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Updating the Hydrological Knowledge: A Case Study

Olga Eugenia Scarpati
National Research Council
La Plata National University

Eduardo Kruse
National Research Council
La Plata National University

Marcela Hebe Gonzalez
National Research Council
Buenos Aires University

Alberto Ismael Juan Vich
National Research Council
Cuyo National University

Alberto Daniel Capriolo
National Research Council

Ruben Mario Caffera
Uruguayan State University

AUTHORS

Olga Eugenia Scarpati is a researcher at the Center of Pharmacological and Botanical Studies of the National Research Council and professor of Physical Geography I (Climatology) at the Geography Department of La Plata National University, Argentina. Member of the Steering Committee, Commission for Water Sustainability of International Geographical Union. Main themes: agrohydrology and climatology.

Eduardo Kruse is a researcher at the National Research Council and a professor of general hydrology in Faculty of Natural Sciences, La Plata National University, Argentina. He has published many papers dealing with flatland hydrology, interaction of surface water and groundwater, and hydrochemistry. Main themes: hydrological and hydrogeological processes in coastal areas.

Marcela Hebe Gonzalez is a researcher at the Center of Atmospheric Sciences at the National Research Council and a professor of general meteorology in the Department of Atmospheric and Oceanic Sciences of Buenos Aires University, Argentina. Main themes: statistical seasonal rainfall forecasting in Argentina.

Alberto Ismael Juan Vich is a researcher at Argentine Institute of Snow, Glaciology and Environmental Sciences of National Research Council. He is a professor and the director of Environmental Studies and Natural Resources Institute belonging to Cuyo National University, Argentina. Main themes: hydrology and water resources.

Alberto Daniel Capriolo is a researcher at the Center of Pharmacological and Botanical Studies National Research Council, Argentina. He has achieved numerous computing programs of hydrological models. Main themes: scientific computation and software, agrohydrology, and climatology.

Ruben Mario Caffera works in Environmental System Unit, School of Agronomy, Uruguayan State University, Uruguay. He is a member of the staff, Multi-country Study on Eco-Bio-Social Research on Dengue and Chagas Diseases in Latin America and the Caribbean UNICEF/UNDP/World Bank/WHO. His main themes are meteorology and climatology.

PREFACE

In this chapter, the hydrology of the southern region of South America is updated. The study region belonging to Argentina and Uruguay Republics has a surface of 3,110,223 km^2. It presents high diversity in its environments, a large Atlantic coast, important mountain masses, vast plains of temperate climate, watersheds of great potential for multiple use, different types of climate, and high availability of natural resources that are associated with the natural basis of the settlement and national economic activities, although some are not sufficiently valued and have been degraded by uncontrolled human intervention. The location and size of both the countries determine a diversity of landscapes and several water regimes. This situation is exacerbated by the high irregularity in the distribution of annual precipitation. The Andes Range and the air masses from the Atlantic and Pacific Oceans are the main regulator of the water cycle.

An important surface of Argentina and almost whole Uruguay belong to Del Plata basin, one of the biggest of the world with 3,200,000 km^2 and which includes other basins of secondary order as those of Paraná, Uruguay, Paraguay, and Bermejo y Pilcomayo Rivers and some of the third order as Iguazú, Entre Ríos province rivers, Pasaje–Juramento–Salado and Carcarañá Rivers. All of them complete the system cited earlier in the considered countries.

The rivers are of pluvial regime with annual precipitations varying from 2000 mm at east of La Plata Basin to 700 mm at its northwestern area. Seventy-five percent of Argentine and Uruguayan populations live there and develop the main productive activities.

This very important region has an important problem: According to a study completed in 1996, the density of hydrological and meteorological stations is low compared with WMO standards. This remarks that there is need for more information to increase the hydrological knowledge.

23.1 Introduction

The aim of this chapter is showing some advances realized in some areas of Argentina and Uruguay, concerning climate variability and its influence over the hydrology of the region. The different Argentine regions analyzed are Pampean Plain with a special study of extreme hydrological events (EHEs) in Buenos Aires Province (BAP) and the behaviors of the rivers of the Andes Mountain Range and those of Comahue.

Water use is dominated by agriculture, and the irrigated areas are growing according to the development in the whole region, so water sustainability is a major theme to be considered in the future.

23.2 Pampean Plain (Argentina Republic)

From a hydrological perspective, large flatlands occurring in humid climates are characterized by a predominance of vertical water movements (i.e., evapotranspiration and infiltration) over horizontal ones (i.e., runoff), and by a strong interrelationship between surface water and groundwater. Such is the case of the Pampean Plain in Argentina and the territory of Uruguay (Figure 23.1). Both of them are almost totally included in La Plata Basin.

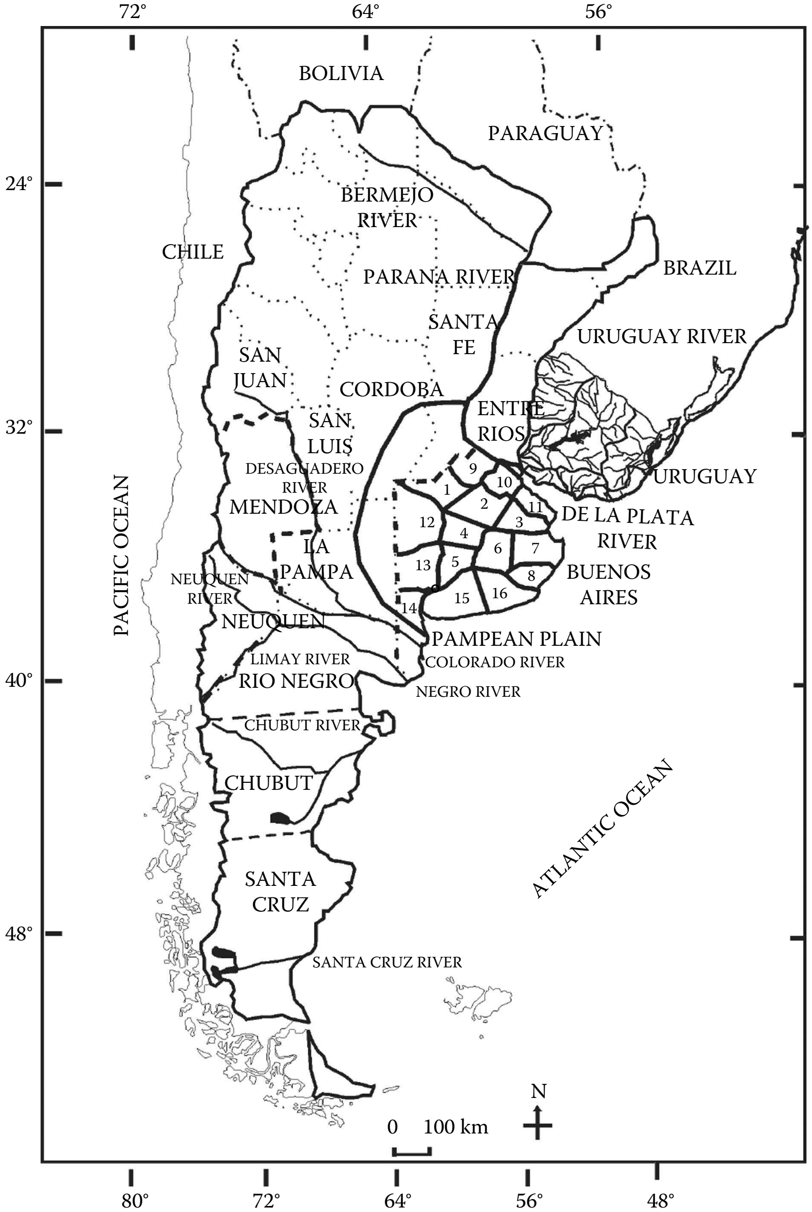

FIGURE 23.1 Southern region of South America.

The Pampean Plain covers approximately 500,000 km^2, with predominant heights below 200 m above mean sea level. It is covered by Quaternary sediments, predominantly silty (loess), which overlie several sedimentary basins of different ages and geological origins.

The landscape is characterized by low topographic slopes (on the order of 1 per 1000 and even below 0.5 per 1000), low drainage density, and the presence of relatively permeable materials on the surface.

The climate is temperate, with a mean annual temperature of 17°C. The mean annual rainfall is on the order of 1000 mm, decreasing toward the west and south. Dry and rainy seasons, which may modify significantly the hydrological conditions, can be observed.

The terms of the hydrological balance in the Pampean Plain have a relevance different from an area with steeper slopes. Such slight slope causes a decrease in surface runoff, which implies a longer period of contact between the water and the surface, increasing infiltration and evapotranspiration. The vertical transport of water and the storage occurring in depressions, the unsaturated zone (USZ), and the saturated zone (SZ) stand out. Besides, there is an influence of interception storage in cultivated areas, depending on their areal coverage and growth stages. Temporary or permanent depression storage is also a significant component, and therefore the simulation models must consider them.

Water movement in the USZ, which connects the surface and subsurface hydrological processes, is a primary objective in the study of the plain.

The combination of geomorphological and climate factors determines hydrological systems ranging from an integrated drainage network to a lack of drainage. In the former case, there is local surface runoff toward the watercourses and regional runoff toward a final point of discharge. In other cases, the lack of watercourses causes that, when precipitation occurs, water fails to have enough energy to run off toward a specific point of discharge.

The slight slope favors the moderating influence of depression storage. Frequently, a drainage basin cannot be determined, as transferences between its divides occur, and in certain cases, there is a plurality of drainage exit points. The drainage network is not a reflection of the weather, and in general, it is modified by anthropogenic activities, such as channelizations or hydraulic works, which seriously distort the natural drainage network. Often, the concept of self-similarity, which expresses the similarity in hydrological response between a portion and the totality of the system, cannot be applied.

In the subsoil, there is local and regional groundwater flow [5]. Locally, groundwater flow is active, and once it has covered a certain stretch, it is discharged into streams or lakes, becoming their base flow. Regionally, groundwater flow is passive and extremely slow, which in a vast plain is caused by the difference between the input and output volumes of local groundwater flow and which must be related to the sedimentary thicknesses of the subsoil in the plain.

The characteristics mentioned earlier and the presence of a shallow water table cause the water in streams and lakes as well as groundwater to be directly related, which is why they should be treated as a single unit.

Possible behaviors may be considered for different areas of the Pampean Plain, taking into consideration whether they occur under dry or wet hydrological conditions. Under wet conditions, input is higher than output. The degree of difference causes a decrease in groundwater storage capacity (rise in the water table) and/or depression storage capacity (increase in flooded areas). Under dry hydrological conditions, output is higher than input. The deficit is compensated for by geological storage, increasing the groundwater storage capacity (deepening of the water table) and/or depression storage capacity (decrease in water level in lakes).

Thus, in order to become acquainted with the hydrological situation, it is relevant to assess the rainfall variations, the influence of evapotranspiration, and the evolution of the water tables and of the areas covered by surface water [6].

Given the hydrological processes that characterize the Pampean Plain, it is necessary to define which are the most relevant elements to be measured, and how and where to do so, once a conceptual model to represent the behavior of the system has been defined.

Measuring the terms of the balance and the vertical exchange of water is necessary, as the latter predominates in the processes occurring in plains. In order to do so, apart from carrying out conventional measurements, depression storage should be assessed by means of accurate topographic surveys.

In the USZ, soil moisture content and potential, from the surface to the water table, including the hydraulic properties of the unsaturated porous media, should be measured.

In the SZ, the variations in the water table and the piezometric level of the underlying aquifers should be recorded.

By means of remote sensing (i.e., aerial photography and satellite imaging), systematic assessments may be carried out concerning the variations in time of the percentage and type of plant coverage, surface storage, soil moisture, rainfall field, heat flow, and areal evapotranspiration, among other variables.

The objective of quantifying the hydrological processes in the Pampean Plain must contribute toward improving the use of water and natural resources in general. This requires not only the knowledge of the current situation, but also the prediction of possible system behavior under different conditions, extreme or not, natural or induced. Such a simulation should try to represent the peculiarities of plain systems, which is why the available conceptual models developed within the framework of classical hydrology are difficult to apply and sometimes even inadequate. It is necessary to adapt or develop simulation models that are adequate for plain hydrology. Even though it is advisable for hydrological models to be developed on the basis of physical parameters, in certain cases, when confronted with uncertainties or heterogeneities, it is convenient to make adjustments in order to achieve a better identification between the model and the prototype.

During the calibration of models adequate to run simulations in plains, it has been proved that groundwater processes (e.g., observable in the system by means of the water tables) and surface hydrological processes (e.g., observable by means of the runoff volume) are highly sensitive compared to the parameters characterizing the USZ. This highlights the key role of the USZ in water table recharge and infiltration, which are the processes interconnecting surface and groundwater hydrology.

In the development of the different stages of calibration, the impossibility of making partial adjustments to the parameters governing surface and groundwater hydrology becomes evident, so a global calibration is necessary, including all of the parameters as a whole. The objective function should contemplate a reliable prediction of surface runoff, groundwater recharge, and water tables, as well as their evolutionary tendencies in time.

23.3 Extreme Hydrological Events in Buenos Aires Province, Argentina

BAP is located in the main rain-fed region of Argentina, the Pampean Plain, and presents a lot of cities of different importance and population. The main soil uses are crops (maize, wheat, and soybean) and livestock for meat or milk production. EHEs are a constant in BAP, and their impacts mainly over the agriculture have been studied with different scales and point of views.

The analysis of the disasters database in Argentina during the period 1974–2002 shows the prevalence of floods, not only because more than 60% of the records correspond to this type of disaster but also because they are the most recurrent and with high negative impact in terms of social and economic effects. The other one is drought, which was very important during 2008 and the summer 2011–2012.

Soil moisture is a significant hydrological variable related to floods and droughts and plays an important role in the process of converting precipitation into runoff and groundwater storage and controls the interaction of the land with the atmosphere.

BAP is a large plain with elevations below 300 m and its surface 307,571 km^2, and it presented significantly increased precipitation during the last decades [3].

The El Niño-Southern Oscillation (ENSO) remote influence on the climate variability of such region has been extensively documented, and there is some evidence that El Niño events have been stronger in recent decades. They appear to be both a giver and a taker in climate change [4,7].

The drainage system of the BAP can be divided into 16 sectors according to their basins [1] and can be seen in Table 23.1 and in Figure 23.1.

The spatial and temporal variabilities of soil water storage were examined using Thornthwaite and Mather soil water balance method, daily precipitation data, and normal daily mean reference evapotranspiration estimated by the Penman–Monteith formula and with soil hydrologic constants—field capacity and permanent wilting point—calculated by means of soil data measured *in situ*.

TABLE 23.1 Sectors of the Drainage Areas Studied

Sector	Name
S1	Northwestern area of the Salado River basin
S2	Central area of the Salado River basin
S3	Salado River mouth
S4	Southern area of the Salado River basin and northern area of Vallimanca River basin
S5	Southern area of the Salado and Vallimanca river basins
S6	Western Channels area at south of the Salado River basin
S7	Channels area at south of the Salado River
S8	Southeastern basin and streams
S9	Arrecifes River basin
S10	Northeastern stream basins
S11	Drainage basin of the La Plata River at the South of Samborombon River
S12	Region without surface drainage
S13	Lagoon area at the southwest
S14	Small rivers and streams with Atlantic drainage
S15	Basins and streams of south (to west)
S16	Basins and streams at south (to east)

The results of the soil water balance, soil water deficit (SWD), and soil water surplus (SWS) were considered triggers of EHE in the BAP. Their temporal and spatial distributions were analyzed using the nonparametric test Mann–Kendall and then an Excel template—MAKESENS—for detecting and estimating trends in the time series of annual values of soil water components.

Tables 23.2 shows the trends and temporal distributions of SWS for different periods.

The resulting trends are not at all statistically significant. During the total studied period (1969–2008), trends are not important; almost all sectors remain stable. SWS trends have three $\alpha = 0.1$ and one $\alpha = 0.05$, and the SWD trends present four $\alpha = 0.1$, three $\alpha = 0.05$, and only one $\alpha = 0.01$.

The EHEs always have different areal distribution, but according to these tables, some patterns can be seen. During 1969–1988, there was a humid period of increasing soil water trends with the exception of Sector 16, mainly during 1969–1978, since 1989 SWDs are increasing in almost all sectors.

23.4 Oriental Republic of Uruguay

Uruguay has as striking physiographic feature and a relatively low landscape too. Situated in a climate transitional zone, the Uruguayan territory shows peculiar patterns. There is not a proper dry season in the area. Nevertheless, westward in the "Litoral," there are two rain maxima centered in spring and autumn jointly with a steep winter minimum. But in the South Eastern portion of the country (Merin Lagoon and Atlantic watersheds), the double peak is shifted forward in a way that the main maximum is during winter and the beginning of spring, the second one lying in late summer (February–March), with the more steep minimum starting late spring (November) and lasting deep into summer (December–January). These patterns persist after the early signs of climate change occurring mainly in the 1980s. These changes imply a general increase in the precipitation regime mainly in central and southern regions of the Rio de la Plata Basin. On an annual basis, the signification of this trend in the Uruguayan territory is referred to the 1948–2000 period. However, from 2004, a number of vacillations in the precipitation patterns occur, with severe droughts (2004, 2008) and big floods (2002), the time length being too short to confirm a new shift in trend of the climatic system in the area. That is why it is common to find that the former annual rainfall values, lying from

TABLE 23.2 Trends and Temporal Distribution of Soil Water Surplus (mm)

	Period				
Sector	1969–2008	1969–1978	1979–1988	1989–1998	1999–2008
S1	=	=	↑	=	↓
S2	=	↑	↑	=	↓
S3	=	↑	↑	↓	↓
S4	=	↑	↑	↑	↓
S5	=	=	↑	=	↓
S6	=	↑	=	↓	↓
S7	=	↑	↑	↑	↓
S8	=	=	↓	=	↓
S9	=	↑	↑	=	↓
S10	↓	↑	↑	↓	↓
S11	↑	↑	=	↓	↓
S12	=	↓+	↑*	↑	↓+
S13	=	↑	=	=	↓+
S14	=	↑	↓	=	=
S15	=	=	↓	=	↓
S16	=	=	=	=	↓

Notes: ↓ diminution, ↑ increase, and = no variation, + significant trend at level $\alpha = 0.1$, * $\alpha = 0.05$.

near 1400 mm northeastward and near 1000 mm in the southeastern bottom, increased by 12%–20% for the period 1982–2003.

But the more typical feature in the Uruguayan precipitation regime is its variability. Conceivably because of the transitional climate features, the variability in monthly precipitation regimes is quite high along the year where March and September are the more stable months in the year, February and April being the more variables.

The seasonal variability, taking into account by the coefficients of variation of 26 raingauges for a long period (1948–2008), is not stable in the decennial timescale. An attempt to deal with new trends shows a decrease in monthly variability roughly in the whole country in October and in April—although this month remains one of the more variable between years—and an increase in variability in the southern part of the country in March and notably in the north in December. These trends are not outlined in the mean flow patterns in the hydrological outlooks cited later. It is to mention that even with these changes, multiannual monthly isohyets remain meridional in the winter months and zonal during summer, with transitional regimes in the intermediate seasons.

In spite of the absence of a proper dry season, the summer "thermal efficiency" of the Köppen Classification implies very high values of evapotranspiration during summer almost tripling those of the winter and determining water deficits in soils in the middle of the warm season. For official and practical purposes, the country has been divided into six "macro-watersheds" Rio Uruguay River (45,750 km^2), de la Plata River (12,400 km^2), Atlantic Ocean (8,600 km^2), Merin Lagoon (28,700 km^2), Negro River (68,350 km^2), and Santa Lucia River (13,250 km^2).

Four of these water bodies are shared with neighboring countries, while the Santa Lucia River pertains entirely to the Uruguayan territory and the Negro River has only a very small portion in Brazil. The Merin Lagoon is currently connected in the Brazilian territory to the Los Patos Lagoon by a canal. The Atlantic "macro basin" discharge is mainly indirectly through coastal lakes (from west to east: José Ignacio, Garzón, Rocha, Valizas, and Negra) with an intermittent surface flow to the sea. Most of the streams discharging in La Plata River and in the Atlantic Ocean show a sandy bar, but even so, salty waters penetrate several kilometers into each of them because of the intermittent river flow intensity and steady favorable wind conditions.

On the other hand, the entire Uruguay River is the second tributary of the big La Plata Basin, with different precipitation regimes. Particularly important are the precipitation originated by summer season mesoscale convective complexes, and winter synoptic activity, producing mostly liquid precipitation. The low-level jet east of the Andes that supplies moisture from tropical South America to the La Plata Basin is observed throughout the year (with some changes in the core's height), supplying moisture and heat from warmer regions at all times of the year, favoring precipitation during both the warm and cold seasons [2]. The entire Uruguay River has a basin of 365,000 km^2 and a mean flow of about 4,500 m^3/s. It shows a varied relief along its 1500 km length, with many small valleys and short water courses. The terrain slope is 0.104 m/km and the fluvial one 0.086 m/km. The longitudinal gradient of the basin is small, while the transverse section of the basin is comparatively narrow, so the lag between river discharge and rainfall is small. This discharge is related to ENSO events more accurately in the Uruguay River than in the river basins belonging to the Uruguayan country. Both are related strongly with the cold phases (La Niña) pronouncing ebbs and, in a weaker way, with the warm phases with high discharges.

For the Uruguayan territory [8,9], different parameters of the main basins can be seen in Tables 23.3 and 23.4.

23.5 Andes Mountain Range (Argentine Republic)

The Andes Mountain Range is the main water cycle regulation system at the continental level. All human activities in the Andes are associated with the mountain range hydrologic cycle. There is evidence that important changes such as the retreat of ice sheets affect the magnitude and seasonality of runoff [10]. The runoff regimes of the main rivers rising in the eastern slope of the Andes in the Argentine Republic are studied in the following text, and special emphasis is laid on the detection of jumps and long-term trends.

The Andes Mountain Range contours the Pacific Ocean coast for 7500 km. It extends from Panama (11°N latitude) down to its southern end (56°S latitude), where it sinks into the Atlantic east of island Isla de los Estados (Argentina). It was formed at the end of the late Cretaceous period as a result of the Nazca plate subduction underneath the South American plate. The tectonic forces brought on by this collision have shaped the configuration of the present relief: high mountains, extensive high plateaus (high cold plateau), deep longitudinal valleys, and transverse valleys in Argentina and Chile.

TABLE 23.3 Summary of Averaged Seasonal Values for Regionalized Gauged Basins

	Precipitation (mm/Month)				Thornthwaite ETP (mm/Month)			
Regions	Annual	April–July	August–November	December–March	Annual	April–July	April–July	December–March
Northern Litoral	114	113	103	126	70	43	43	107
North central	121	128	102	134	71	45	45	109
Northeast	131	133	119	140	69	44	44	105
Southern Litoral	103	87	94	127	67	41	41	105
Southwest	97	88	93	109	66	43	43	100
South central	106	108	104	107	65	42	42	99
East central	121	131	116	117	67	44	44	102
East	118	126	109	120	65	43	43	99
Southeast	106	112	103	102	63	43	43	94

Note: Quarterly and annual precipitation and potential evapotranspiration calculated by Thornthwaite method (1980–2004).

TABLE 23.4 Summary of Averaged Seasonal Values for Regionalized Gauged Basins

	Runoff Coefficient				Runoff Sheet (mm/Month)			
Regions	Annual	April–July	August–November	December–March	Annual	April–July	April–July	December–March
Northern Litoral	0.35	0.49	0.32	0.16	40	61	36	24
North central	0.38	0.52	0.33	0.20	46	73	35	30
Northeast	0.43	0.54	0.45	0.20	56	76	56	35
Southern Litoral	0.31	0.40	0.33	0.19	32	37	32	26
Southwest	0.21	0.26	0.23	0.10	20	24	23	13
South central	0.34	0.41	0.37	0.13	36	49	41	17
East central	0.37	0.47	0.40	0.15	45	67	48	21
East	0.41	0.46	0.51	0.18	49	63	57	26
Southeast	0.35	0.40	0.41	0.15	37	48	45	17

Note: Quarterly and annual runoff coefficient and runoff sheet (1980–2004).

The Andes range regulates the flow of air masses from the Atlantic and the Pacific and shapes the fluvial regime of the rivers originating on its slopes. The area under study is the basins on the eastern slope of the Andes northwest of Argentina and Patagonia along a wide latitudinal gradient that extends practically all over the national territory. The Andes are known by different names along their strike (Figure 23.2).

The hydrological year runs from September to August for the rivers in the north of Argentina (Cordillera Oriental, Sierras Subandinas, and Sierras Pampeanas); from July to June, for the rivers corresponding to the Cordillera Frontal, Principal, and Precordillera, including the Colorado River; and from April to March for the Patagonian rivers (Cordillera Principal, Patagónica, Antecordillera, and Sierras Patagónides), with the exception of the Santa Cruz River for which the hydrological year runs from September to August. The fluvial regimes are classified according to the seasonal variations in the volume of water, using Parde's classification.

The Arid Diagonal, which traverses the South American continent from the north of Peru to the Patagonian coast, could be considered as the boundary of the Atlantic and Pacific influences on the Andes. This area with little rainfall is the boundary between the quasi-monsoon (Atlantic) and Mediterranean (Pacific) climates on the slopes of the Cordillera. There are seasonal, annual, and long-term fluctuations that respond, among other factors, to latitudinal variations in the pressure fields of

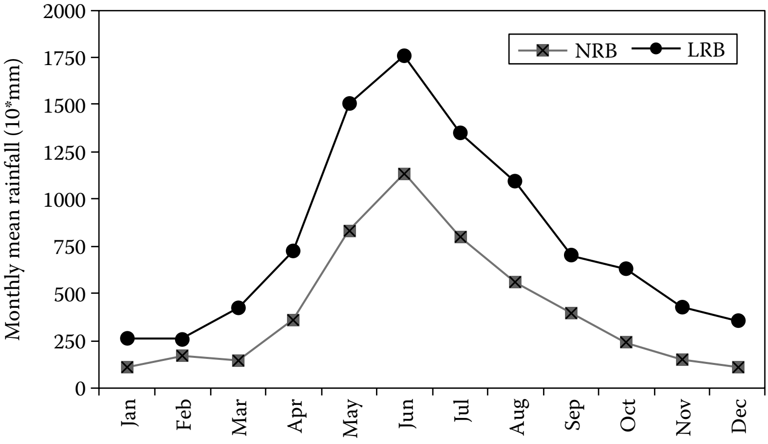

FIGURE 23.2 Mean annual cycle of rainfall in NB (gray, square points) and LB (black, circle points).

South America. From December to February, the Atlantic influence is stronger on the eastern slope of the Andes between 22°S and 35°S latitude, while the Pacific influence is stronger in winter. This atmospheric dynamics gives rise to different rainfall patterns. More than 50% of the total annual rainfall is concentrated north of 28°S, with a quasi-monsoon rainfall pattern and heaviest rains occurring between December and February. In the Cordillera Principal, rainfall originates in the Pacific and occurs from May to August. In the Patagonia, with a Mediterranean climate regime, rainfall originates in the Pacific and occurs in winter; summers are dry. South of 45°S–47°S, rainfall is mainly of Pacific origin and is evenly distributed year round.

23.5.1 Fluvial Regime

The Bermejo River basin straddles Bolivia and Argentina. The river rises in the eastern slopes of the Cordillera Oriental and Sierras Subandinas. The basin collects surplus water from the mountain front between 21°S and 25°S. The area is characterized by intensive erosion processes and heavy summer floods. Precipitation seasonality and intensity in the upper basin affect erosion rates on bare soils and on the steep relief. The Sierras Pampeanas receive more than 1800 mm/rainfall per year on the eastern slope. The Sali-Dulce endorheic basin originates in a mountain arch (heights up to 5000 m) between 26°S and 28°S and discharges into the Mar Chiquita lake system. The river headwaters have a very dense natural drainage network, significant flows, and marked seasonality; the Las Cañas River is representative of this part of the Sali-Dulce basin. The Bermejo and Las Cañas rivers have a tropical rainfall regime with rainfall concentrated in the summertime and extending beyond it to give rise to a characteristic hydrologic regime.

The central-western part of Argentina, between 28°S and 33°S, is drained by the vast hydrographic system of the Desaguadero–Salado–Chadileuvú River. From north to south, it includes the Bermejo River and the Jachal, San Juan, Mendoza, Tunuyán, Diamante, and Atuel rivers that rise in the Cordillera Frontal, Precordillera, and Cordillera Principal. After leaving those elevations, the rivers become allochthonous, and in the plains, they are used for irrigation purposes, and the rest of their flows is lost by infiltration. The Pincheira River, with a significant specific water flow, is a small affluent of the Malargüe River and an inlet to the Bañados de Llancanelo (wetlands, endorheic basin).

There are different hydrological regimes in the area. One of them is the mountain nival regime, in which the orographic effect of the cordillera contributes to a more lasting source of water. The melting period is more or less prolonged and not too marked due to the altitude gradient in the basin. This leads to decreases in temperature and evaporation and to increases in the fraction of solid precipitation. The sequence of occurrence of high flows results in two subtypes. The first one, the nival–glacial subtype (December, January, February, and November), which is characteristic of the Mendoza and Diamante River basins, receives water from snowmelt accumulation; snowmelt proceeds upward and is regulated by temperature increases during the warm months. The second is the purely nival regime subtype (December, January, November, and February), which is characteristic of the San Juan River basin: snow accumulates from April to September and melts completely during the warm months from November to February.

Due to their latitude and altitude, the Cordillera Frontal and Cordillera Principal have a significant glacier-covered area, so that water contributions to the basin are the product of glacier ablation and snowmelt. This regime, which differs from the others in the flooding period, also has two subtypes. The classic glacial subtype (January, February, and December), characteristic of the Mendoza River basin, and the glacial atténué subtype, with high waters occurring earlier than that in the former subtype and a sequence of maxima in January, December, and February. Surface glacier ablation causes great and outburst floods depending on the magnitude of the rise in temperature. Continuous in-depth melting ensures minimum water flows in winter. The regime of the Tunuyán and Atuel rivers is of the glacial atténué subtype. The Pincheira River has a purely nival regime with maximum water flows occurring in December, January, November, and February.

The Colorado is an allochthonous river formed by the confluence of the Grande and Barrancas rivers. It drains the Cordillera Principal between 35°S and 37°S along a 270 km front. In its medium reach, it sometimes receives very limited flows from the Desaguadero–Chadileuvú–Curacó system. The Grande River is the largest of all Andean rivers in the Cuyo region. The regimes in the basin are of the nival atténué or transitional snow type with a greater influence of the pluvial component. The purely nival regime in the upper basin is the result of the combined regimes of its affluents. The pluvial component is greater downstream and leads to a fluvial regime of the nival–pluvial type; spring rains anticipate flood peaks.

The Negro River, formed by the Limay and Neuquén rivers, collects rainwater and snow- and ice-melt water from an important mountain front located between 37°S and 41°S on the Cordillera Patagónica and from the mountain range Patagónides. The complex drainage system of the Limay has 40 glacier lakes of significant size and depth. The Neuquén River differs from the Limay in rainfall pattern: rains are much less abundant, they tend to be seasonal, and there are practically no lake basins. The Chubut River basin extends from 41°S to 44°S. Its headwaters receive numerous tributaries from the mountain range Patagónides, and it becomes allochthonous downstream as it runs through the Patagonian plateau. The regimes in the basins are the result of a mixture of solid (snow and ice) and liquid (rain) contributions from the upper basins. Their main characteristic is that there are two flood peaks and two low-water-level periods, though not always clearly marked. The upper basins are characterized by snowmelt and glacier ablation and by high water levels in the spring, which are rapidly depleted. Rainfall occurs in winter and gives rise to a nival–pluvial Mediterranean regime, while in the lowlands, it results in a pluvial–nival Mediterranean regime. These regimes are regulated by numerous lakes that act as natural reservoirs. Flood waves caused by snowmelt and rains are similar and lead to a flow with two maxima (July and November).

The Santa Cruz is the second most important river in Patagonia after the Negro River. Its headwaters lie in the Southern Patagonian Ice Fields between 49°S and 51°S. It is the outlet for lakes Viedma and Argentino, which are connected by the La Leona River. The waters of both lakes originate from snowmelt and glacier ablation. The Santa Cruz is an allochthonous river up to the point where it discharges into the Argentine Sea. It is a typical example of a glacier-melt fed river, with glacier-melt contributions from lakes Argentino and Viedma. It has one peak flow event in March and one low-flow event in September. The abrupt changes in the Santa Cruz River levels are due to sudden flood waves triggered by ice calving on the Perito Moreno Glacier.

23.5.2 Detecting Gradual and Abrupt Changes in Runoff

In order to detect gradual and abrupt changes in fluvial regime, several tests were conducted at 30 sites (gauging stations) to assess the maximum daily flow; the daily flow exceeded 355 days in a year and the annual flow series. Changes in trend were detected in 28% of the series, mostly during low water periods. Annual flows show a positive trend only in the Bermejo, Las Cañas, Tupungato, Mendoza, and Atuel rivers. The maximum daily flow tends to be higher in the Bermejo, Mendoza, Salado, Atuel, and Neuquén rivers, but it probably decreases in the Limay River. The maximum daily flow occurs earlier in the Las Cañas River and later in the Los Patos River. In both cases, the magnitude does not change. According to hydrologic records, the minimum daily flow tends to be higher in most of the sites under study except in the Neuquén, Limay, and Chubut rivers, where the minimum flow is likely to be lower. Only the Bermejo and Mendoza rivers show statistically significant trends in most hydrological variables.

The methods for determining abrupt changes in the hydrological variable series yield relatively different results. This is so because in most cases, the basic assumptions for the tests are not met and give rise to a significant degree of uncertainty. The break point occurs in the 1970s, when there is evidence of changes in the annual and minimum daily flow hydrological variables at most of the gauging stations included in the study. Changes in the Patagonian rivers Limay, Chubut, and Santa Cruz are negative (Table 23.5). Since different methods have been used, a restrictive criterion was adopted based on the fact that in order to accept the condition under analysis, none of the methods should reject the null hypothesis.

TABLE 23.5 Trends and Jumps in Some Variables of the Rivers

			Trend			Jumps		
Basin	South Latitude	West Longitude	Q_{max}	Q_{355}	Q_{YEAR}	Q_{max}	Q_{355}	Q_{YEAR}
Bermejo	22°43′	64°22′	ns	+	+	ns	1978 (+)	1972 (+)
	23°06′	64°13′	+	+	+	1974 (+)	1980 (+)	1973 (+)
Las Cañas	27°24′	65°59′	ns	+	+	ns	1975 (+)	1972 (+)
Los Patos	31°57′	69°42′	ns	+	ns	ns	1978 (+)	1977 (+)
	31°53′	69°41	ns	+	ns	ns	1978 (+)	1945 (−)
San Juan	31°20	69°06′	ns	ns	ns	ns	1982 (+)	Ns
	31°32′	68°53′	ns	+	ns	ns	1978 (+)	1945 (−)
Vacas	32°61′	69°46′	ns	ns	ns	1972 (+)	1972 (+)	1972 (+)
Cuevas	32°51′	69°46′	ns	+	ns	1977 (+)	1978 (+)	1972 (+)
Tupungato	32°51′	69°46′	ns	ns	+	1978 (+)	1979 (+)	1977 (+)
Mendoza	32°51′	69°16′	+	+	+	1977 (+)	1978 (+)	1977 (+)
Tunuyan	33°47′	69°25′	ns	+	ns	ns	1979 (+)	1972 (+)
Diamante	34°40′	69°19′	ns	ns	ns	ns	1980 (+)	ns
Atuel	35°05′	69°36′	ns	ns	ns	ns	ns	ns
	35°04′	69°07′	ns	ns	ns	ns	ns	ns
	35°02′	68°52′	+	+	ns	1972 (+)	1978 (+)	1978 (+)
Salado	35°13′	69°46′	+	ns	ns	1977 (+)	1952 (−)	1972 (+)
Pincheira	35°31′	69°48′	+	ns	ns	1982 (+)	1978 (+)	1978 (+)
Grande	35°19′	70°18′	ns	+	ns	1987	1991	1987
	35°52′	69°53′	ns	ns	ns	ns	ns	ns
Valenzuela	35°19′	70°18′	ns	−	ns	ns	ns	ns
Chico	35°48′	70°05	ns	ns	ns	?	?	?
Poti Malal	35°52′	69°57′	ns	ns	ns	ns	1985	ns
Colorado	37°06′	69°44′	?	?	ns	?	?	1977 (+)
Neuquén	38°32′	69°25′	+	ns	ns	1971 (+)	1967 (−)	1913 (+)
Limay	40°32′	70°26′	ns	−	ns	Ns	1940 (−)	1952 (−)
Chubut	42°06′	71°10′	ns	−	ns	1983 (−)	1991 (−)	1985 (−)
	43°51′	68°30	ns	ns	ns	ns	1966 (+)	1985 (−)
Santa Cruz	50°16′	71°54′	ns	+	ns	ns	1994 (+)	ns

Notes: ns, non significance at level $\alpha = 0.05$; +, positive trend at level $\alpha = 0.05$; −, negative trend at level $\alpha = 0.05$; ?, no data.

23.6 Comahue Region (Argentine Republic)

The Comahue region is located in the area of the Andes Mountain Range, between 38°S and 43°S encompassing the Argentinean provinces of Neuquén, which limits with Neuquén River in the north and Limay River in the south. There, the low-level flow prevails from the west, and moist air can enter the continent from the Pacific Ocean because the height of the Andes mountain rainfall falls from 3000 to 1500 m south of 38°S. Most of the energy resources of Argentina come from hydroelectric stations operating in the region. Neuquén River Basin (NB) is the main affluent of Negro River and occupies an area of 49,958 km^2. Limay River Basin (LB) covers an area of 23,600 km^2, and its mean flow is 734 m^3/s. The hydroelectric dams of Alicurá, Piedra del Águila, Pichi Picún Leufú, and El Chocón are on this river. The interannual variability of rainfall influences the flow of both rivers and, therefore, the power generation, the water schedule release, the probability of flooding, and high drainage level from irrigated valleys; for that reason, the study of rainfall is relevant and so the use of some predictors for seasonal rainfall.

23.6.1 Study of the Rainfall in Comahue Region

Mean monthly rainfall in LB and NB for the period 1975–2007—using data of high quality and selected stations—is depicted in Figure 23.3. The low-frequency variability of the annual precipitation series was analyzed using a linear trend method of minimum squares, and statistics significance was tested using Student test.

To improve the detection of rainfall extreme periods that could produce significant consequences in dams operation, the standardized precipitation index (SPI) using 6 month period was calculated to quantify deficit or excess of precipitation.

The computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for LB and NB. The parameters of the gamma distribution were estimated for each 6 month accumulated rainfall series. SPI value greater (lower) than zero indicates water excess (deficit). A wet (dry) period according to the SPI is defined as the period during which the SPI is continuously positive (negative). The magnitude of the index allows classifying the 6 month accumulated rainfall in categories that go from extreme drought to extreme excess (extremely dry, severe dry, moderate dry, normal, moderate wet, severe wet, and extremely wet).

The main feature is a defined annual cycle with a peak in late autumn and winter over both basins and that rainfall in LB exceeds the NB all along the year. Rainfall decreases in both basins, 2.4 mm/year in NB and 3.2 mm/year in LB. However, trends are not statistically significant since correlation coefficient is near 0.13 in both cases because of the number of years considered. Statistical significant rainfall trends were detected only in a few stations very near the Andes Mountain Range [4].

SPI using 6 month period was calculated in order to be representative of accumulated rainfall over the whole 6 month period. In order to describe extreme events, the maximum positive (minimum negative) SPI in each year is detected in order to be representative of extreme excess (drought) event. The maximum and minimum series are adjusted using a Gumbel distribution, which is well suited for modeling extreme hydrologic events. The fitted Gumbel distributions to annual maximum SPI at LB and NB will be used later to illustrate some of the results concerning the recurrence period for wettest and driest SPI. The recurrence period for SPI >1.5 (severe or extreme excess) is approximately 7 years and for SPI < −1.5 (severe or extreme drought) is approximately 5 years in both, LB and NB. SPI calculated with

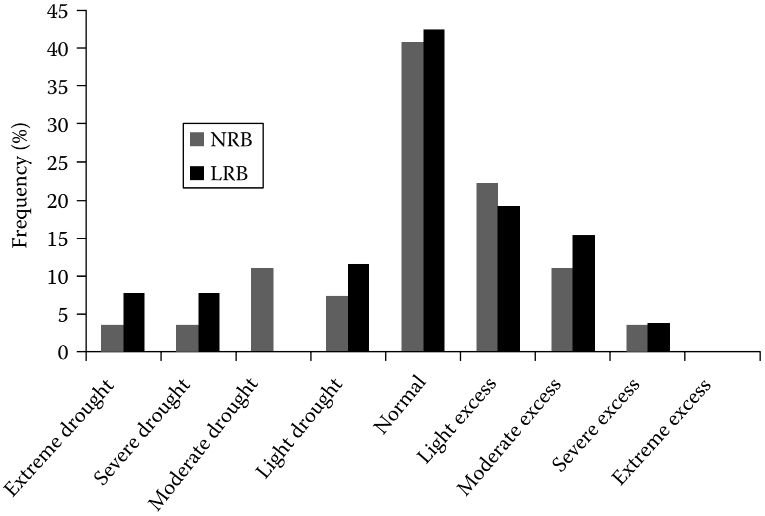

FIGURE 23.3 Percentage of different categories for Sset for the period 1980–2007 in NB (gray bars) and LB (black bars).

accumulated rainfall since April to September (Sset) is representative of the most quantity of rainfall as the annual cycle shows that winter is the typical rainfall season (Figure 23.2). Figure 23.3 shows the percentage frequency of different categories of Sset. It can be noted that there are more cases of excess than droughts: 37% of the years has excess meanwhile 25.9% has droughts in NB, and these values are 38.5% and 26.9% respectively for LB.

There is some indication that wet (dry) cases tend to occur in warm (cold) phase of ENSO. Therefore, correlation between sea surface temperature in EN34 region and SPI is 0.38 in LB and 0.37 in NB, both significant at 95% confidence level. Although better response is detected from July to February, with maximum signal in late spring (correlation of 0.47 in November in LB and 0.46 in October in NB), meanwhile no significant relation is present in autumn.

23.7 Summary and Conclusions

The natural hydrological system of the Pampean Plain and Uruguay is characterized by its fragility and its fluctuations from droughts to floods, which frequently produce negative effects on human activities. In general, anthropogenic alterations have intensified such effects, which become evident in the greater severity of droughts and floods, pollution, and decrease in freshwater reserves. Advances in the understanding of these atypical hydrological conditions have been based on the readaptation of technological tools developed for more rugged environments.

There is a deficiency in the field concerning the measurement of hydrological variables all over the countries and the development of appropriate models to simulate the involved processes.

Adequate assessment and monitoring of the hydrological processes become more important every day, not only to provide efficient water use management, but also to prevent any qualitative and quantitative alterations in the water resources of Southern South America.

As in future years a significant increase in water-related problems is foreseeable, preventive measures to avoid inadequate water use and any possibility of contamination and to foster an increase in water reserves must be taken.

To provide effective water management and promote the sustainable development of natural resources, there is a lack of basic data and in-depth knowledge of the physical medium that would make it possible to achieve a global understanding of hydrological behavior.

Risk assessment in general is hampered by lack of records as well as climate change and climatic variability.

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