locals and foreigners), and traders, most of which were published beginning in the middle of the 19th century. These old books can be found in specialized libraries and museums in Buenos Aires: *Museo Mitre*, *Biblioteca Nacional* (National Library). The *Archivo General del Ejército* (General Archive of the Army) has information on the war of the Triple Alliance (1864–1869), whose battlefields were in the Chaco region.

2.1.2. Sources

2.1.2.1. Documentary sources for the colonial period. The principal sources for the colonial period were recorded at the same time or immediately after a climatic event (primary or first-hand sources). The colonial part of most archives has a section with government reports, letters, and articles sent to the Spanish Crown by viceroys, governors, and military and colonial officials, which have information on regional issues. There are reports of hydrological and meteorological extremes that affected the regional economy such as droughts, floods, and excessive rains. The first continuous reports of swells and floods for the Bermejo River and the region begin around 1600. There are reports of priests who traveled to the area to evangelize indigenous groups, letters from functionaries of the Spanish Crown, and reports of royal officials and soldiers that went into the forest to fight the natives.

To a lesser degree, we also considered secondary sources, but these may include distortions or exaggerations. The best-known of these are the *crónicas*, a literary genre written by conquistadores, soldiers, or priests who wanted to extol their own real or supposed deeds by lauding their poverty or bravery. They were often written long after the events they describe, making their chronologies questionable (see Fig. 1).

Old maps also provide important information on a region's past climate. For example, there is a collection of maps in the AGI and AGN which show the successive courses of rivers to over three hundred years. One of the most illustrative is Father Caamaño's map, which shows the change in course of the Salado River, located near the Bermejo River, as a result of to extremely high waters in 1787 (Fig. 2). Most of these maps were compiled by Father Furlong in his *Cartografía Jesuítica del Río de la Plata* (1936).

Beginning in the 18th century there were a number of "naturalist missionaries," notably José Jolís (1767), who was involved in the *reducciones* in the Gran Chaco from 1762 to 1767 and traveled around the Bermejo and Grande Rivers. Others include Fray Antonio Lapa (1779), Fernández Cornejo (1790), Felix de Azara from 1781–1801 (1941) and Francisco Murillo (1780), who carried out the first expedition to navigate the Bermejo by ship.

2.1.2.2. Documents from the republican period. Documents used for this period were principally accounts about the navigation and exploration of the Bermejo River by explorers, adventurers, and later, traders. They focused on determining the river's navigability and forming navigation societies.

The Franciscan Order resumed its evangelization of the region after the Jesuits were expelled in 1767. This period includes numerous reports and documents by priests going to the missions. These include Cuadernos Franciscanos (1858), which refer to the extraordinary floods of the Bermejo in 1858 and 1863 (Pellichi, 1868) and writings of the other Franciscans (Pellichi et al., 1995). Starting in 1860, there was an increase in the number of books published by naturalists and adventurers on their explorations along the river.

Government and military reports began with the Indian Wars carried out by the Argentine government beginning in 1884, which produced an extensive bibliography on the features of the region, written by soldiers and functionaries such as Fontana (1977) and Aráoz (1886) who report the extraordinary floods of 1872, Gobelli (1912), and Carranza (1884). Victorica (1885) deserves special mention.

Information from newspapers is available beginning in 1870. Data from the national newspapers *La Nación and Clarín* were used to complete and calibrate the historical series with the instrumental period that began in 1940.

2.2. Treatment of the information

It was necessary to make a selection of documents to extract and categorize data. To verify the validity of the information, we used the linguistic technique of content analysis, which that makes it possible to derive climatic data from historical documents. This transforms information with different purposes into hydroclimatic data that can be treated statistically. It technique allows

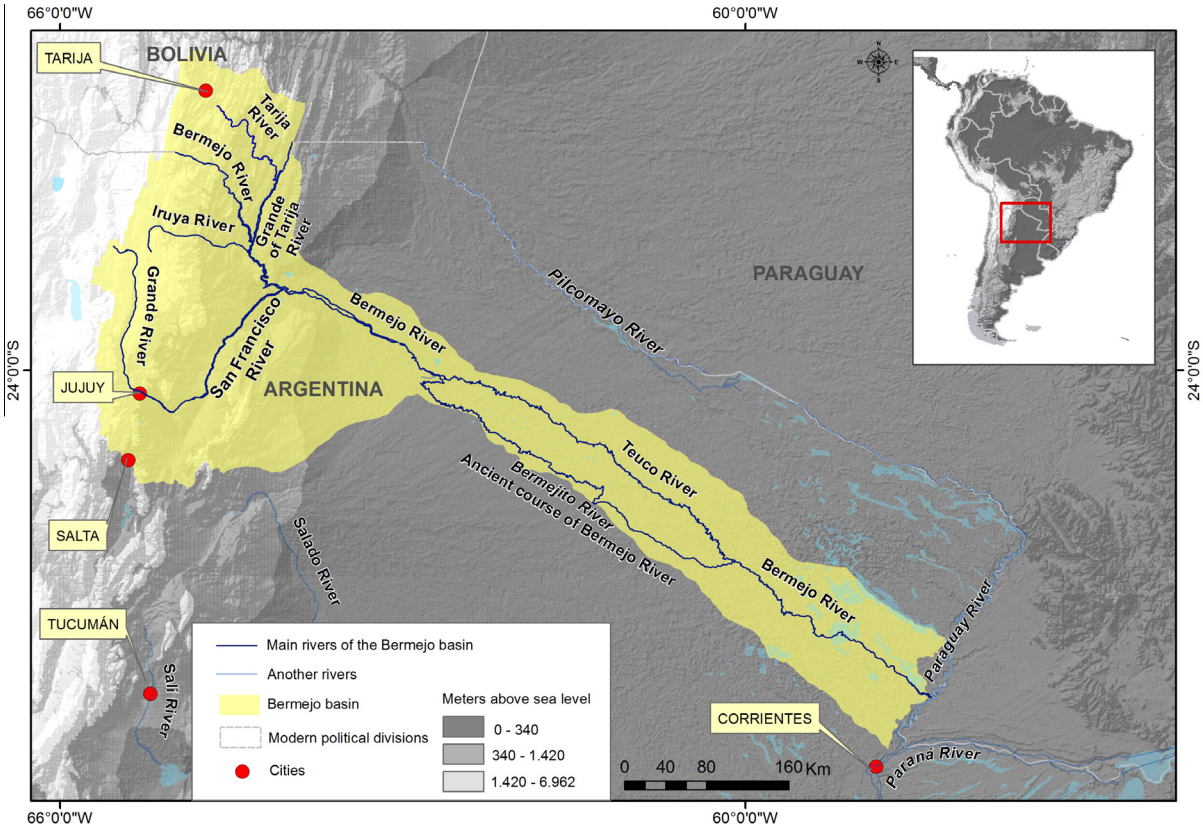

Fig. 1. Study area: Bermejo basin.

researchers to interpret past observations and compare them to modern climate standards (Moodie and Catchpole, 1975; Baron, 1982).

Based on an analysis of the language of the past, environmental data can be inferred objectively and systematically. To do this, it is necessary to clearly define each term to be used in reference to modern parameters. For this study we use Alonso's (1982) definition, which defines floods or an excess of water as "accumulations of standing water of shorter or longer periods in the soil, which are derived from extreme meteorological events in unfavorable topography or frp, inadequate management of river basins." Another category to be considered is periods with minimal flow volume (drought).

A normal year (scored as 0) can be defined by the absence of information on the river flow in the available documents or because a document specifically refers to a year's normality (Prieto and Richard Jorba, 1991; Herrera et al., 2003). Once the relevant set of documents had been identified, a thematic guide was constructed. This facilitates searching and systematizing the information. The guide used here used (1) direct indicators, which are based on the concrete occurrence of a specific climatic event and (2) indirect indicators, which are interpreted from events that arise from the event.

(a) Direct indicators
Periodic swells
High-water pattern
Beginning and ending date
Extraordinary swells
Duration
Magnitude
Size of flooded area
Water depth

(b) Indirect indicators
Famine and epidemics
Death of livestock
Flooding of agricultural fields
Settlements being isolated
Agricultural plagues
Loss of crops

The database was based on transcribing all the documents in which the above indicators were found. Each record was carefully evaluated in context, taking into account the type and detail of the information, the person or institution that provided the information and its value as an indicator of high or low water in the river.

Once complied and organized, the information's reliability was verified. We started with the premise that the phenomena under study have a specific climatic origin, precipitation, which has two extreme consequences: the complete or partial lack of water in the river over a more or less extended period and the overabundance of water, which can lead to extraordinary swells in a river's tributaries. The range between these two points could be infinite, but easy-to-determine values were used, based on the analysis and study of the language in historic documents. A five-point scale was established that is explained in Section 2.3.

Next, documents were reviewed for nouns, adjectives, and verbs that directly described conditions of humidity, drought, and floods in these or equivalent terms. The language used to describe anomalies is repeated over time with minor variations. The same phenomenon is referred to by a large number of similar terms. For example, the category *extraordinary swells* (+2) was based on phrases such as powerful swell, the land looked like a sea, appalling flooding of the rivers, furious torrent of water, the old men say that have never seen such high water, calamitous floods that are convulsions of nature, the fields were transformed

Fig. 2. Fragment of Father Caamaño's map, 1789.

into an overflowing ocean, etc. The same approach was used for the rest of the categories.

2.3. Constructing climatic series

2.3.1. Development of a five-point scale

Content analysis also was used to define five categories, which were principally based on Victorica's (1885) observations. He defined five categories of depth for the Bermejo River. The five-point scale ranges from −2 to +2.

Very low flow = −2. The river is low and cannot be navigated.
Low flow = −1. The rivers rises but there is no flooding.
Normal flooding = 0. This may include flow above normal as long as it does not cause damage. This is the same as Victorica's "normal" category.
Large swells = +1. The river runs over its banks a few hundred meters. There is damage to buildings, streets, and fields, but it is not irreparable. This would be Victorica's "medium flow."
Exceptional floods = +2. Changes in the course of the river and relocating of cities. The floods cover many miles of lands and field. Roads are cut, ravines form, and buildings and fields are permanently ruined. This would be Victorica's "high flow."

The critical depth of the Bermejo River at the latitude of Balapuca and Pozo Sarmiento was used as the average magnitude

of each large flood. The depth of the water is considered critical when there is flooding, which is 9 m at Balapuca and 9.58 m at Pozo Sarmiento (COREBE, 2006).

2.4. Calibration

Once the data series was created, we calibrated it. To do this, we began with a data series from newspapers from 1940–2008. Indices were derived with the same methodology described above (Neukom et al., 2009). We focused on the national newspaper *La Nación* (Buenos Aires) and local newspapers from the Corrientes Province. This series was compared to instrumental data from the same period, which was transformed to the same five categories.

For the instrumental data, the baseline value was 374 m^3/s (equivalent to 0 on the five-point scale). This was the monthly average for flow volume over 68 years. Each year was assigned scored from −2 to +2 based on quartile breaks and the standard deviation of the complete set of instrumental data. Finally, the newspaper and instrumental series were compared. They were significantly correlated ($R = 0.6$, 94% confidence, using Spearman's coefficient).

3. Results

3.1. Construction of the historic data series of flow volumes of Bermejo River

Based on the categories described above, a flow series was constructed for the Bermejo River. Fig. 3 shows the sequence of changes in the river's depth. Notably, extraordinary swells have become more frequent since 1800. The decadal frequency of large and extraordinary flooding of the Bermejo River was calculated over the whole period. The minimum frequency was shortly after 1600, when there was a prevalence of years with very low flow.

It should be clarified that Fig. 3 shows extreme events without averaging. Hence, if there were six "very low flow" events in a decade, the figure shows −6, even if during the same decade, there were three "exceptional flood" events (+3), as in 1599–1610. For decade values of 0 (e.g. 1651–1660), it is not an average, but a decade with no mention of extreme events or only mentions of normal conditions. The spline curve on the same figure shows decadal averages. Extreme flooding has increased since 1800. Even though there was a decrease in the first half of the 20th century, flooding frequency has increased notably in the last few decades. Droughts have been less frequent since 1891 (only two from 2001 to 2008).

Beginning in 1730 there was a high period with maximum values in 1731–1740 (3), 1751–1760 (3), and 1781–1790 (5). This suggests anomalous behavior during the second half of the 18th century, which was accompanied by extraordinary floods in other rivers in the region, such as the Salado and Pilcomayo Rivers in 1758 and 1787, respectively.

Beginning in 1800, there was a tendency for river levels and high-water frequencies to drop. Beginning in the decade 1851–1860 there was a remarkable increase, with a maximum of five floods in 1881–1890 and 1911–1920. After a period of low frequency (1921–1930 to 1981–1990), with only one flood per decade, another humid cycle began in 1991–2000. The resulting sequence shows the decadal frequency of the Bermejo River and the tendency—mostly extraordinary floods—has increased steadily since 1600.

It is important to note that extraordinary swells sometimes caused rivers to change course. The best-known is the change of 1870, when the Bermejo River began flowing along the old Teuco River, tens of kilometers to the north, to its current course. The divergence took place at approximately 23°41′19.48″W, 63°15′24.89″S, along the southern arm, called "Bermejito."

3.2. Comparison of the data series for the Bermejo and Mendoza rivers

Analysis of instrumental records from the 20th century shows inverse tendencies in rivers volumes in northern and southern Argentina. During the 20th century, the flows in northern Argentina increased, for example the Bermejo River, while flow in southern basins decreased, for example the Limay River. An intermediate case is the Mendoza river, which shows a slightly decreasing tendency (Villalba et al., 2002; Luckman et al., 2012; SSRH, 2011). Fig. 4 shows the long-term tendencies of annual

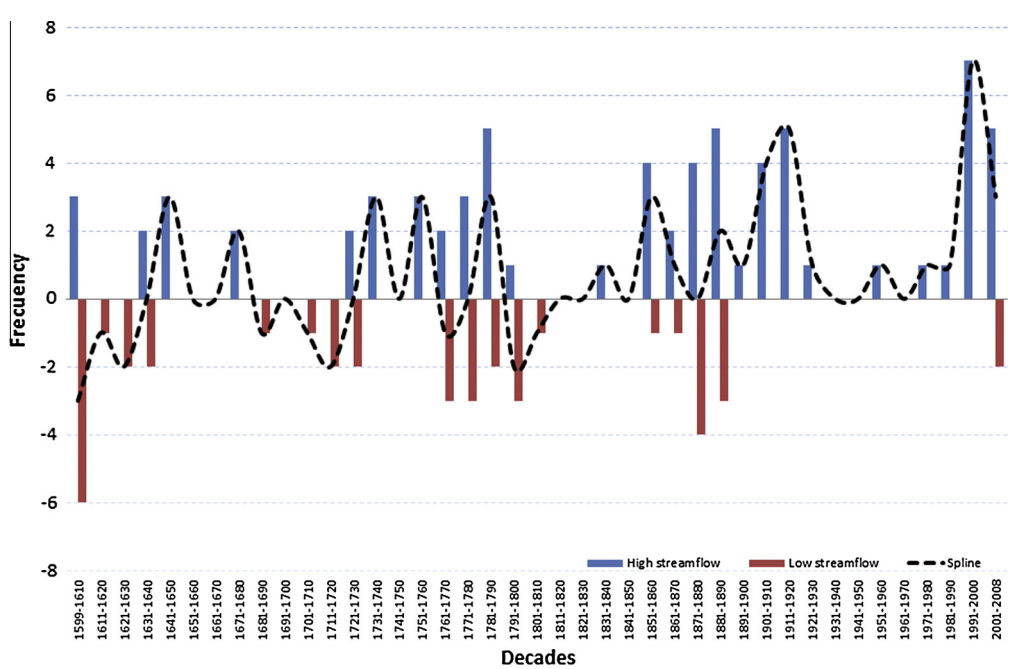

Fig. 3. Bermejo River flood series.

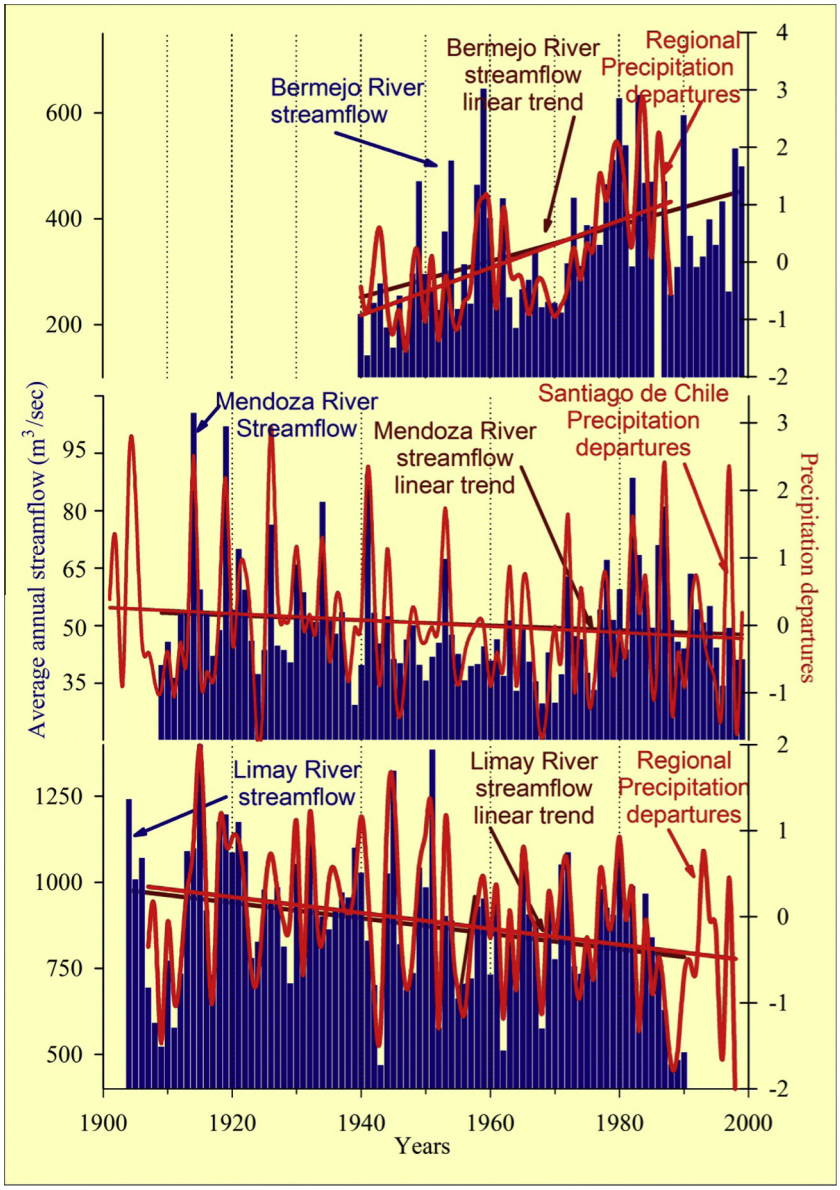

Fig. 4. Instrumental record of the Mendoza, Bermejo, and Limay Rivers.

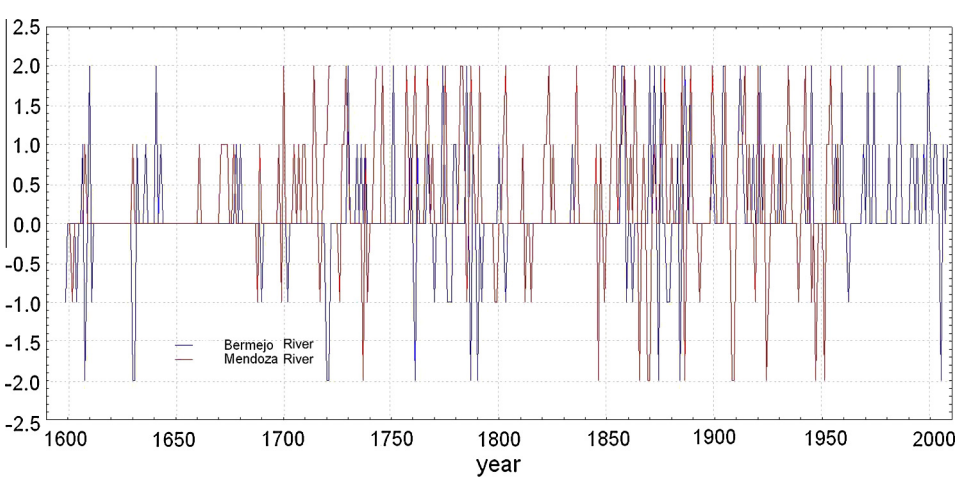

Fig. 5. Correlation between the historical data series of the Bermejo and Mendoza Rivers.

spillover and regional precipitation in these three Andean river basins. Regional precipitation data comes from five weather stations (Jujuy, Yuto, Yala, Calilegua, and San Pedro) for the Bermejo River, four stations for the Limay River (Bariloche, Esquel, Valdivia, and Puerto Montt) and two stations for the Mendoza River (Guido and Cacheuta) (Villalba et al., 2002). Instrumental data show that humidity in the Atlantic and over the continent has increased at subtropical latitudes while the input from the Pacific has decreased at middle to high latitudes.

Recent measurements show that flow values in the Paraná–Paraguay River Basin increased in the last third of the 1900s, as compared to the first two-thirds of the century (SSRH, 2011). The intensity of precipitation also increased substantially during the same period. The combined effect of these two phenomena led to particularly severe swells and floods. Similarly, the Bermejo River had 20 swells from 1940 to 2000, 10 in the last 20 years, and four in the last 10 years (COREBE, 2006).

The next step was to verify this conclusion by comparing the historically-reconstructed series of the Bermejo and Mendoza Rivers (developed using the same methodology). Comparisons were aimed at seeing whether this tendency was constant over time and determining the differences and similarities between the rivers in previous centuries. This comparison shows no significant correlation ($R = -0.04$; 95% confidence; Fig. 5), similar to the relationship suggested by the instrumental data.

4. Conclusion

The principal finding of this paper shows that extraordinary swells have progressively increased since 1800. Even though the frequency of extraordinary swells dropped in the first half of the 20th century, it increased significantly at the end of last century. The scarcity of large droughts since 1891 is also notable.

There is no significant correlation between the flow volumes of the Mendoza and Bermejo Rivers, as seen in historic documents. Instrumental data from these rivers show a similar tendency, though they only date to the 20th century. These results make it possible to postulate that differences between the rivers in northern vs. central and southern Argentina have existed for centuries, as in the case of the Bermejo, Mendoza and Limay Rivers.

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