Background and context of the risk analysis in the water security of the Laguna del Sauce Basin related to climatic and non-climatic factors

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South American Institute for
Resilience and Sustainability Studies

Complete document

PROJECT

Bridging the Water Adaptation Gap:
An Interdisciplinary and Transdisciplinary
Comparative Perspective on Regional Risks
and Vulnerabilities in Canada and Latin America.

OBJECTIVE 2

Identification of the main hazards, exposure,
and vulnerabilities to water security
in the Laguna del Sauce basin.

Report, 31th August 2023

Cerrando la brecha de acceso al agua
Rutas de Adaptación en Regiones Vulnerables

SARAS
South American Institute for Resilience and Sustainability Studies

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Contents

1. Introduction

This document is a contribution to the analysis of the main hazards, exposures and vulnerabilities related to water security in the Laguna del Sauce basin (Maldonado-Uruguay), conditioned by climatic and non-climatic factors. In this sense, this report represents a first stage of risk assessment. It also identifies challenges in the short, medium and long term, organized by the following components: ecosystems, users and livelihoods, primary economy, infrastructure and governance. The extent of the system, its main subsystems and key attributes, as well as the main interactions, is based on Ostrom's (2009) proposal: a common framework for analyzing the sustainability of social-ecological systems (Figure 1).

The research strategy considered three approaches: review of background information (scientific articles, books, technical reports), semi-structured interviews with key actors, discussion groups with members of the Laguna del Sauce Basin Commission and key actors from public institutions, academia and civil society organizations. There were four focus groups: economy, livelihoods, infrastructure and ecosystems. Annex 1 shows the questions and key issues that were considered as triggers for the focus groups.

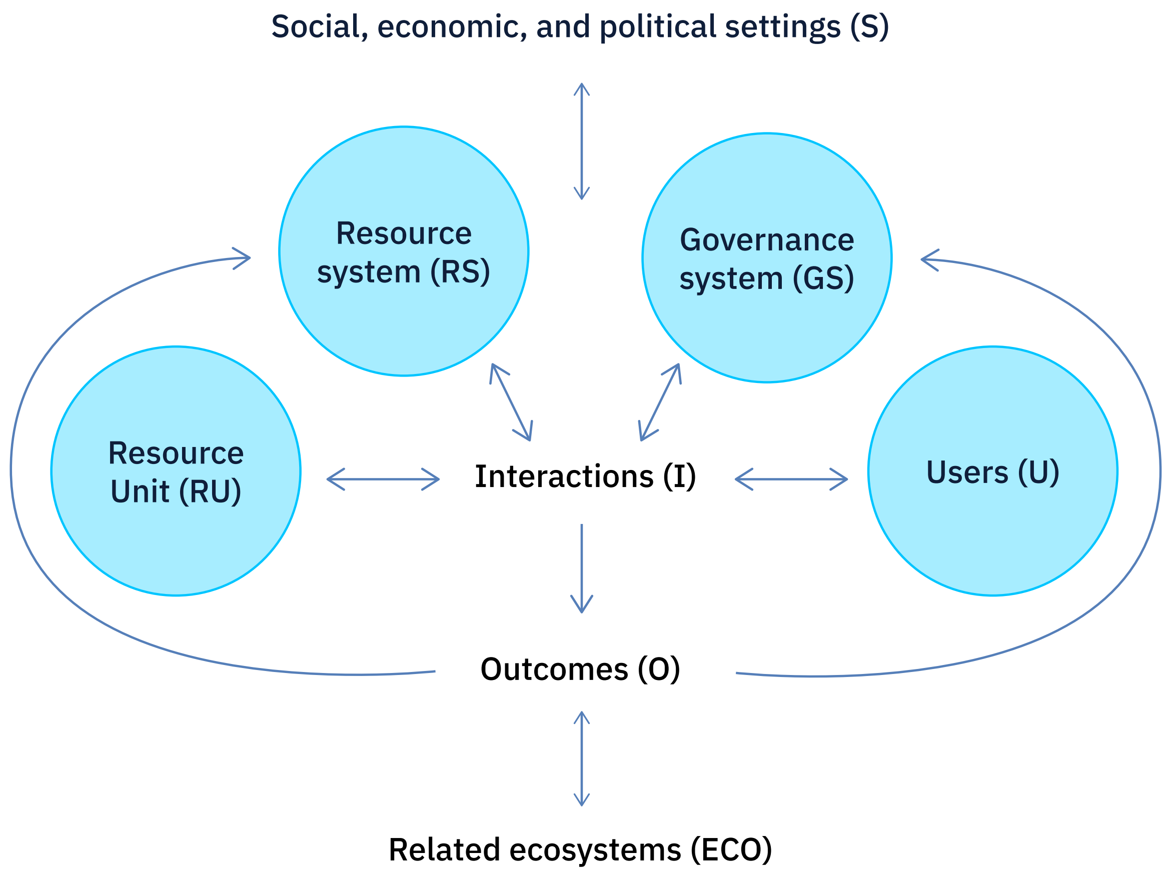


Figure 1. Subsystems and interactions considered in the analysis of social-ecological systems. Source: Ostrom (2009).

Risk is the probability of adverse consequences (impacts) to a system. Risk is the product of the interaction of *Hazards* (or Threats), Exposure and Vulnerability. A hazard may be a single factor or a combination of factors. Climate (e.g. precipitation variability) and non-climatic factors (e.g. land use change) and their interactions are considered in this document. Exposure refers to system components that may be affected by the hazard, such as the economy, livelihoods, infrastructure, and ecosystems. Finally, *vulnerability* includes the analysis of the sensitivity of the system, which depends on the anticipation and adaptive capacity built on a set of pillars and capitals (GIZ-EURAC, 2014, Figure 2).

Water security implies the provision of water that is acceptable in quantity and quality for health, production of goods and services, and livelihoods, with an acceptable level of risk (Grey and Sadoff 2010).

Finally, the spatial extent of the study area presents important challenges. The basin provides key goods and services that are used by connected areas (outside the water basin) to ensure socioeconomic development. For example, Laguna del Sauce is the second largest freshwater reservoir in the country in terms of people served, most of whom are located outside the water basin. The concept of *hydro-social territory* (Boelens et al., 2017) or *water territory* (Panez, 2019) seeks to take into account the inseparability of physical and social spaces.

Hydro-social territories are the spatially delimited imaginary and socio-environmental materializations in which people, water flows and ecosystem services, ecological relations, infrastructure, economy, legal agreements (or not), institutions and cultural practices are defined and mobilized. These territories generate processes of inclusion and exclusion, development and marginalization, and unequal distribution of benefits and harms that affect people in different ways. A hydro-social territory may or may not coincide with a basin, so there may be more than one in the same area due to juxtaposed narratives of social actors (Boelens et al., 2017). In this context, the concept of *hydro-social* cycles emerges as a way to overcome the hydrological cycle, which allows addressing the problem of access to water in a multifactorial way (e.g., legal frameworks, institutions, cultural practices) (Larsimont, 2014). The hydro-social cycle is a socio-natural process through which water and society are reciprocally constructed and reconstructed through space and time (Budds and Linton, 2018).

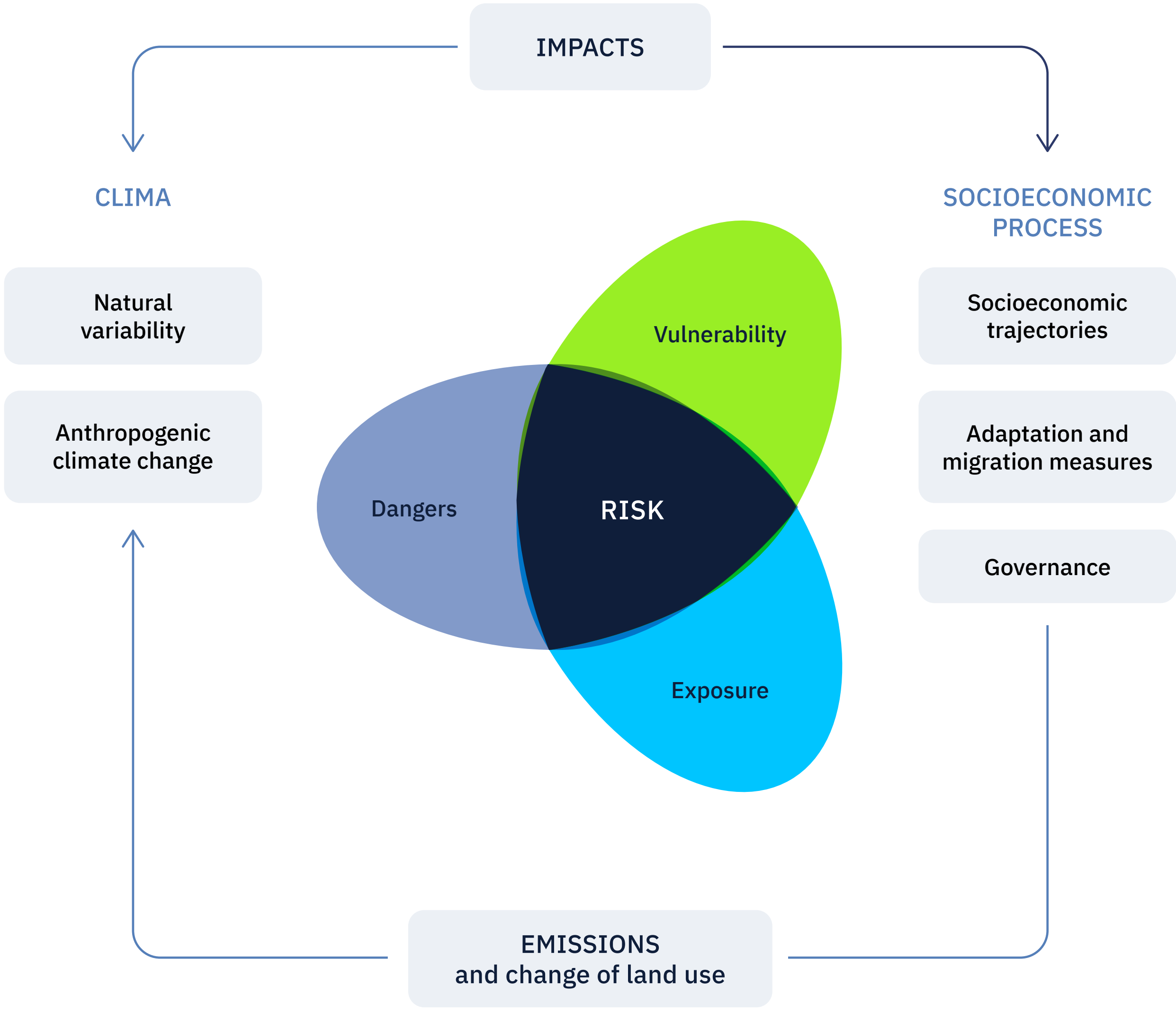


Figure 2. Outline of the basic concepts of Working Group II of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report. Source: IPCC (2014, p. 1046).

2. Laguna del Sauce Basin and hydro-social territories

2.1. GENERAL ASPECTS OF MALDONADO DEPARTMENT

The entire Laguna del Sauce water basin is located in the Department of Maldonado, Uruguay (Figure 3). The departmental capital, Maldonado, and the cities of Punta del Este and San Carlos form the second most populous metropolitan area in the country. In 2018, the population of the department comprised 163,518 inhabitants, distributed in 59,775 households. The rural population represented 2.8% (4,630 inhabitants) and was distributed in 1,823 households. With 4,793 km², Maldonado is the third smallest department in Uruguay, after Canelones and Montevideo. It ranks third behind Montevideo and Canelones in terms of population and population density (34.3 inhabitants/km²).

Population growth in Maldonado is higher than in the rest of the country, with an important component of internal migration for economic reasons linked to the demand for labor generated by tourism and related construction activities. This demographic growth explains much of the densification of the existing urban fabric and its expansion through the incorporation of previously rural land.

Of particular relevance are the population centers with a notorious population growth, such as La Capuera and El Pejerrey, adjacent to the Laguna del Sauce system. The combination of tourism development, its new neo-exclusive modalities - both in coastal, suburban and rural areas (Gadino et al., 2018) - and internal migration has conditioned an accelerated territorial segmentation (Lafourcade, 2019). Migration shows a marked polarization between the geographical areas of Punta del Este and La Capuera, Sauce de Portezuelo and Ocean Park, which is an expression of an accelerated territorial segmentation that groups migrant individuals with their own characteristics within their group and, at the same time, well differentiated between groups (Lafourcade, 2019).

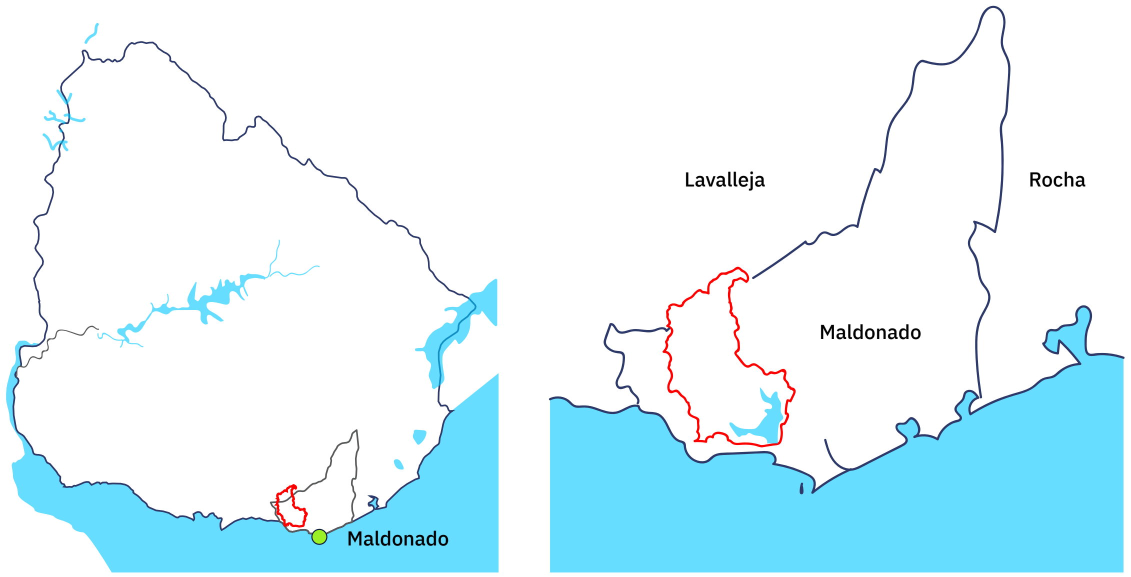


Figure 3. Geographic location of Laguna del Sauce basin

The departmental GDP represents approximately 5.5% of the national GDP, and the departmental primary sector GDP represents 1.3% of the national GDP. Tourism is an important economic activity in Uruguay due to its contribution to the balance of payments and employment generation. In 2018, tourism accounted for 8% of GDP (Altmark and Larruina, 2021). The Department of Maldonado is one of the key areas of this economic sector. According to the latest available data, tourism generates more than 40% of the department's GDP (Alonsopérez, 2009).

During the summer of 2022, Uruguay received a total of 400,000 tourists and 40% of them visited Maldonado. This means that the population of Maldonado, approximately 164,300 inhabitants (INE, 2011), was visited by 160,000 tourists, practically one tourist per resident. It is estimated that the department has 22,000 hotel rooms, which shows the importance of second homes in the destination. In 2011, according to the National Census, there were 41,815 temporary homes in Maldonado (INE, 2011). On the other hand, according to data collected by the departmental government, during the period 2012-2020, 2,731,436 m2 were constructed in Maldonado.

2.2. POPULATION AND URBAN CENTERS OF THE LAGUNA DEL SAUCE BASIN

The Laguna del Sauce basin represents 15% of the surface area of the Department of Maldonado. The urban areas in the basin represent 4.4% of the territory (3,090 ha). It is composed of six localities (Nueva Carrara, Gerona, Pan de Azúcar, Ruta 37 and 9, La Capuera and Las Cumbres), which include four municipalities (Maldonado, Pan de Azúcar, Piriápolis and San Carlos), with a total population of 10,346 inhabitants (INE, 2011). Most of the population centers are located south of the basin (Figure 4).

The most populated town is Pan de Azúcar with 6,597 inhabitants, followed by La Capuera with 2,838 inhabitants. The latter recorded the highest growth in the country between 2004 and 2011 (474%) (Table 1). The rest of the towns recorded an increase in population of 29.5% between the 2004 and 2011 censuses. This evolution is in line with the trend of sustained population growth in the department of Maldonado since the 1950s. It is important to note that data from a new national census conducted in 2023 will soon be available.

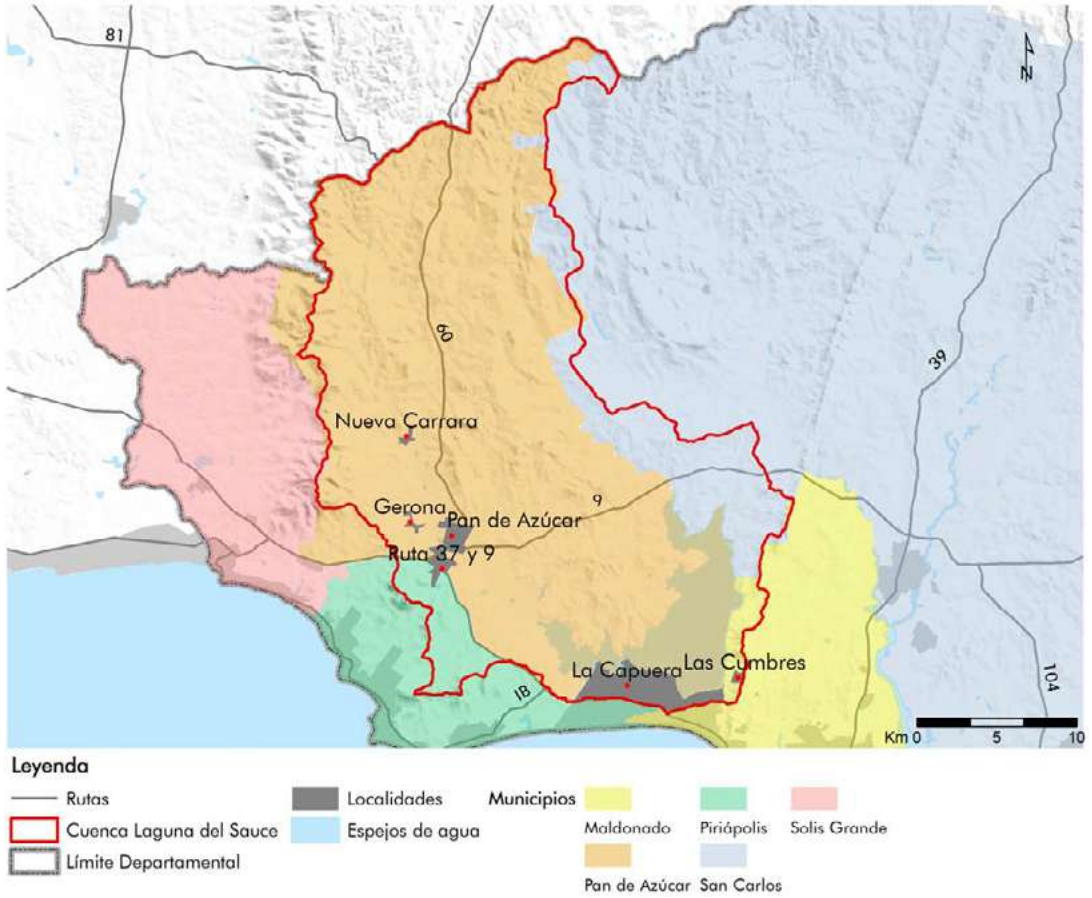


Figure 4. Localities of the Laguna del Sauce basin and municipalities with territory within the basin.

Table 1. Population and growth rate in the municipalities of the basin, 2004 and 2011 censuses.

Town	Population 2004	Population 2011	Growth rate
Pan de Ázucar	7.098	6597	-7,06
La Capuera	494	2838	474,5
Gerona	506	670	34,2
Nueva Carrara	118	156	32,2
Ruta 37 y 9	140	62	-55,7
Las Cumbres	6	14	133,3
Total	8.362	10.346	23,7

Source: National Institute of Statistics (INE).

Diversity of productive activities on the margins of Laguna del Sauce

2.3. LAND USE, COVERAGE AND PRODUCTIVE ACTIVITIES

Productive land use in the basin, according to 2018 affidavits registered by the Ministry of Livestock, Agriculture and Fisheries (MGAP), includes the following categories and associated areas (Table 2).

Table 2. Information on the land tenure system and main uses declared in the MGAP.

	Basin (ha)	Percentaje
Field owners	281	
Natural field	32.659	
Artificial forest	5.042	
Improved field	2.458	
Artificial prairies	2.608	13,5
Forage crops	841	
Fertilized field	98	
Tilled land	421	
Orchards and fruit trees	95	
Total	44.503	

The analysis of satellite images for the period 2020-2021 shows that most of the surface of the Laguna del Sauce basin corresponds to natural fields, regenerated natural fields or a combination of natural fields, pastures and stubble (62.8%), the main resource of the livestock sector. This is followed by native forest (mountain and riverine forest, 11.2%) and forestry (10.6%) (Figure 5, Table 3).

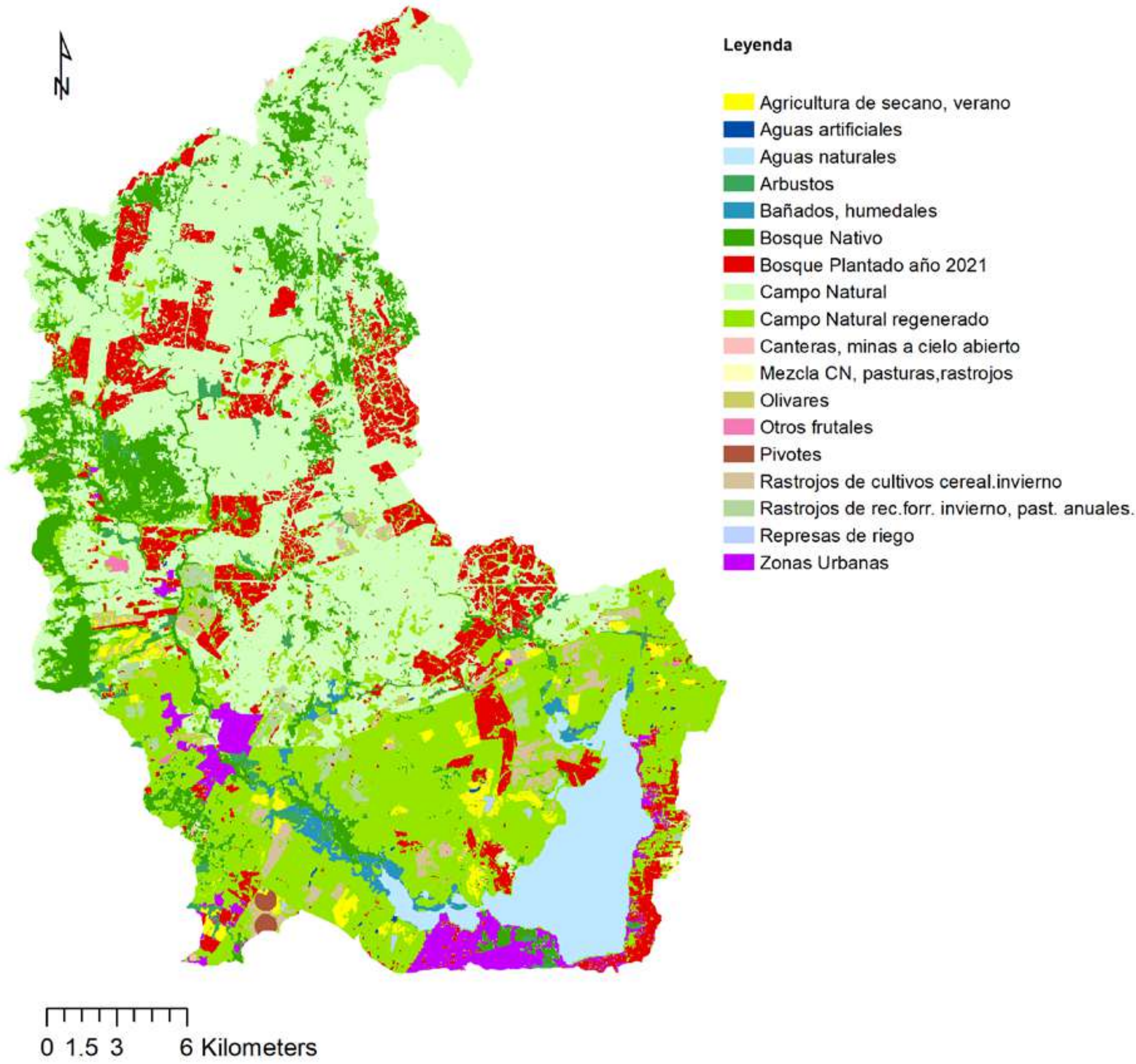


Figure 5. Major land uses detected by satellite imagery in 2020-2021. Source: MGAP 2020-2021 Land Cover and Land Use.

Table 3. Areas of major productive uses shown in Figure 3.

Land cover and land use 2020-2021	Area (ha)	Area (%)
Rainfed agriculture, summer	1.069,4	1,52
Artificial waters	45,9	0,07
Natural waters	4.144,0	5,90
Shrubs	761,5	1,08
Wetlands	728,5	1,04
Native forest	7.867,7	11,20
Planted forest in 2021	7.460,9	10,62
Natural field	26.756,2	38,09
Regenerated natural landscape	17.261,6	24,58
Quarries, open pit mines	68,3	0,10
Mixed natural grassland, pastures, stubble	64,5	0,09
Olive groves	95,1	0,14
Other fruit trees	81.2	0,12
Pivotes	127,2	0,18
Stubble of winter cereal crops	1.284,4	1,83
Stubble of winter fodder resources, annual pastures	602,5	0,86
Irrigation dams	53,7	0,08
Urban areas	1.764,0	2,51

2.3.1. LIVESTOCK

Cattle raising is the main productive activity in the basin. It is a purely cattle-breeding area (over 40% of cows breeding/stock) and has an average of 0.72 livestock units per hectare. The area has a low proportion of sheep, with a sheep/calf ratio of 0.7. This activity is carried out, in most cases, in farms smaller than 50 ha, under the extensive production mode (MGAP-SNIG, 2016). However, there are some cases of intensive production in the area (MGAP-SNIG, 2022), for example at the mouth of the Sauce stream. According to the information collected during the 34th FUCREA Economic Information Workshop, the capital income in the livestock sector is on average US$86/ha (US$25-166) per year, while the income in the same period is US$65/ha.

It should be noted that livestock production is largely developed on natural fields and regenerated pastures. The area of this land cover has not changed significantly in the last 15 years. The area of improved pastures, including artificial pastures, fertilized fields, improved fields and fodder crops for livestock, increased by 8% between 2003-04 and 2013-14. For the department of Maldonado (used as an approximation because more recent information on this indicator is not available for the specific area of the basin), the area of improved pastures increased by an additional 10% between 2013-14 and 2019-20.

As part of the livestock activity, it is common practice to build small dams and cutwaters to ensure water supply during summer or dry periods. The fodder supply, in addition to the primary production of the natural field, can come from improved or artificial pastures within the farm or from neighboring productions or other regions of the country.

2.3.2. FORESTRY

Forestry activity in the basin consists mainly of *Eucalyptus spp*. plantations for the paper industry or as an energy source. In addition, there are *Pinus* plantations (a very small area) and smaller forests related to urbanization. From the data obtained from the analysis of satellite imagery in the period 1984-2015, it can be observed that the forested area has experienced a sustained growth in the last 15 years (Taveira et al., 2018). Within the basin, the area classified as priority forest occupies 48.4%. In terms of sub-basins, the “Pan de Azúcar” stream currently has an area of 10.0% allocated to this category and the “Sauce” stream 21.96% (unpublished data, Paula Levini thesis). Table 4 provides detailed information on the activities of the forestry sector recorded by MGAP for 2018.

Table 4. Information on the different components of the forestry sector associated with MGAP records for 2018 for the Laguna del Sauce basin. Data provided by the San Carlos Regional Office.

Class	Área (ha)	Área (%)
Trees for Shade and Shelter	79	0
Natural forest	6.755	9
Eucalyptus globulus	4.706	7
Eucalyptus grandis, dunii y saligna	340	0
Mixture	1.307	2
Other eucalyptus	171	0
Pinus ellioti and *taeda*	13	0
Pinus pinaster	8	0
Total forest	14.719	20

2.3.3. AGRICULTURE

Agricultural activity has shown a sustained expansion process over time, going from occupying 1,171 ha in 2008 to 4,302 ha in 2015, representing 6.1% of the total area of the basin. The main crops are rainfed, mainly soybean, sorghum, rapeseed and wheat. The indicated growth is observed in the southern sector, very close to the water body and on soils at risk of erosion (Figure 5, Table 3).

In this sector, a very small number of producers have been identified (about five) who use irrigation systems in their production.

2.3.4. VINEYARDS AND OLIVE GROVES

In the last two decades, ventures related to olive oil and grape production have been established, occupying a relatively small area within the basin (Figure 5, Table 3) (DIEA, 2020). Olive plantations exhibit both irrigated and non-irrigated practices. The spatial distribution of production is primarily in the middle and upper basin. The spatial arrangement is strongly influenced by proximity to mills, as the time between harvest and oil production cannot exceed 24 hours.

Regarding vineyards, there is evidence of a shift in cultivation from the metropolitan area of Montevideo, Canelones, and San José towards hilly regions. This phenomenon is driven by various factors, one of which involves changes in precipitation patterns and minimum temperatures during winter. The hills and slopes enable better management of excess precipitation during rainy summers, while still achieving the necessary temperatures during winter months.

2.3.5. FAMILY FARMING

As of 2018, there were 92 registered family productive units distributed across 192 land parcels within the basin. These units involve approximately 225 individuals and cover an aggregate area of 4,583 hectares, with an average size of 50 hectares each. The primary productive activities associated with family farming are detailed in Table 5.

Table 5. Main items associated with family farming registered by the MGAP. Data provided by the Regional Office of San Carlos.

Cobertura y uso del suelo 2020-2021	Área (ha)
Dairy Farming	656
Horticulture	60
Beekeeping	34
Wool Livestock	20
Dairy	20
Agriculture	5
Poultry	4
Cheese making	4
Pigs	3
Forage	2
Fruit growing	2
Horse breeding	1
TOTAL	111

The criteria defining a family farmer include:

- Engaging in productive activities while employing up to two permanent non-family wage workers or their equivalent in seasonal wages (250/year/worker).
- Operating on an area of up to 500 hectares, CONEAT index 100, under any form of land tenure.Residir en la explotación o a menos de 50 km de distancia
- Residing either on the farm or within a distance of less than 50 km.
- Ensuring that nominal family income generated outside the farm remains below 14 bases of benefits and contributions (BPC) on average per month.

Currently, there are no productions with specific designations of origin in the basin; instead, there are those associated with organic production, agroecology, and the “Alianza del Pastizal.”

2.3.6. TOURISM

Analyzing the economic impact of tourism in Maldonado requires consideration of tourist demand, supply, employment, and tourism investment in the department. The tourist demand in the department consists of three types of tourism: inbound (residents abroad), domestic (residents in Uruguay), and cruise tourism.

Table 6. Information on visitors entering Uruguay, by destination area, duration of stay, and spending, collected by the Ministry of Tourism in the first quarter of 2023.

			Spending in USD		
Destination area	Total visitors	Duration of stay	Total USD	P/person	P/p/día
Punta del Este	343.870	10,1	393.989.762	1145,8	113,8
Colonia	101.177	2,8	21.573.551	213,2	76,2
Montevideo	188.802	6,5	101.130.770	535,6	82,2
Costa de Oro	60.871	10,6	31.044.791	510,0	48,3
Piriápolis	94.294	10,6	76.789.388	814,4	76,8
Costa de Rocha	83.767	10,7	53.909.017	643,6	59,9
Litoral termal	151.979	4,4	24.343.160	160,2	36,7
Tránsito	92.749	0,9	4.712.800	50,8	54,4
Otros - sin dato	101.689	6,9	33.146.152	326,0	47,5
Total/Media	1.219.198	7,4	740.639.391	607,5	82,6

In terms of inbound tourism, in the first quarter of 2023, Punta del Este welcomed 343,870 non-resident visitors who spent nearly 400 million dollars during an average stay of 10 days. In Piriápolis, during the same period, 94,294 non-resident visitors arrived, contributing to an expenditure of almost 77 million dollars with an average stay of 10.6 days (Ministry of Tourism, 2023).

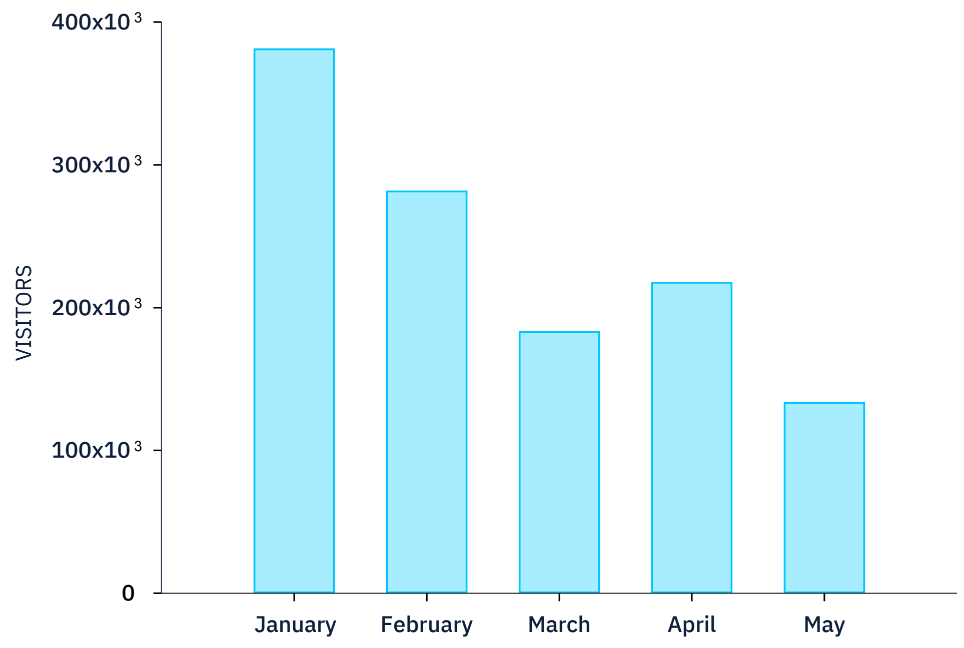


Figure 6. Information on the movement of cell phones by resident visitors in Maldonado surveyed by the Ministry of Tourism and ANTEL, first quarter of 2023.

As for domestic tourism, during the first quarter of 2023, according to data collected from the movement of residents' cell phones, the department of Maldonado hosted 845,370 visitors (Figure 6). In January alone, 380,951 resident visitors entered, with an average stay of five days (Ministry of Tourism 2023, in collaboration with Antel).

During the 2019-2020 season (latest available data), 47 cruise ships arrived at the port of Punta del Este, with 73,628 passengers disembarked and an expenditure of 2,074,161 dollars (Ministry of Tourism, 2020).

The tourism offerings in the department, as of July 2023, according to the Ministry of Tourism's Tour Operator Registry, comprise 92 travel agencies, 141 tourist accommodation establishments, 24 rural establishments, 10 tour guides, 447 real estate agencies, 7 car rental agencies, 18 convention halls, and 2 adventure tourism operators. Additionally, the role of second homes as a form of accommodation is highly significant in this destination. According to the 2011 Census, at that time, Maldonado had 41,815 temporary-use homes, representing almost

40% of the individual-category homes in the department. The concentration index of temporary-use homes in Maldonado indicates that the localities with the highest relative weight of second homes are Laguna Blanca (95), San Vicente (92), Bella Vista (83), and Las Flores (81) (Alonsopérez, 2015).

Table 6. Information on the occupancy status of individual homes in Maldonado, according to the 2011 Census.

CONDICIÓN DE OCUPACIÓN - INDIVIDUAL		
	Cantidad	Porcentaje
Ocupada con residentes presentes	57.167	51,7
Ocupada con residentes ausentes	1.448	1,3
Desocupada de uso temporal	41.815	37,8
Para alquilar o vender	4.782	4,3
En construcción o reparación	2.262	2,0
Ruinosa, destruída o inhabitable	692	,6
Desocupada vacante	2.016	1,8
Sin dato	408	,4
Total	**110.590**	**100,0**

According to data collected in the Continuous Household Survey of 2014 (the latest available data), tourism employment, considering both primary and secondary employment and taking into account nationally defined tourism-related activities, amounts to 10,464 jobs in Maldonado. If specific tourism-related activities in the department, such as construction and associated activities, and the organization of conventions and commercial events, are added, the number of jobs increases to 14,077. Therefore, following this line of analysis, the number of tourism-related jobs in Maldonado was 24,541. The total working-age population (individuals over 14 years old) in Maldonado during the same period was 84,702, and the total number of jobs amounted to 93,092. Consequently, tourism represented 26.36% of the total jobs.

Detailed information is not available to quantify tourism investment in Maldonado. According to data collected by the departmental government, between 2012 and 2020, 2,731,436 square meters were constructed in Maldonado.

2.3.7. NEW RURALITY

Since the late 1990s, a transformation of rural land use has been occurring in the department of Maldonado, including the Laguna del Sauce basin. This transformation is linked to new residential uses, either permanent or semi-permanent, by a population migrating from urban areas. This process may involve a change in land category from rural to suburban (with all the associated changes), or simply the subdivision of rural plots into units that cannot be smaller than 5 hectares, as per current regulations (Acuña et al., 2012).

A significant portion of the real estate offering comes in the form of private neighborhoods, highly sought after by segments of the population seeking and willing to pay for perimeter security, prestige, and an exclusive connection with nature. However, this pursuit often leads to a considerable transformation of the natural landscape itself (Gadino et al., 2022). Depending on the final land category, the size of the resulting new plots, and the sales strategy, the names can vary, including terms like maritime estates, estate clubs, country clubs, among others. In addition to the individual plots, these developments provide their owners with shared services and infrastructure for recreation and sports, such as a social club, sports courts, sun decks, docks, boating, etc. (Varela, 2017).

In both closed and open plot modalities, rural-oriented developments often incorporate variations, such as shared production systems (livestock, vineyards, and olive groves), with the benefits distributed among the property owners.

The factors driving these new rural modalities are manifold. Telecommuting and Uruguay's impressive telecommunications and internet infrastructure are key contributors to this transformation. Motivations related to healthier and more sustainable lifestyles, whether or not associated with exclusivity, also play a role. In this context, the COVID-19 pandemic catalyzed this process of change and brought about modifications where, akin to many other countries globally, owners of second homes relocated from cities to low-density areas (Zoğal et al., 2022).

The more rapid growth of this transformation is constrained by the education infrastructure in the territory and the current commuting requirements. However, simultaneously with this demographic change, in the Punta Ballena-Punta del Este-José Ignacio region, there is an opening—or announcements of opening—of private national and international educational institutions at all levels, including university. This type of progress in new developments with their own services, such as educational facilities, has been extensively analyzed in Argentina, a country that evidently propels such dynamics in Uruguay (Vidal Koppmann, 2014).

Quantitative information in this sector is currently very limited. Data from the 2023 Census will contribute to advancing its study, a matter of singular relevance given the magnitude of this driving force for change.

2.3.8 HYDROSOCIAL TERRITORY

All economic activities in the Laguna del Sauce basin and a significant portion of the department of Maldonado depend directly or indirectly on the supply of drinking water, goods, and services provided by the hydrographic basin. It is important to consider that the provision of drinking water for the department of Maldonado is sustained by various systems of surface water and groundwater.

The main population centers in the department of Maldonado – Piriápolis, Pan de Azúcar, San Carlos, Maldonado, and Punta del Este – depend on the water supply from Laguna del Sauce. Additionally, the supply system for the coastal region to the east of the Maldonado stream (a tourist area in full expansion) includes three lagoons: Laguna del Sauce, Laguna Blanca (Manantiales), and Laguna Escondida (José Ignacio). The systems are currently interconnected. The plants at Laguna del Sauce and Laguna Blanca operate permanently, while the one at Laguna Escondida operates during the summer season. The Laguna Blanca plant has the option of water intake from the San Carlos stream at a location near the city of the same name.

In summary, the majority of the population that relies on drinking water from Laguna del Sauce resides in territories that are not part of its hydrographic basin. Therefore, the basin scale must be combined with other territorial scales (hydro-social) in risk analysis. This aspect becomes particularly relevant for the tourism sector of the department.

3. Climatic and ecosystemic factors that influence the production of goods and services in the water basin

3.1. CLIMATIC PATTERNS AND CLIMATE VARIABILITY

According to the Köppen climate classification, Uruguay is characterized by having a "Cfa" climate type (Uruguayan Meteorological Institute [InUMET]), also known as humid subtropical. According to this classification, based on annual and monthly averages of temperature and precipitation, Uruguay exhibits a humid climate typical of middle latitudes, featuring warm summers and mild winters (the coldest month has an average temperature ranging from -3 to 18°C) (type C). Additionally, precipitation is well-distributed throughout the year, resulting in all seasons being humid, with a typical annual average between 800 and 1650 mm (type f). Finally, summers are generally long and hot (average temperature of the warmest month exceeding 22°C) (type a) (Prohaska, 1976).

3.1.1. GENERAL CLIMATE CHARACTERISTICS OF THE COUNTRY

Temperature

According to the climatology developed by Inumet for the period 1981-2010, Uruguay has an average annual temperature of 17.5°C (InUMET). The lack of significant topography in the territory results in a pattern of isotherms determined primarily by solar radiation, roughly parallel to the circles of latitude (Barreiro et al., 2019a). This overall isotherm pattern indicates a decreasing temperature gradient from northwest to southeast, with the highest isolines in the northern part of the country and the lowest along the southern/southeastern Atlantic coast. On average, the northern region is approximately 3°C warmer than the southern region (InUMET). During the fall and winter seasons, the gradient takes on a north-south direction, with lower temperature values shifting towards the west, and the lowest temperatures occurring in the southern part of the country (Río de la Plata coast) (Figure 7).

This variable is characterized by a pronounced seasonal variation and interannual variability that is highest during winter. The highest mean values (23.4°C) occur during summer (December, January, and February), while the lowest (12.3°C) occur during winter (June, July, and August). On average, July is the coldest month in the country and the one with the greatest variability. During autumn (March, April, and May), March has the highest mean temperature, with a clear decrease as the season progresses, marking the transition between summer and winter. Lastly, spring (September, October, and November) exhibits significant interannual variability, with, on average, approximately one out of every two years having mean records outside the standard deviation (InUMET). The spatial heterogeneity of temperature is depicted in Figure 7. Table 7 provides detailed information on mean temperatures for each season, as well as the absolute maximum and minimum temperatures recorded in each season.

Table 7. Annual and seasonal mean temperature (summer, autumn, winter, and spring) for the entire national territory, and absolute maximum and minimum mean temperatures for each temporal scale: https://www.inumet.gub.uy/clima/climatologia-estacional

	T media	T máx. media	T mín. media
Annual	17,5°C	19,0°C	16,0°C
Summer	23,4°C	29,2°C	17,6°C
Autumn	18,3°C	23,4°C	13,2°C
Winter	12,3°C	17,1°C	7,5°C
Spring	17,5°C	18,2°C	16,9°C

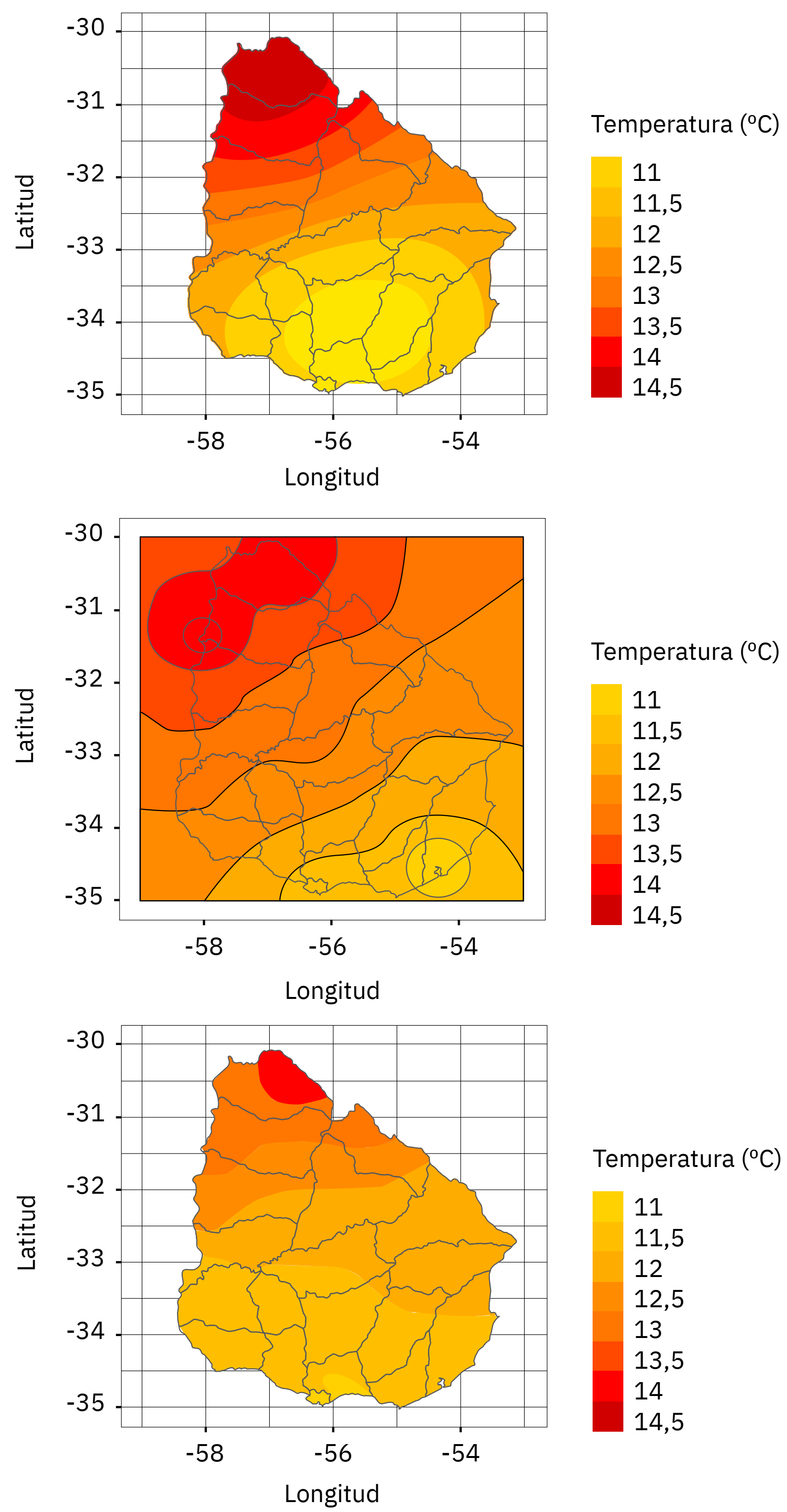


Figure 7. Seasonal mean temperature [°C] for Uruguay, based on the climatology of 1981-2010. Summer (top left), autumn (top right), winter (bottom). Source: Images generated by the Uruguayan Meteorological Institute, from: https://www.inumet.gub.uy/clima/climatologia-estacional.

Regarding interannual variability at the national level, one of the main sources is the El Niño-Southern Oscillation (ENSO) phenomenon. While no significant impacts are observed in general, it has been noted that during La Niña years, higher maximum temperatures can be detected throughout the country in the summer, and lower maximum temperatures in the northern part of the country during El Niño years (Barreiro et al., 2019b).

Precipitation

Precipitation is characterized by spatial irregularity and variability, primarily in liquid form, with occasional occurrences in the form of hail (InUMET). Throughout the year, the country experiences a positive balance of precipitation-evaporation, indicating that there is more rainfall than evaporation, except during the summer when the opposite occurs. This highlights the need for lateral moisture transport to Uruguayan territory for precipitation to take place. Precipitation exhibits a marked regionalization of accumulated values, with a distribution of rainfall during spring, summer, and autumn showing an average increase from the south/southwest (around 300 mm) towards the north/northeast (peaking at 400 mm) (Figure 8). During winter, this latitudinal gradient (south-north) transforms into a longitudinal gradient (west-east), with higher values (and greater variability) on the eastern coast and lower values (and lesser variability) on the western coast, averaging 300 mm and 200 mm, respectively (InUMET; Barreiro et al., 2019a).

The average annual precipitation is approximately 1300 mm, typically evenly distributed across the four seasons with values around 300-350 mm per quarter, although there are significant differences between quarters and regions of the country (Barreiro et al., 2019a). Regarding intra-seasonal variability, the months of February, April, June, and October stand out, with, on average, higher precipitation accumulations nationwide for the summer, autumn, winter, and spring seasons, respectively. In the case of spring, the mean behavior is almost uniform, with minimal differences between the constituent months (InUMET). Table 8 summarizes the seasonal variability of precipitation, detailing the mean seasonal value and its range of variability (determined by the difference between the absolute maximum and minimum over the period).

Table 8. Mean precipitation (PP) and seasonal variability range (summer, autumn, winter, and spring) for the entire national territory. Source: https://www.inumet.gub.uy/clima/climatologia-estacional

	PP media	Rango de variabilidad
Summer	346 ± 130 mm	521,6 mm
Autumn	365 ± 134 mm	583,7 mm
Winter	256 ± 72 mm	298,6 mm
Spring	329 ± 108 mm	424,7 mm

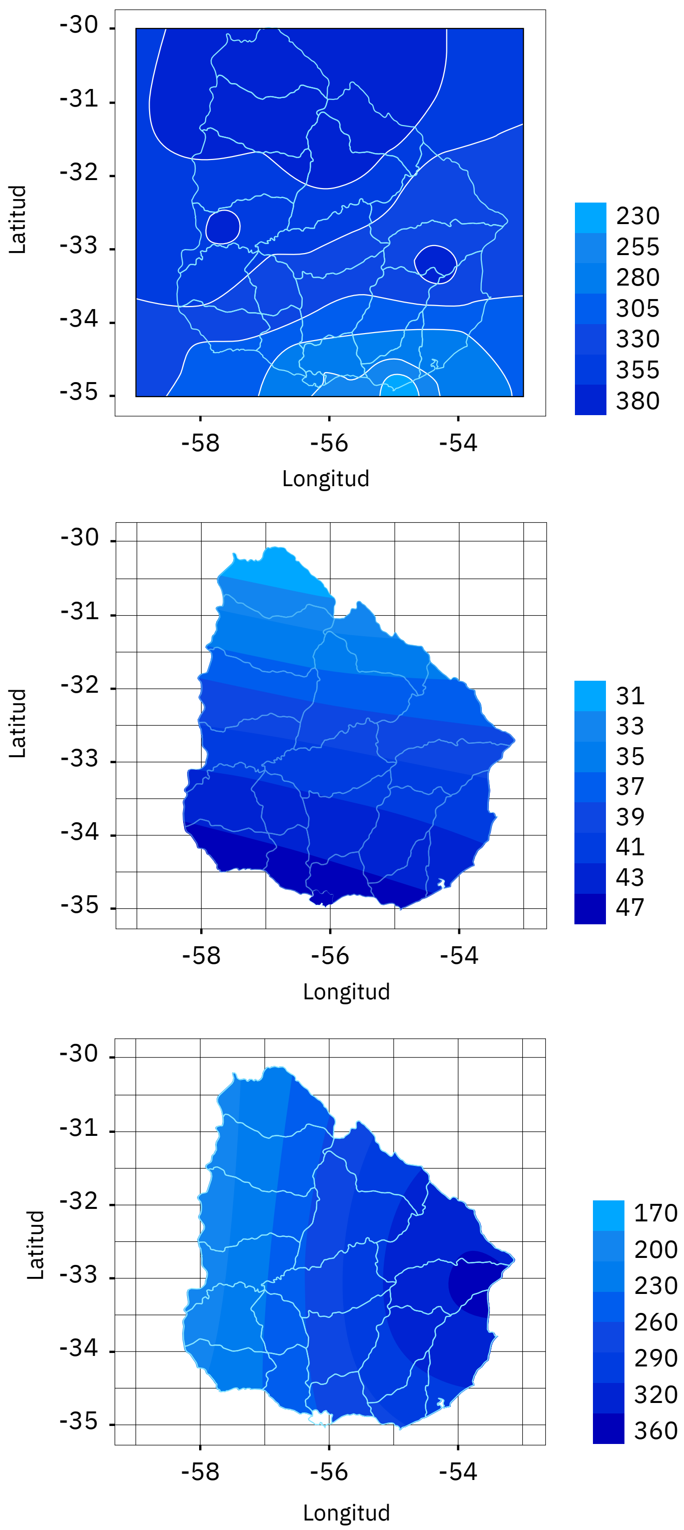


Figure 8. Mean accumulated precipitation [mm] for Uruguay, based on climatology 1981-2010. Summer (upper left), autumn (upper right), winter (lower). Source: Images generated by the Uruguayan Meteorological Institute, from: [https://www.inumet.gub.uy/clima/climatologia-estacional.](https://www.inumet.gub.uy/clima/climatologia-estacional)

Precipitation shows significant interannual variability, with greater variability in the northern part of the country than in the south. Furthermore, the variability tends to be lower during winter across the entire country but increases during autumn, especially in the Uruguay River basin (InUMET; Barreiro et al., 2019a). Much of this interannual variability is related to the El Niño-Southern Oscillation (ENSO) phenomenon, which impacts not only monthly and quarterly totals but also the frequency and intensity of extreme daily rainfall events. El Niño years are characterized by above-average rainfall, primarily in the northern regions, during spring, summer, and autumn, with a more pronounced effect in the summer. This is attributed to increased north-northeast winds during El Niño, transporting moisture to the country and promoting precipitation (Barreiro et al., 2019b). Conversely, La Niña years entail a deficiency in rainfall across the entire territory during the spring, summer, and autumn seasons.

Wind

The wind climate in Uruguay is influenced by regional meteorological phenomena, which, in turn, contribute to the average conditions and variations in temperature and precipitation (Barreiro et al., 2021b). This field of average winds is heavily dependent on the position of the semi-permanent South Atlantic anticyclone, which exhibits seasonal variations (southward displacement in summer and northward displacement in winter) (Barreiro et al., 2019a). Winds from the northeast to east sectors prevail significantly, with average speeds of 4 m/s and a mean maximum of 7 m/s along the southwest coast (Figure 9). Winds exceeding 30 m/s are relatively common (InUMET).

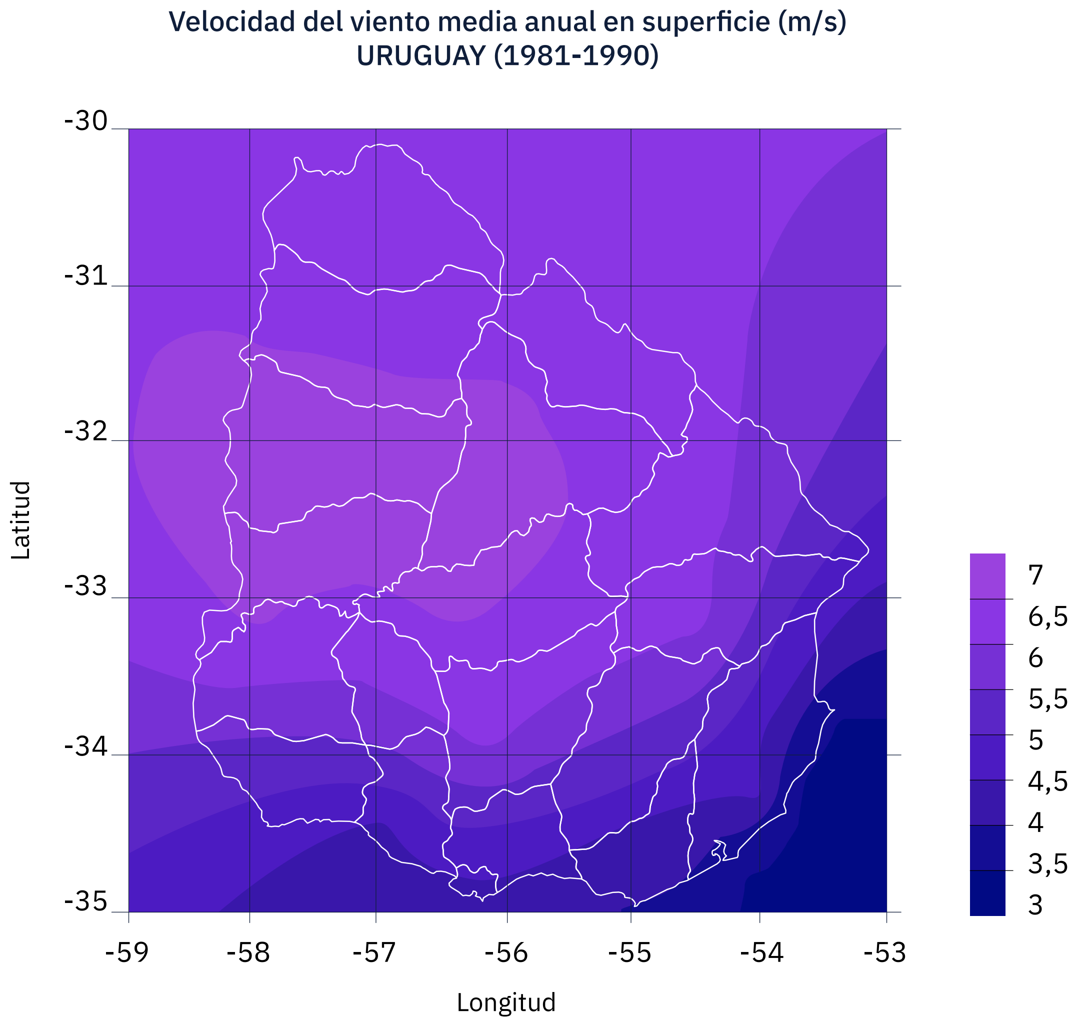


Figure 9. Annual average surface wind speed [m/s] for Uruguay, based on the climatology of 1961-1990. Source: Image generated by the Instituto Uruguayo de Meteorología, from: www.inumet.gub.uy/clima/estadisticas-climatologicas/caracteristicas-climaticas.

During the summer, the winds are primarily from the northeast and relatively intense, while during the autumn, they maintain a north component but are weaker. In winter, the semi-permanent anticyclone enters the continent, generating winds with an east to north component and west to south in the country, with a marked increase in intensity. Finally, during the spring, the average winds are mainly from the east and relatively weak. These seasonal average winds result from the daily average of winds that have different directions and intensities. The daily variation in the predominant wind direction is greater during winter (Barreiro et al., 2021a).

Intense winds in the country are associated with mesoscale phenomena (convective complexes) and extratropical cyclones. During severe storms, strong winds can reach speeds of 200 km/h for a few minutes, causing considerable damage in their path. Uruguay is one of the major regions for the formation of extratropical cyclones in South America, which typically then move southeast and intensify over the Atlantic Ocean (Barreiro et al., 2021b). During extratropical cyclones (with typical scales of hundreds of kilometers, larger than storms), sustained wind speeds can reach up to 100 km/h in extreme cases, with gusts that may be higher in coastal areas (Barreiro et al., 2021a). Additionally, cyclone formation plays a significant role in rainfall occurrences in the country, primarily in winter but also in spring (Barreiro et al., 2019a).

In Uruguay, cold fronts pass through the country throughout the year. On average, there are about ten during the summer and twelve during the winter, with a typical translation direction from southwest to northeast and often associated with a low-pressure center located in the Atlantic Ocean. Cold fronts can bring rain, storms, and strong east-southeast winds, commonly known as “sudestadas” (Barreiro et al., 2021b).

3.1.2. REGIONAL CLIMATIC CHARACTERISTICS NORTH/SOUTH

The climatic characteristics described so far apply to the entire national territory. Using the Rio Negro as a reference, two regions can be defined: north and south. We will focus on the southern region, where the Laguna del Sauce basin is located (figure 1).

As expected, due to the latitudinal gradient and variation in solar radiation incidence, the temperature in the southern region is lower in all quarters compared to the northern region (with an average difference of 1.4 °C). Precipitation is also lower in the southern region compared to the northern region (with an average difference of 66 mm), except during winter when it is higher south of the Rio Negro.

The average temperature during the summer is 22.6 °C, and the average cumulative precipitation is 311 mm, with a variability range of 203.3 mm. The predominant wind comes from the east, typically more intense in the late afternoon in the coastal region. During this season, an intensification of north winds bringing warm and humid air from southern Brazil and Paraguay is also observed (Barreiro et al., 2021b). In the fall, the average temperature for the southern region of the country is 17.8 °C, with precipitation of 332.8 mm. In winter, the average temperature is 11.7 °C, and the average precipitation is 263.1 mm; this is the only case where precipitation is higher than in the northern region (247.3 mm). Regarding the wind, during winter, the west component of the wind becomes more important in the southern region of the country. Finally, in spring, the average temperature is 16.5 °C, with an average precipitation of 305.9 mm (InUMET).

Defining strong winds as those with gusts exceeding 80 km/h, a threshold velocity beyond which damage begins to be reported (Durañona et al., 2016), it is reported that most events occur between October and February, with prevailing winds from the south-southwest (in line with the typical direction of front passage). However, in the south and east of the country, they are particularly more frequent during October and November (Barreiro et al., 2021a).

Local Hydroclimate of the basin

Regarding the specific region of the Laguna del Sauce basin, the monthly flow behavior in the Pan de Azúcar sub-basin is analyzed (Figure 10). This sub-basin has a total area of 318 km² and represents approximately 45% of the entire basin (709 km²). It contains the Pan de Azúcar stream, which flows through the western part of the basin from north to south and is one of the main tributaries of Laguna del Sauce. Figure 11 shows that the mean seasonal cycle of runoff is flat (average in red), indicating very little seasonal amplitude, consistent with the annual precipitation cycle. However, both the specific flow at 80% (q80, magenta dashed line with triangles) and the minimum (blue dashed line) are an order of magnitude lower during the summer compared to the winter, showing a typical feature of low water levels in dry years.

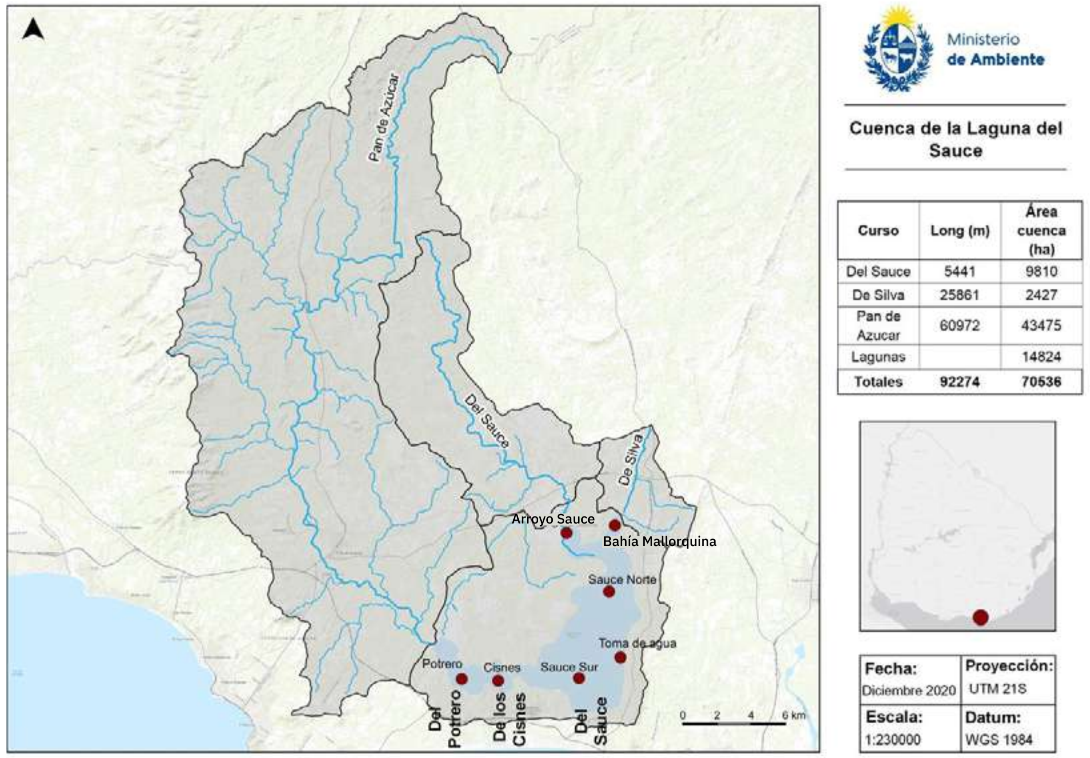
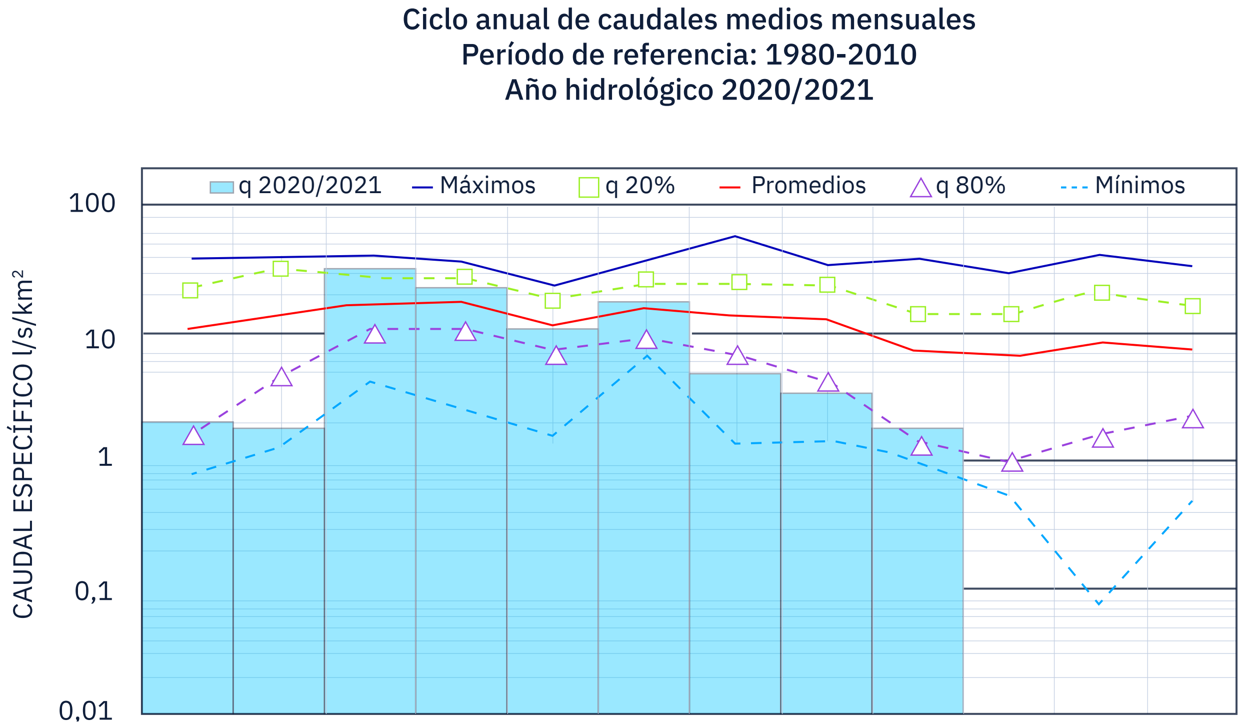


Figure 10. Basin of Laguna del Sauce and its respective sub-basins: Pan de Azúcar, Del Sauce, De Silva and the lagoons. The red dots on the map indicate water quality sampling stations. Source: Ministry of the Environment.



1980-2010													
cm	ABR	MAY	JUN	JUL	AGO	SET	OCT	NOV	DIC	ENE	FEB	MAR	ANUAL
cm	3.68	4.53	5.46	5.59	3.68	5.14	4.39	4.04	2.3	2.07	2.71	2.48	4.09
cm MIN	0.24	0.44	1.35	0.89	0.52	2.2	0.43	0.45	0.32	0.17	0.02	0.17	0.17
cm MÁX	12.38	11.86	12.91	11.42	7.61	12.06	18.66	10.85	12.13	9.39	13.18	10.76	18.66
cm 20%	7.12	10.28	8.8	8.78	5.9	8.29	8	7.72	4.37	4.59	6.88	5.29	
cm 80%	0.51	1.55	3.47	3.55	2.34	2.95	2.2	1.37	0.44	0.33	0.52	0.72	

Figure 11. Annual cycle of monthly mean flows of the Pan de Azúcar sub-basin (No. 29514), Maldonado. Source: Ministry of the Environment-DINAGUA.

In recent decades, the lowest water levels (below -0.4 m) of the Laguna del Sauce were observed in 2000, 2009, 2011, 2015 and 2016. We now add 2023, which is not included in the series, but which reached a level lower than -0.4m. During the same period, exceptional levels (above +1.5m) were recorded in 2010, 2014, 2016 and 2017. The last event caused several damages due to the flooding of houses on different margins of the Laguna del Sauce system and various controversies in the management of the reservoir level (Figure 12).

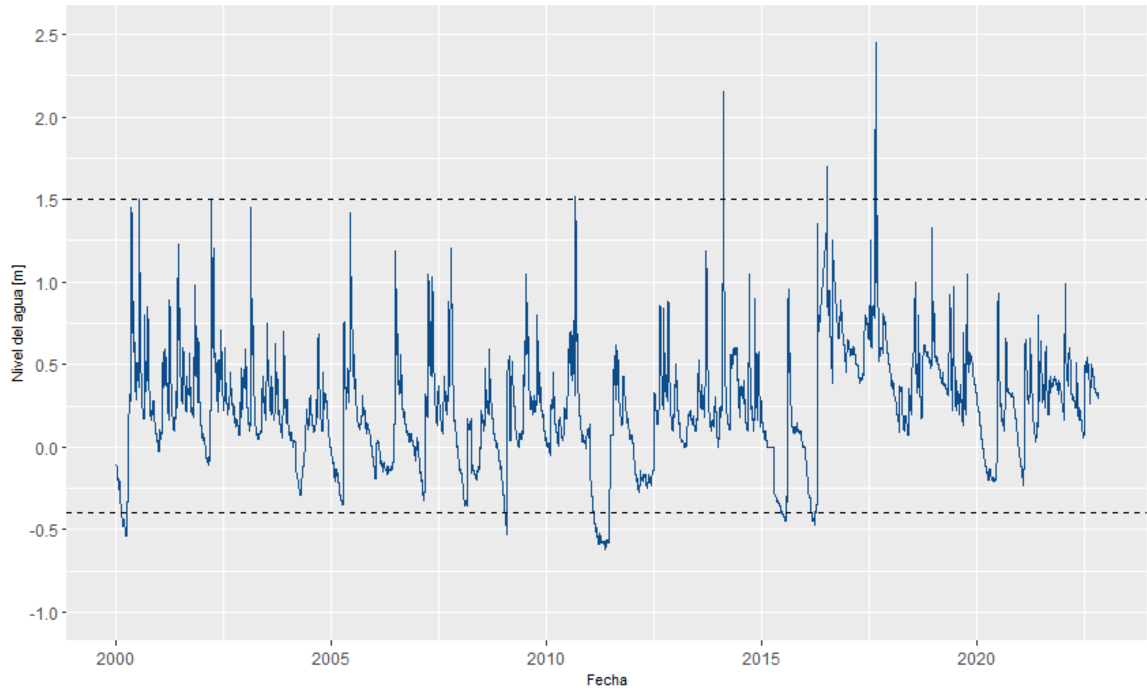


Figure 12. Water level variation of Laguna del Sauce in the period 2000-2022. The dotted lines indicate high (+1.5m) and low (-0.4m) water levels. 0 = +6.01 Warthon

3.2. LAGUNA DEL SAUCE

Laguna del Sauce is a complex of interconnected shallow systems (Figure 10). During the Holocene, the system was part of bays and coastal ecosystems, depending on sea level variations. According to paleontological information, during dry and cold periods of the Holocene it was restricted to flowing watercourses, streams and gullies (Mazzeo et al. 2010a). Darwin's descriptions of this system allow us to recognize an important evolution of the dune system in the southern sector, which obstructed the drainage of the basin. The natural dynamics of the system depended on the opening and closing of the sand bar, which occurred over periods of several years, depending on the accumulation of water and storms. In summary, Laguna del Sauce was a coastal lagoon connected to the sea. Since the end of the 19th century, the dune system has been stabilized by *Pinus pinaster* plantations.

Laguna del Sauce was dammed in 1946, an action linked to the installation of a U.S. Naval Air Base for seaplane operations. The dam regulates the variation of the water level of the system by overflow and has cement partitions 50 cm high that allow the storage of water above level 0 (+6.01 Warthon). The volume stored by the management of the partitions represents the consumption of drinking water for the month of January, the main period of tourist activity.

Laguna del Sauce is a system with significant nitrogen and phosphorus content (characteristic of systems classified as eutrophic or hypereutrophic) (Table 9), with recurrent algal blooms in the main body of the system (where the raw water intake is located) and excessive growth of aquatic plants in the Laguna del Potrero sector (Gónzalez-Madina et al., 2018, 2021; Mazzeo et al., 2010a; Rodríguez et al. 2010). Eutrophication is a process of nutrient enrichment (nitrogen and phosphorus of anthropogenic and/or natural origin) that causes an increase in the production and biomass of primary producers: cyanobacteria, microalgae and/or aquatic plants (Mazzeo et al., 2010b).

Aerial view of the Laguna Potrero, Laguna del Cisne and Laguna del Sauce systems (background).

Table 9. Main physical and chemical characteristics of Laguna del Sauce, 2015-2023

	2015-2016 (15)	2016-2017 (18)	2017-2018 (19)	2018-2019 (22)	2019-2020 (23)	2020-2021 (21)	2021-2022 (26)	2022-2023 (21)	Temporal CV
Temp	24.04 (19.73; 27.65) 0.9	24.22 (20.56; 28.51) 1.5	23.38 (18.32; 27.17) 0.76	22.51 (16.31; 27.82) 0.64	22.25 (16.49; 27.42) 1.17	23.11 (19.75; 27.68) 1.20	21.79 (12.74; 26.69) 0.67	23.8 (15.08; 28.25) 11,50	3,82
Cond	0.18 (0.15; 0.27) 12.18	0.15 (0.13; 0.20) 11.67	0.16 (0.11; 0.21) 9.1	0.14 (0.08; 0.211) 10.1	0.16 (0.12; 0.23) 14.43	0.15 (0.09; 0.24) 12.64	0.16 (0.11; 0.25) 5.66	0.203 (0.178; 0.25) 7,81	12,24
Alc				50.62 (18; 90) 16.33	59.45 (42; 92) 19.43	47.68 (30; 94) 24.70	53.68 (34; 94) 10.64	61.38 (40; 90) 16,02	10,61
pH	7.71 (6.95; 8.94) 2.57	7.47 (6.73; 8.52) 1.61	8.08 (6.29; 9.02) 1.22	7.31 (6.18; 8.18) 2.83	7.46 (6.53; 9.15) 3.53	7.5 (6.22; 8.59) 1.49	7.59 (6.02; 8.53) 3.04	7.16 (6.04; 9.24) 7,80	3,66
Turb	14.27 (1.28; 47.15) 41:31	19.45 (3.82; 38.47) 36.63	12.9 (3.84; 26.14) 24.4	12.09 (2.44; 29.11) 21.06	13.3 (0.82; 48.52) 19.88	15.39 (2.08; 43.86) 38.72	12.55 (2.68; 42.79) 21.38	20.2 (3.98; 67.83) 49,04	20,95
Real C.				167.81 (69; 385) 4.7	116.27 (17; 260) 11.13	182.33 (61; 375) 13.51	172.85 (44; 315) 2.52	178.69 (70; 331) 39,10	16,52
Transp	78.30 (30; 200) 35.32	19.45 (3.82; 38.47) 36.63	80.2 (45; 130) 15.26	91.63 (45; 190) 11.46	89.33 (26; 250) 15.89	89.82 (30; 210) 19.54	80.69 (30; 180) 10.21	64.31 (25; 160) 39,90	13,69
Chlo a	8.34 (2.97; 33.36) 34.2	5.91 (1.06; 19.45) 32.35	5.56 (0; 16.64) 18.46	6.12 (3.32; 13.94) 4.21	8.93 (0.73; 64.78) 27.41	5.65 (1.98; 12.62) 11.55	5.38 (2.66; 30.31) 7.57	3.4 (0.2; 9.1) 47,79	28,34
Phyco	3830.15 (809.75; 26116.20 46.95	2113.27 (823.33; 14775) 61.6	2079.86 (804.2; 9369.11) 21.74	2217 (1001.67; 14543) 16.26	9150.75 (1053; 64579) 44.37	1976.22 (629.5; 3475) 6.49	2080.31 (4.82; 9307.4) 15.61	5901.44 (843.78; 67594) 180,40	70,99
TP	79.06 (24.22; 161.61) 16.42	87.99 (41.10; 118.49) 7.68	72.19 (16.74; 178.53) 4.13	65.91 (17.58; 175.16) 5.48	40.61(7.49; 97.17) 14.92	60.59 (16.46; 140.22) 7.93	73.90 (18.49; 142.65) 14.12	71.18 (19.46; 179.97) 41,51	20,42
SRP	25.64 (0.24; 80.19) 29.7	87.99 (41.10; 118.49) 7.68	44.94 (0.85; 93.26) 3.40	38.75 (2.23; 85.44) 6.01	9.46 (0; 46.84) 30.33	31.79 (0.28; 79.99) 22.74	49.31 (3.89; 98.44) 19,58	35.63 (0; 108.43) 65,76	38,63
TN	714.26 (433.81; 1362.41) 18.71	519.94 (286.40; 945.90) 3.49	199.55 (87.26; 530.35) 5.74	381.88 (102.70; 711.07) 2.47	511.09 (159.46; 1422.27) 6.73	406.56 (183.59; 1384.01) 2.95	417.29 (182.87; 916.37) 4.26	451.75 (223.23; 880.86) 25,52	32,38
NO_3	173.95 (100.21; 286.76) 11.03	257.26 (104.13; 569.56) 21.03	70.28 (6.25; 223.21) 10.07	95.30 (1.36; 342.90) 13.76	172.96 (10.58; 361.08) 7.16	185. 86 (7.29; 727.92) 11.97	226.6 (45.75; 417;05) 2.95	310.65 (201.73; 529.9) 28,60	42,58
NH_4	106.81 (5.92; 843.20) 32.16	41.78 (5.02; 149.55) 21.99	20.70 (0; 162.24) 39.86	16.37 (0; 62.97) 18.56	23.97 (0; 135;52) 28.85	21.79 (0.29; 172.55) 37.46	20.68 (0; 93.01) 15.65	22.35 (0; 131.68) 80,68	88,22
N:P	9.91 (4.23; 27.82) 9.51	6.0 (2.84; 11.40) 10.99	3.03 (0.68; 13.32) 6.73	16.37 (0; 62.97) 18.56	14.41 (2.54; 77.51) 17.12	7.98 (2.41; 20;74) 6.95	6.40 (2.27; 21.15) 12.16	7.13 (2.6; 20.39) 38,15	42,98
Nivel	-0.1 (-0.46; 1.35)	0.55 (0.39; 0.73)	0.33 (0.07; 0.75)	0.56 (0.32; 1.25)	0.08 (-0.2; 0.56)	0.18 (-0.2; 0.62)	0.37 (0.17; 0.7)	0.11 (-0.3; 0.35)	

Paleolimnological information confirms the occurrence of an accelerated eutrophication process in the last century, resulting from the damming of the El Potrero stream in 1946, land use changes, and the climatic conditions of the last 150 years (Mazzeo et al., 2010a). The analysis of the phosphorus content of the surface sediments of Laguna del Sauce shows a three- to fivefold increase in the last decade, a pattern consistent with the above paleolimnological information (unpublished data).

The increase of nutrients in the Laguna del Sauce is due to several current factors and its recent evolution, among which the following stand out: absence or partial coverage of sanitation systems in the populated centers of the basin; poor fertilization practices in agriculture; livestock overpopulation and excretions directly on the water body and its main tributaries; fragmentation or elimination of buffer zones such as wetlands and coastal zones (coastal or native forest). Damming has favored the trapping of sediments and nutrients in the system, which is clearly reflected in paleolimnological analyses.

Phytoplankton growth is controlled by a number of resources (Figure 13), principally nutrients and the availability of light in the water column (water transparency), and by several processes that condition the loss or removal of biomass, such as herbivory by zooplankton or mussels, sedimentation, and export of biomass from the system by flushing associated with major precipitation events. Water residence time controls several key processes, particularly the export and removal of biomass by primary producers and the dilution or concentration of nutrients. During periods of water deficit, the shallower the reservoir depth, the greater the likelihood of sediment resuspension (for a given wind intensity, resuspension is greater at shallower depths in the water column). Cyanobacterial blooms occur preferentially under conditions of elevated water temperature, moderate and high nutrient content, and long water residence time (Dolman et al., 2012; Havens and Paerl, 2015).

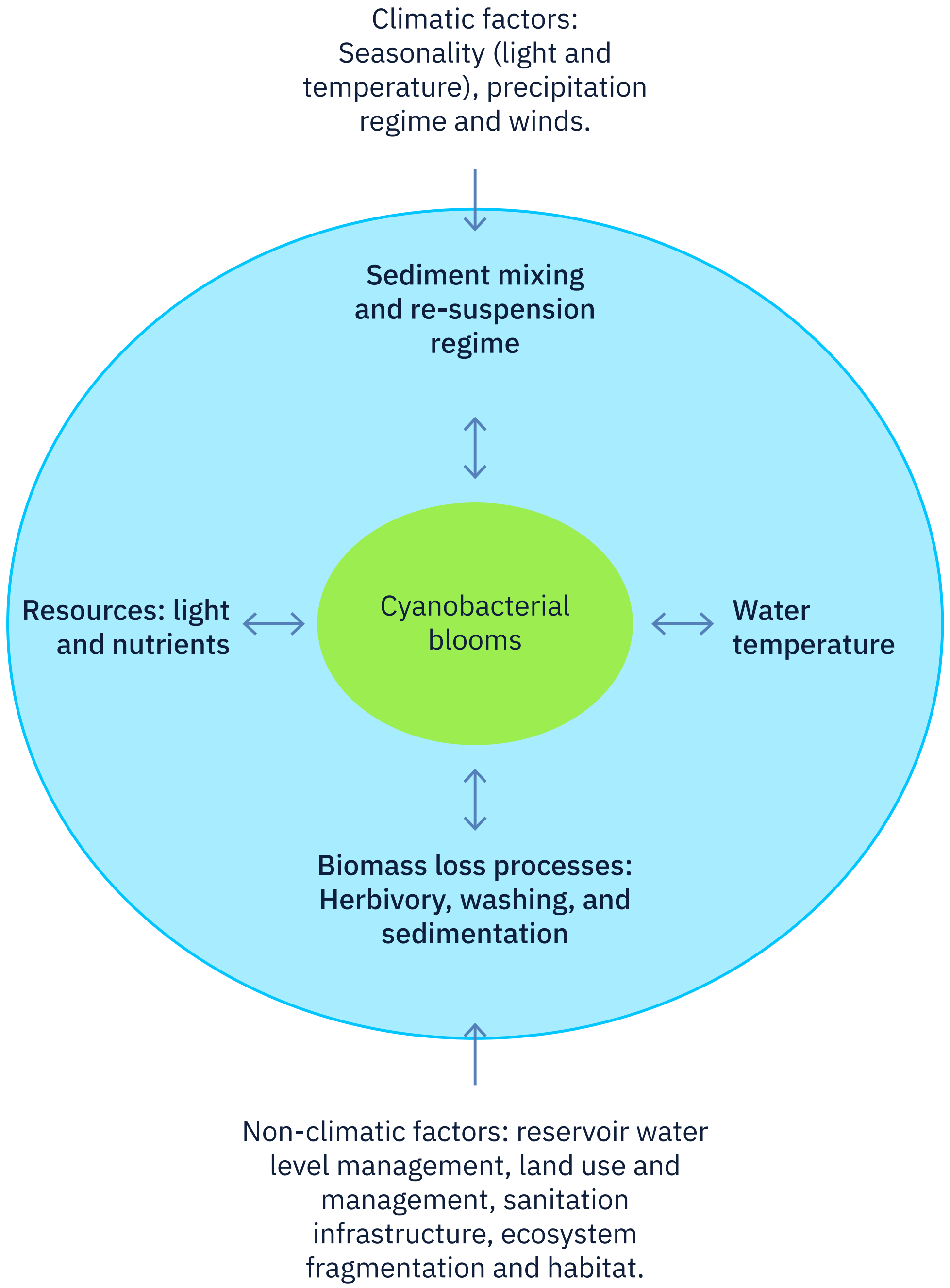


Figure 13. Major factors that directly or indirectly control algal biomass and cianobacterias and of Cyanobacteria in Laguna del Sauce (phytoplankton).

Eutrophication processes have several positive feedback mechanisms (Scheffer and Carpenter, 2003). Nutrients promote increased primary production (phytoplankton or aquatic plants) and the accumulation of organic matter, which can create hypoxic and anoxic conditions in the sediment through decomposition processes. The absence of oxygen favors the release of phosphorus, a phenomenon that occurs in advanced stages of the eutrophication process and ensures the supply of nutrients. On the other hand, the increased development of phytoplankton reduces the transparency of the water and increases the daily variation of the oxygen concentration. Both factors reduce the abundance of piscivorous fish (top predators) and thus (indirectly through so-called trophic cascade interactions) the herbivory pressure of zooplankton on phytoplankton. In short, in eutrophication processes, the effects on water quality are amplified by the above-mentioned feedbacks.

The temporal dynamics of algal and cyanobacterial blooms in Laguna del Sauce are strongly linked to the variability of water turbidity and color, that is, to the availability of light in the water column (Crisci et al., 2017; González-Madina et al., 2018, 2021) (Figure 14).

Turbidity in this system is controlled by the interaction of wind dynamics (mainly extreme events from the southern quadrant), rainfall regime and extreme precipitation events, reservoir level, and their effects on sediment resuspension. The same controls condition the variability of water color, fundamentally associated with the contributions of dissolved organic matter from the wetlands and terrestrial ecosystems of the basin. In both limnological attributes, there is significant interannual variability and no characteristic seasonal pattern.

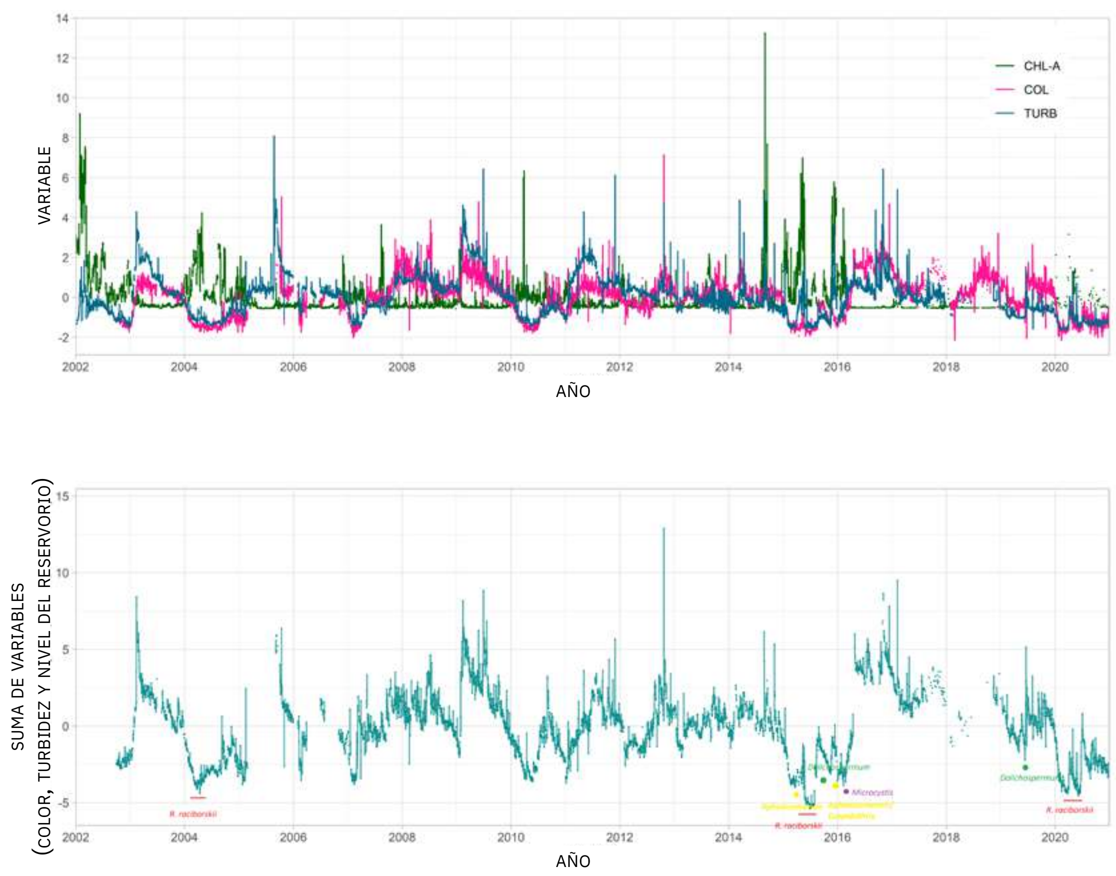


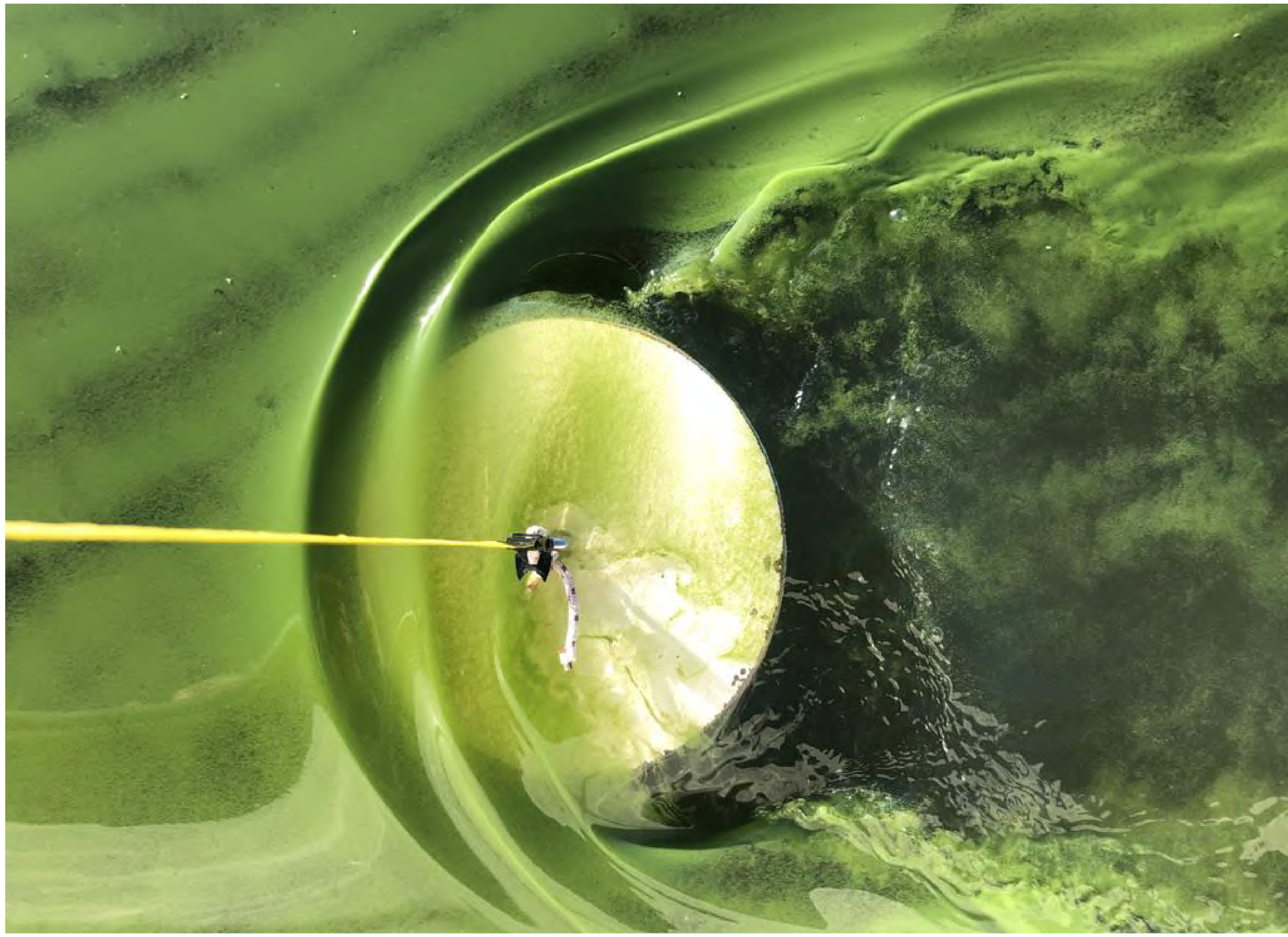
Figure 14. Temporal variation of chlorophyll a (Chla) in the Laguna del Sauce subsystem (immediate area of the water intake of the water treatment plant) 2003-2020. Source: González-Madina et al. 2021)

In Figure 14a, the variables have been standardized (subtracting the mean and dividing by the standard deviation). Figure 14b shows the additive contribution of turbidity, water color and reservoir level, as well as their temporal variation (each variable was standardized). From 2015, two *R. raciborskii* blooms were identified (see horizontal bars, 3-4 months in duration); the rest of the cyanobacterial blooms have shorter durations (one month maximum). The *R. raciborskii* bloom was also observed in 2004.

Cyanobacterial blooms occur almost exclusively during the warmer months of the year and involve a wide variety of species, including the genera *Aphanizomenon, Dolichospermum, Aphanocapsa, Microcystis, Cuspidothrix, Raphidiopsis,* among others. Several of these species have the ability to regulate their position in the water column (and control light limitation), fix nitrogen gas, produce toxins and may be associated with the generation of taste and odor episodes (due to the production of geosmin or 2-methyl-isoborneol).

In addition, they produce resistance structures that are deposited in the sediment and ensure colonization of the water column when conditions are favorable. *Dolichospermum crassum* produces geosmin, anatoxin and microcystin*; Aphanizomenon* cf. gracile synthesizes geosmin, cylindropermopsin and saxitoxin; *Cuspidothrix issatschenkoi* produces geosmin, cylindropermopsin and saxitoxin; *Microcystis aeruginosa* produces Beta-cyclocitral and microcystin (Jüttner and Watson, 2007).

Cyanobacterial blooms reduce water transparency and limit access to light for aquatic plants, benthic algae, and microalgae. At the same time, they increase pH, which can have sublethal effects on fish; they reduce the concentration of available CO2, affecting competition between phytoplankton groups; they produce toxins, which can have sublethal or toxic effects on fish, zooplankton, macroinvertebrates, birds, and aquatic vertebrates. Finally, they can increase their size (of cells and/or colonies and filaments) and reduce grazing pressure by zooplankton and energy transfer in the trophic web (Stüken Marin, 2010). During the bloom collapse, hypoxia and anoxia conditions occur, which increase the ammonium concentration in the water column (Stüken Marin, 2010). Algal blooms have important economic impacts through impacts on water treatment systems, costs of monitoring and surveillance programs, prevention and mitigation measures, and finally health impacts (Merel et al., 2013).



Blooming of cyanobacteria (Raphidiopsis raciborskii) in Laguna del Sauce during the summer-autumn of 2020. Device to evaluate water transparency (Secchi disk).

Temperature increases observed in the paleolimnological record of Uruguayan coastal lagoons during the Holocene and their response in trophic state (Del Puerto et al., 2011), as well as predicted temperature increases associated with climate change (Bidegain et al., 2013), allow us to anticipate a higher recurrence of cyanobacterial blooms (Kosten et al., 2012; Meerhoff et al., 20-22; Moss et al., 2011) in Laguna del Sauce. Periods of precipitation deficit may promote blooms due to reduced loss rates associated with flushing (in this case, export of biomass out of the system associated with drainage through El Potrero Creek).

The increase in annual cumulative precipitation observed in the historical meteorological record at the national level (Bidegain et al., 2013) may have two major opposing effects: on the one hand, an increase in biomass loss rates by flushing and, on the other hand, an increase in nutrient transport by surface runoff. The outcome depends entirely on land use, the adaptive capacity of production systems, and the incorporation of best practices in fertilization and buffer zone management. At the same time, greater interannual variability in the precipitation regime is expected (Bidegain et al., 2013), i.e. rainy years will record higher annual accumulated values, without implying a reduction in the frequency or intensity of dry years. In dry years, the risk of cyanobacterial blooms increases as residence time increases and biomass loss rates decrease. In addition, nutrient enrichment and increased phosphorus export from the sediment to the water column may occur. It is interesting to note that the classical nutrient concentrating effect in periods of lower precipitation has not been demonstrated so far, considering the last years of weekly sampling during the summer season (Table 9).

In recent years, taste and odor disturbances have been observed in the purification and distribution processes, the causality of which is not yet fully understood. In some cases (fall 2015), they could be associated with planktonic or benthic cyanobacteria, the latter in periods of high water transparency. In other circumstances, they could be associated with decomposer microorganisms from different sources of organic matter, for example, related to the collapse of cyanobacterial blooms or other algal groups, or significant inputs of organic matter from the wetlands associated with the Pan de Azúcar and Sauce streams.

Laguna del Sauce is an ecosystem that shows different spatial responses to the same factor: increased nutrient concentration. While phytoplankton blooms are observed in the main body of Laguna del Sauce, an overgrowth of submerged and floating vegetation is observed in Laguna del Potrero (Mazzeo et al., 2010a). The size, morphology, and exposure (including orientation and fetch) of Laguna del Potrero favor the establishment of aquatic vegetation, conditions that do not occur in the main body. At the same time, the extensive wetlands associated with Pan de Azúcar Creek, located between Route 9 and Laguna del Potrero, retain much of the particulate matter. Therefore, the water of this tributary has a high transparency, which favors the establishment of aquatic vegetation.

Laguna del Potrero plays a key role in buffering nutrient inputs to the system. Under certain conditions and times, it is very efficient in reducing nitrogen levels, which indirectly favors those species of cyanobacteria that fix nitrogen. The second most important tributary (Sauce Creek) also has a well-preserved wetland area between Route 9 and Laguna del Sauce that promotes denitrification processes.

Laguna del Sauce has presented biological invasions mainly related to the benthic bivalve component (Mazzeo et al., 2018). The Asian clam (*Corbicula fluminea*) and the golden mussel (*Limnoperna fortunei)* play a very important role in phytoplankton consumption and nutrient recycling. Scientific evidence shows that under certain conditions they effectively control the development of algal biomass. However, they have also been shown to promote blooms of species that can regulate buoyancy and thus evade filtration at the water-sediment interface (Marroni et al., 2014). Filtration eliminates potential competitors of non-consumptive phytoplankton groups, as well as herbivores of zooplankton of smaller size and lower swimming ability. Finally, it promotes a more rapid recirculation of nutrients. In summary, the interaction of all these factors favors the development of microalgal and cyanobacterial species that escape consumption by bivalves (Marroni et al., 2014; 2016). Within this group of species are several of the recurrent cyanobacteria in Laguna del Sauce.

The consumption of phytoplankton by zooplankton is strongly limited in this system by the absence of large herbivores due to the structure of the fish community, which exerts a strong predation pressure that eliminates the species with the greatest impact on the consumption of microalgae and cyanobacteria (Mazzeo et al.,

Camalotes in the northern sector of Laguna del Sauce, said vegetation comes from the Arroyo Sauce wetlands.

2010a; 2018a). It is important to consider that there are extensive coastal zones and wetlands dominated by shrub vegetation (e.g. P*hyllantus sellowianus, sarandi*) of a deciduous nature and free-floating vegetation that senesces and decomposes during the cold months. Therefore, the metabolism of the system is maintained by the contribution of these primary producers and associated decomposition processes, which allows us to understand the abundance of macroinvertebrates and fish in this system. In conclusion, the predators (zooplanktivorous fish) of phytoplankton herbivores (zooplankton) present an extraordinary abundance and control capacity; and they are not coupled to the classical predator-prey dynamics. The classical trophic web (phyto-zooplankton-fish) represents a much smaller energy channel than the coastal zone + wetlands - benthic macroinvertebrates - fish.

Recent studies on the presence of pesticide residues in Laguna del Sauce, in different abiotic (sediment) and biotic (fish and bivalves) matrices of the system (Stábile, 2018), indicate the presence of different compounds (atrazine, metalaxyl, metolachlor, pirimiphosmethyl, pyraclostrobin and trifloxystrobin) at very low concentrations at the moment (below the limit of quantification). The presence of pesticide residues should be monitored in a systematic and robust manner using the set of matrices mentioned above. Such monitoring programs have not yet been established. Preliminary studies on genetic damage (micronuclei and comet assays) in Laguna del Sauce bivalves (*Corbicula fluminea*) indicate early warning signals that should be incorporated into monitoring and evaluation systems (Kröger, 2020).

KEY MESSAGES FOR RISK ANALYSIS

The phenomenon of eutrophication involves several positive feedback mechanisms that intensify the process over time. These mechanisms are related to nutrient recirculation and phytoplankton grazing pressure. As it evolves, eutrophication, in scenarios where no control of external nutrient inputs is implemented, ensures increased nutrient availability through translocation of nutrients from the sediment to the water column, as well as reduced phytoplankton consumption pressure due to the disappearance of larger herbivores and zooplankton filtering capacity. At the same time, blooms of several species of cyanobacteria create resistance structures in the sediment that ensure their recurrence over time when environmental conditions are favorable.

Considering the main forcing factors related to climate (mainly rainfall variability), nutrient inputs and the internal dynamics of the system itself, it is highly probable that the frequency and intensity of cyanobacterial blooms will increase over time. The recovery of Laguna del Sauce implies reaching a lower nutrient level (corresponding to the trophic state known as mesotrophy), which would reduce the probability of adverse responses to the drinking water supply, such as cyanobacterial blooms. If external nutrient inputs are controlled, the system will exhibit various resilience mechanisms that will condition the persistence of medium and high nutrient levels for a considerable period of time (decades), thus requiring various additional internal management measures (see below, source water remediation). Accordingly, it is essential to incorporate additional strategies to mitigate the impact of the Laguna del Sauce water quality on the water purification process (control of the consequences of the eutrophication process).

3.3. MAIN FACTORS AFFECTING WATER HARVESTING IN THE BASIN

Water harvesting in the basin involves two closely related aspects: quantity and quality. The flow regime and the hydrological yield of the basin (balance between rainfall and flow) are determining factors, since they condition several key processes in the Laguna del Sauce system: water transparency through the contribution of suspended matter, organic matter dissolved from soils or productive systems, fertilizer and pesticide residues, regulation of residence time and export processes (loss) of primary producers (algae, cyanobacteria, aquatic plants). Land use management therefore has a direct impact on the problem of eutrophication and the ability to adapt to current and future climate variability.

Within this chapter, the expansion of the forestry sector deserves special attention, since its impact on hydrological yield in dry years is significant in basins that reach or exceed 25% of the area dedicated to this use in the country (Silveira and Alonso, 2009; Silveira et al., 2016). The Laguna del Sauce basin does not have specific studies on the subject, which does not preclude the definition and establishment of precautionary criteria according to the available international and national scientific evidence.

The basin has a complex system of groundwater upwelling to the surface, an aspect that is virtually unknown and that plays a key role in the dynamics of baseflow, as well as for water supply and forage production in areas of natural field. Both the generation of basic knowledge and the development of management strategies are relevant challenges in the short and medium term.

Recent studies (Levrini, 2017; Díaz et al., 2021) on the spatial pattern of nitrogen and phosphorus in the basin tributary network and their relationship with soil type and use, geology, geomorphology, position in the tributary network and vegetation cover (including the presence and conservation of riparian forest) show that a significant percentage of the spatial variation of phosphorus and nitrogen can be explained by a reduced set of basin attributes. In general, it was found that the most important attributes for total nitrogen are those related to soil type: deep soils with a positive relationship (+, the greater the area of deep soils, the higher the concentration of nitrogen in water) and light soils with a negative relationship (-, the greater the area of light soils, the lower the concentration of nitrogen in water), native forest cover (-), crops (+), and suspended solids content in the water channel (+).

The basin attributes considered are able to explain 42% and 41% of the spatial variation observed in 118 sampling sites during the winter-spring and summer-autumn transitions, respectively. In the case of total phosphorus, the attributes are related to soil type: light (-) and deep (+) soils, crop cover (+) and grassland (-), riparian zone condition (-), and channel oxygen content (-). This set of attributes explains 54% and 40% of the spatial variation in the winter-spring and summer-autumn transitions, respectively. In summary, nutrient levels in the tributary network depend on both natural factors (e.g., soil type) and anthropogenic controls (e.g., land use).

KEY MESSAGES FOR RISK ANALYSIS

La contribución de los diferentes usos del suelo, así como el estado de conservación de la zona riparia en los niveles de fósforo y nitrógeno total en la red de tributarios, permite identificar acciones necesarias para minimizar las exportaciones de nutrientes desde la cuenca hacia Laguna del Sauce. Dentro de estas se destacan la necesidad de implementar prácticas a nivel predial, como controlar la carga de ganado y su acceso a los cursos del agua, controlar las dosis y calendario de aplicación de fertilizantes, conservar la zona riparia y la integralidad de las márgenes, dar mayor cobertura y mejorar la infraestructura de saneamiento de los centros poblados. Al mismo tiempo, el efecto de la forestación requiere evaluaciones que incorporen otras escalas espaciales (por ej. cuenca) además de la predial. Estos aspectos resultan de singular importancia en el ámbito del ordenamiento territorial, tanto para revertir el procesos de eutrofización como para contar con una mayor capacidad de anticipación.

4. Infrastructure

The Laguna del Sauce Water Treatment Plant supplies water to the cities of Maldonado, San Carlos, Punta del Este, Piriápolis and Pan de Azúcar. It serves the western part of the department and, during the summer season, it supports the water supply of the coastal area east of the Maldonado River (La Barra, Manantiales).

Water consumption shows considerable temporal variability. For most of the year, it serves the needs of the department's stable population, most of which is located outside the Laguna del Sauce basin. However, during the summer season, sun and beach tourism can represent a population increase of almost 600,000 people in very favorable economic periods in the region (mainly Argentina and Brazil). The summer period with the highest number of tourists runs from December 20 to January 31.

The most important user in terms of water consumption is the government agency in charge of drinking water supply: OSE-UGD (Obras Sanitarias del Estado - Unidad de Gestión Desconcentrada). There are other water catchments in the system that are much smaller in relation to the consumption of the OSE-UGD and the volume of the reservoir. They are used for the irrigation of nurseries, the supply of water to a dairy farm located near the basin, water consumption and irrigation of houses located on the banks of the Laguna del Sauce. Sauce.

The Laguna del Sauce water treatment plant began operating in 1970. The original infrastructure was modified at the beginning of this century and at present. The first one was related to the transformation of the classical process of flocculation and filtration in a sand mantle to an inverted system with floc flotation and its removal. This modification required an investment of nearly USD 10 million, fully

Water treatment plant located on the edge of Laguna del Sauce.

justified by the limitations of the original infrastructure in a system with high inorganic turbidity and recurrent algae and cyanobacteria blooms. The second modification is currently underway. It involves a new treatment system that includes the use of ozone and biological filters. The investment for this is approximately USD 25 million. The final figure will be known soon when the bidding process for the ozone component is completed.

The main sanitation works in the Department of Maldonado have been developed in the last twenty years. Part of the gray infrastructure has made it possible to sanitize the southern region of the Laguna del Sauce basin (Solanas, Portezuelo, La Capuera). However, household connections and the construction of secondary networks are significantly delayed due to the lack of agreement on their prioritization and financing. This aspect is particularly relevant to the strategy for the treatment of nutrient inputs associated with domestic wastewater.

In urban areas, there is a predominance of surface drainage systems, curb and gutter, or simple displacement of water through the infrastructure of streets and sidewalks, and its discharge into gullies or onto the beach itself. During periods of excessive rainfall, partial flooding occurs. This phenomenon is more important in all urban expansions in flood plains, such as Pan de Azúcar.

The dam is a fundamental infrastructure because of its role in regulating the level of Laguna del Sauce and in water storage. This infrastructure was designed for a totally different function than the current one. The water level management capacity is very limited, so are the responses to periods of water deficit and extraordinary rainfall events. Moreover, hydraulic management to control the eutrophication process is practically nonexistent with the current infrastructure.

KEY MESSAGES FOR RISK ANALYSIS

The water supply and sanitation infrastructure has undergone significant changes in recent decades. Sanitation is an unavoidable factor in controlling the causality of eutrophication. The maintenance and management of the dam is key to the ability to adapt to the current and future variability of the rainfall regime, and to the management and rehabilitation of the eutrophication process. The construction of a new dam is an option that should be considered.

5. Governance

5.1. WATER MANAGEMENT

In the last 15 years, water management and governance systems have undergone important changes, moving from a rigid, fragmented and centralized governance model to an integrated management model (Cabot et al., 2020; Giordano et al., 2020; Lázaro et al., 2021; Mazzeo et al., 2021; Zurbriggen et al., 2022).

The most important milestone in this transformation process was the constitutional reform of 2004 in response to the privatization processes tested in Maldonado. These resulted in services with high tariffs and highly questionable quality, due to the poor design of the privatization processes and the failure to deliver on promised investments. This situation provoked a broad citizen mobilization, led by the National Commission for the Defense of Water and Life, which achieved the approval, with 64.7% of the vote, of a constitutional reform that added Article 47. This article enshrined access to drinking water and sanitation as fundamental human rights and assigned to the State the responsibility of providing public sanitation and water for human consumption. At the same time, it included the participation of civil society in the planning, management and control of water resources, introducing fundamental changes in water management, known in water governance as integrated water resources management (IWRM) (Pahl-Wostl et al., 2015).

These principles were consolidated with the enactment of the National Water Policy in 2009 (Law 18610), which institutionalized a "sustainable, integrated and participatory management" of water. A fundamental aspect was to establish the water basin as the unit of action for planning, control and management of water resources, in the policies of decentralization, territorial planning and sustainable management (art. 8). The law also establishes that users and civil society must participate effectively in the formulation, implementation and evaluation of plans and policies (art. 19). The law created consultative spaces at the national level: the National Water, Environment and Territory Council; three at the regional level, called Regional Water Resources Councils; and 13 Basin and Aquifer Commissions. Each has a tripartite composition, with members from the government (national and subnational), users (public and private) and civil society (social and non-governmental organizations, trade unions, teaching and academic institutions). These new spaces are defined as coordinating, consultative, deliberative and advisory bodies, non-binding, supervised by the Ministry of Environment (Trimble et al., 2021).

The first Basin Commission in Uruguay was created in 2010, in Laguna del Sauce. Basin commissions are an important innovation in the Uruguayan institutional scheme. They are bridging structures that seek to ensure inter- and intra-institutional coordination and interaction between the national and sub-national levels, while incorporating the participation of the main users. The Laguna del Sauce Basin Commission has several characteristics: it is a space that has functioned regularly and continuously for twelve years; the group of public and private stakeholders has a significant capacity to generate proposals and actions. This is demonstrated by the elaboration of the Laguna del Sauce Action Plan; the contributions to the Basin Land Use Plan, the current process of constructing the Basin Management Plan. In addition, it is important to consider the construction of inter-institutional monitoring programs and the development of knowledge in the interaction between technical and academic staff, which has made it possible to have systems for predicting the occurrence of cyanobacterial blooms and assessing the contribution of nutrients.

In a context of multiple changes and considerable uncertainty, management systems must evolve to incorporate appropriate management of uncertainty and promote learning and continuous improvement (Pahl-Wostl, 2015). The Laguna del Sauce has a considerable accumulation of scientific-technical information. In recent years, the capacity for monitoring, analysis and forecasting has increased. The experience of the Laguna del Sauce Basin Commission shows that the predictive capacity for the occurrence of cyanobacterial blooms or abrupt changes in key physicochemical properties, such as turbidity or pH, can be increased through interdisciplinary and interinstitutional interactions (Crisci et al., 2017a, 2017b; Madina-González et al., 2021). On the other hand, it shows that an important part of the human and infrastructural resources are currently available capacities. However, the human resources related to the advances indicated perform a variety of tasks and duties in their respective institutions, so that the time allocated to the improvement of predictive capacity is limited and not functional to the problem posed.

The future dynamics of eutrophication, the possible increase in climate variability, the lack of knowledge about the fundamental aspects (causality) of taste and smell disturbances, and the evolution and emerging novelties of other intervening factors require important organizational changes to improve the predictive and anticipatory capacity.

Transdisciplinary constructions are currently the main obstacle to overcome, although the elaboration of the Basin Management Plan shows very interesting progress. The current process of elaboration of the Laguna del Sauce Basin Management Plan implies a significant degree of progress in the consolidation of agreements and proposals resulting from the interaction of the various stakeholders involved in the management of the territory's water resources. The work carried out in the preparation of the Plan has generated several benefits prior to its final drafting and approval. These include the identification and systematization of a series of critical issues of particular interest for water management: imbalance between availability and demand; loss of quality and ecological integrity of water resources; impact on water flow morphology; impact of water runoff on cities; ineffective individual sanitation solutions; weakness of administrative tools and procedures for management; insufficient information in key decision-making processes; weakness in dissemination, training and research on water; impact of extreme events such as droughts and floods; potential risks associated with water infrastructure.

The process of identifying key issues also included alternatives for addressing and overcoming these critical issues in projects and programs, as well as possible synergies and articulations to make the work of each public and private actor involved more effective. Currently, there are about 24 projects and programs that address the critical issues identified within the guidelines and objectives of the National Water Plan. This constitutes a territorial programmatic basis for the planning of future actions.

The Basin Commission presents challenges in its governance model, such as excessive centralization, inter- and intra-institutional fragmentation in the implementation of agreements, and its consultative (non-binding) nature. These are key factors in the limited progress in the implementation and monitoring phases of the agreed actions and strategies. Similarly, the public institutions have not been able to internalize the consultative role of the commissions or the important changes introduced in the rules governing the decision-making processes.

The various academic and professional disciplines associated with water management exhibit distinct power dynamics and occupy different positions within the network of actors. These disciplines have well-defined roles in the institutional, research, and knowledge production system, as well as in professional practice. Consequently, specific viewpoints, primarily sectoral, are developed, and interactions among actors often follow a disciplinary tradition. In this context, uncertainty is viewed as a shortcoming in the realm of knowledge generation rather than an intrinsic characteristic of complex systems. These paradigmatic principles present significant challenges for interdisciplinary or transdisciplinary approaches. The obstacles become particularly evident when striving for transdisciplinarity. Integrating diverse knowledge systems and expertise remains a complex task in technical and academic spheres. Hence, the current commission requires facilitation skills, the establishment of dialogues between knowledge systems, overcoming power and information asymmetries, and the development of effective communication and controversy management strategies.

The public institutional structure of the basin commission includes representatives from the Ministry of Environment, the Ministry of Livestock, Agriculture, and Fisheries, and the Ministry of Housing and Territorial Planning. At the departmental level, representatives from executive departmental offices of the Departmental Government and the Departmental

Workshop dynamics linked to the construction of the OSE Master Plan for the Department of Maldonado.

Board (council members) participate. Representatives from some municipalities within the basin and associated hydrosocial territory also take part. Users in the basin commission include representatives from OSE-UGD, neighborhood associations, and sectors related to production. The academic sector is represented by members of the University of the Republic (Udelar) and the SARAS Institute.

The basin commission exhibits a flexible composition, particularly in the inclusion of civil society associations that wish to participate and collaborate. However, key national-level public actors, such as the Ministries of Tourism and Economy, are not included.

5.2. TERRITORIAL PLANNING AND MANAGEMENT

Territorial planning instruments play a crucial role in enhancing basin governance. The regulatory framework of the Law on Territorial Planning and Sustainable Development (2008) represents a set of rules that promotes comprehensive territorial development, the coordination of scales and levels of government, and ultimately includes the participation of the involved actors. However, there are considerable gaps between the capacities and possibilities provided by the regulatory framework and the usual practices in place.

The existing regulatory framework assigns a key role to the departmental levels in guiding and leading the implementation of the law. In this regard, a significant challenge for subnational levels has been the development of capacities in this field. The Directorate of Territorial Planning (DINOT), currently under the Ministry of Housing and Territorial Planning, serves as the main node at the national level. All processes for approving instruments outlined in the law undergo analysis by DINOT and approval by departmental boards.

The law envisions the meaningful participation of territorial actors through consultative spaces involving various instruments. In the stipulated public hearings, there is a considerable lack of awareness and trust in the legal and institutional framework, as well as the adequacy of associated technical evaluations, by some civil organizations. Several actors colloquially describe the participatory procedures outlined in the law as “purely symbolic.”

The department of Maldonado was a trailblazer in implementing the law and crafted the Departmental Guidelines through an extensive consultative process (Acuña et al., 2009; Acuña et al., 2013). However, this commendable process gradually deteriorated for various reasons. Conflict resolution and the integration of academic perspectives or those endorsed by civil society organizations were generally overlooked or incorporated in a partial and limited manner. Simultaneously, during changes in political parties and government coalitions, significant disparities emerged regarding the State’s role in territorial planning. In certain periods, these processes became exclusively subservient to the dynamics of capital and speculation, vividly highlighting phenomena examined globally, involving the engagement of significant international capital in real estate production (sensu Harvey, 2014). Within this context, incentives provided by national and local governments to facilitate such processes are evident in both coastal and rural territories at the departmental and national levels (Gadino et al., 2022; Hidalgo et al., 2014; Sousa et al., 2016; Van Noorloos, 2015, among others).

The instruments associated with environmental management, such as environmental impact assessments or strategic evaluations, display considerable weaknesses, both from a technical perspective and in terms of procedural design, due to their lack of independence from investors or proponents (Gadino and Taveira, 2020). This aspect significantly undermines the credibility of the regulatory framework established by society as a whole.

In addition to the aforementioned challenges, the formulation of the Territorial Planning Plan for the Laguna del Sauce basin, currently undergoing approval by the Departmental Board, highlights significant obstacles that need to be addressed. There is limited experience in planning rural frameworks in Uruguay. The integration of knowledge fields related to the management of ecosystem services, the inclusion of the ecosystem processes ensuring them, the valuation of these processes, and the goods and services associated with them, as well as the equitable distribution of their benefits throughout society, has been severely restricted until now. The disparities between technical teams at the national and departmental levels during the development of the aforementioned plan have revealed substantial differences that have persisted for several years. In fact, the process of formulating and approving the plan has spanned over nine years and is yet to be concluded.

Ultimately, the capacity for prevention, anticipation, and adaptation of territories to changes in climatic factors or land use is also severely limited. As a result, strategies tend to be predominantly reactive, centered around managing consequences and responding to associated crises.

5.3. MANAGEMENT OF PRODUCTIVE SYSTEMS

Given the significance of the agricultural sector in the basin, the Ministry of Livestock, Agriculture, and Fisheries (MGAP) plays a key role in the case study. This ministry encompasses multiple directorates and programs, with a particular emphasis on the Directorate General of Rural Development (DGDR) due to its links between producers and public institutions. The DGDR, established by Law 17930 of the National Budget 2005-2010 and operational since April 2008, is tasked with designing differentiated policies for agricultural activities. The goal is to achieve rural development through a new conceptual model of production that prioritizes economic, social, and environmental sustainability, with active participation from stakeholders in the territory.

The design of sectoral policies must be capable of overcoming the limitations of previous production models with the aim of achieving a fair distribution of wealth among producers, wage earners, and society. Rural development goes beyond the strictly agricultural sphere, making it, at its core, an inclusive effort involving all sectors of our society. Its central goal is the well-being of the rural population.

The DGRN has played a key role in the last two decades in soil conservation and use. The design and implementation of land use and management plans constitute a recognized pillar at the regional and global levels, directly contributing to land and water management. Building upon this foundation, there is room to address challenges such as a more efficient and sustainable use of fertilizers and pesticides.

Buffer zones between the agroecosystems and Laguna del Sauce.

In this regard, it is crucial to consider modifications to this specific instrument for basins dedicated to the supply of drinking water. This would allow for the incorporation of diverse productive activities and specific requirements to ensure proper water harvesting.

A key component in the decentralization process of MGAP has been the Rural Development Tables. This area of intra- and inter-institutional coordination facilitates the implementation, construction, and monitoring of public policies in rural territories, promoting the organization of the population and their participation. These tables are understood as units that coordinate MGAP's actions throughout the national territory and foster the connection with public-private institutional frameworks, promoting sustainable development in rural territories.

The MGAP has a multitude of strategies and plans to increase adaptation capacity during drought periods through credits for building water reservoirs (tajamares) or support for the acquisition of forages. At the same time, significant progress has been made in monitoring droughts and proposing evaluations of the adaptive capacity of productive sectors (Climate Change Adaptation Plan for Productive Sectors, 2019). In summary, the trajectory of actions and plans directly or indirectly related to the management of the causes and consequences of water deficit periods allows for cycles of evaluation, improvement, and adjustment, taking into account the accumulated experience.

Finally, it is important to highlight the lines of action related to the design of more sustainable productive transitions through various projects (INIA, World Bank project), as well as the enactment and application of the Agroecology Law. This set of instruments represents a significant advancement in the control and substitution of external inputs (fertilizers, pesticides), and thus in the greater conservation of soil, water, and biodiversity. These strategies also contribute to better adaptation to climatic variability, the reduction of greenhouse gas effects, and the conservation of biodiversity. Gradually, there is an increasing coordination between development and equity, climate, and biodiversity agendas, strongly driven by international cooperation funding. All these processes have consequences for the eutrophication of aquatic systems.

In the Laguna del Sauce basin area, it is important to highlight the presence and role of the regional office of the MGAP, located in San Carlos, as well as its participation and leadership in territorial development tables. This context, along with other MGAP departments, is involved in the Laguna del Sauce Basin Commission.

KEY MESSAGES FOR RISK ANALYSIS

Uruguay and the analyzed territory have regulatory frameworks related to the management of primary natural assets, including mechanisms for intra and inter-institutional coordination, intergovernmental coordination, and participatory spaces for civil society. However, significant gaps between existing regulations and their actual functioning constrain the capacity for adaptation and anticipation of both global and local changes. Fragmentation persists at its maximum expression in the implementation, oversight, and monitoring of agreements, extending to intermediary structures such as basin commissions or development committees.

6. Interactions and responses

6.1. CRISIS: CAUSES AND EFFECTS

In recent history, three significant water supply crises have occurred, each with varying degrees of public visibility. The first crisis occurred in the fall of 2015, following a collapse of a major cyanobacterial bloom, and was associated with taste and odor interferences in the drinking water supply, the causality of which could not be established. Immediately after this event, Laguna del Sauce experienced a bloom of a toxic cyanobacterium (*Raphidiopsis raciborskii*) with a high and persistent production of saxitoxin (neurotoxin), posing serious challenges to the water treatment plant. In December 2015, a new water supply collapse occurred due to filter clogging caused by abrupt changes in water pH associated with cyanobacterial blooms that interfered with flocculation and filtration processes. In 2017, an extraordinary period of heavy rainfall led to home flooding and sparked a debate about the management of the dam, whose capacity to control the lagoon's water level is very limited.

According to the temporal dynamics of socioecological systems (Gunderson and Holling 2002; Cosens and Holling 2018), these crises triggered multiple changes, often in a highly reactive format. The Laguna del Sauce Action Plan, drafted in 2011 by the Basin Commission, was finally approved by the responsible public institutions in 2015, following the significant crisis involving taste and odor interferences. This process allowed for significant collective learning: windows of opportunity for change are very limited and usually tied to the emergence of crises. Changes occur through a combination of windows of opportunity and prior preparation. In addition to the approval of the Action Plan, noteworthy responses have included the development of interinstitutional monitoring programs to anticipate potentially toxic cyanobacterial blooms and increased coordination and interaction among public institutions in the management of the lagoon and its associated basin (Crisci et al., 2017a, 2017b; González-Madina et al., 2021).

However, there are still multiple information gaps and considerable uncertainties. Advances in knowledge have been supported by public institutions (OSE, OSE-UGD, MA, MGAP, Udelar, SARAS Institute) through various sources of funding, agreements, projects, undergraduate and graduate theses, and resources from various national and international research agencies. The significant reliance on competitive funding and instability in some interinstitutional financing mechanisms means that progress in knowledge generally does not align with the demands of the management sphere, particularly within the required timeframes. It is therefore advisable to consolidate the monitoring and tracking of system evolution to support decision-making and define anticipatory strategies for interference in water treatment processes.

6.2. KEY DIVERGENCES

There are multiple divergences in water management that are essential for understanding the operational dynamics, as well as the primary advancements and limitations. In both the Laguna del Sauce basin and at the national level, there is a profound divergence regarding the non-binding nature of the basin commissions. It is important to note that the Uruguayan model operates through social control, which is currently very limited due to the absence of communication platforms that allow understanding and contributing to the work agenda, comprehending the causality and consequences of the main issues and challenges, contributing to the design of overcoming alternatives, and knowing the progress in the implementation of agreements (plans, strategies). These aspects remain unknown to society as a whole. Additionally, there is an assumption that transitioning to a binding mode can lead to an immediate change. This overlooks issues associated with excessive bureaucratization, limitations on the participation of civil society actors, and inflexibility in the formation and interactions of the network of connected actors.

Another controversial aspect to be considered is the role of different anthropogenic activities in the causality of eutrophication processes or other types of water quality degradation. In particular, the significance of diffuse contributions over point sources of nutrients has been a focal point of extensive debates and academic-corporate disputes. The introduction of no-till farming has played an important role in controlling soil erosion, but has not anticipated changes in the dynamics of nutrient inputs from agroecosystems to aquatic ecosystems (Goyenola et al., 2021). In the case of the Laguna del Sauce, a system very sensitive to eutrophication processes due to its shallow depth and considerable retention time, each of the inputs (punctual or diffuse) can generate eutrophication conditions by itself (Levrini, unpublished data).

The impact of *Eucalyptus* afforestation on hydrological yield in Uruguayan basins (Silveira and Alonso, 2009; Silveira et al., 2016), and its potential effect on the residence time of lentic ecosystems during dry periods, has sparked significant disagreements and hindered the implementation of key criteria in territorial planning. The observed impacts on hydrological yield during drought periods are not adequately incorporated in basins with stagnant (lentic) water systems, particularly in terms of retention time. In the Laguna del Sauce basin, as well as in the rest of the country, caution and anticipation in this matter are currently lacking.

Controversies also center around the field of production and development models, particularly the sustainability of a mainly primary economy heavily reliant on natural resources usage, with multiple externalities considered negative in environmental, social, and economic terms (Mazzeo et al., 2021). At this point, a comprehensive debate emerges concerning the conservation and modification of ecosystems, posing complexities and generating epistemic challenges, new demands in the economic realm, contributions from diverse fields of knowledge and techniques, as well as considerations regarding resilience and ecosystem integrity.

Water management calls for the creation of spaces where the resource is understood as a participant in the network of economic actors and in relation to ecosystem dynamics that determine its availability and quality. These spaces can elevate water to a level where it becomes an agent setting limits on anthropic effects based on economic models that fail to recognize the inherent limits of ecosystem services, thus impacting water security. These differences severely constrain the territorial planning of basins dedicated to the supply of drinking water, which requires ensuring ecosystem processes. This necessitates management at the farm and multi-farm scale, multisectoral planning of productive activities, and the equitable distribution of benefits from a proper water harvest throughout society.

On the other hand, in recent years, significant productive transformations with similar trends at the national and departmental levels have been observed. The increase in forested areas and rainfed crops in the Laguna del Sauce basin illustrates this statement. Although the rainfed crop area in the analyzed case is small relative to the total area of the basin, it is primarily located in plots adjacent to the water body. In some cases, these are shallow soils with significant slopes, and therefore have a considerable risk of erosion. The land use and management plans of the Ministry of Livestock, Agriculture, and Fisheries (MGAP) represent a significant advancement if effectively implemented, monitored, and evaluated for their effectiveness. At the same time, in basins dedicated to the supply of drinking water, it is necessary to include additional good practices that regulate the application of pesticides and fertilization practices, the main causes of eutrophication.

Infrastructure works and investments are intricate endeavors that involve various actors within the network. They play a pivotal role in addressing critical water-related issues, such as enhancing capacities or treatments in drinking water purification, expanding sanitation coverage in populated areas and suburban zones, and improving the reservoir's level management capacity. Public stakeholders often fail to reach a consensus on the best measures to resolve these problems. Proposed solutions undergo a cycle of debate, imposition, suspension, rejection, or revival, depending on the dynamics of actors competing for influential positions. These dynamics are influenced by political party dynamics, diverse engineering perspectives, economic considerations, varied consultancy outcomes, individual personalities, and group dynamics.

6.3. EMERGING

The model of residential tourism and second-home tourism that characterizes our country involves increasingly expansive land use patterns (tourist farms, gated communities, all-inclusive resorts). This has led to transformations from rural to suburban land uses in large areas, particularly south of Route 9, influencing the growth of

Laguna del Potrero, sector close to the connection with Laguna del Cisne. Urban matrix corresponding to La Capuera, part of the constructions on the margins correspond to public spaces.

demand for basic services scattered throughout the territory. The speed and magnitude of these transformations (spatial scale, investment, number of users in short periods of time), combined with the limited number of approved or implemented territorial planning instruments to date, create a scenario of lack of foresight in the provision of essential services (e.g., water and sanitation). In summary, territorial decisions are geared towards short-term benefits for the real estate market and associated industries, with very little impact on fundamental sustainability aspects. The discontinuity and changes in territorial planning guidelines and policies over the last four departmental governments prevent the establishment of clear rules of the game that would enable compatibility and the generation of synergies among the different ecosystem services provided by the territory ensuring its socio-economic development and the provision of essential goods and services. Currently, the dynamics of land use transformations are largely dictated by market forces, irrespective of their long-term sustainability, which adversely impacts the attractors of economic development.

The long-term analysis of land use in the department of Maldonado is clearly linked to the development of tourism. So far, the department promotes international real estate investments as a way to maintain its position as an elite destination, as well as to boost employment and departmental finances. Some negative aspects of developments driven by real estate speculation are already visible in the territory: carrying capacity exceeded; loss of ecosystem services due to tourism; strong socio-territorial fragmentation, displacement of local populations (green gentrification) (Gadino et al., 2018).

The ongoing transformations and the assurance of services such as drinking water supply require the incorporation of the sustainability dimension in all public or private practices, particularly in development models or strategies. Territorial planning must be analyzed from a sustainability perspective, overcoming the dominance of fragmentation generated by sectoral planning and short-termism. The challenges posed and the resolution of the negative externalities mentioned require urgent progress on definitions that transcend departmental government periods. These definitions must include capacities and competencies for future use, to generate collective constructions of shared meaning with the community (permanent residents, producers, landowners, entrepreneurs, government actors, and academia), and the definition of clear and defensible objectives that determine the actions to be taken by all territorial managers. A considerable part of the issue of drinking water sources requires very significant transformations in the analysis and management capacities of the territory. Considering the working time horizon until 2030, it is expected that a large part of the difficulties and limitations discussed will persist for most or all of the analyzed period.

6.4. REHABILITATION OF THE BASIN FROM THE PERSPECTIVE OF WATER SECURITY

Rehabilitation of the basin involves returning to a condition prior to the occurrence of major disturbances or disruptions. In the case of Laguna del Sauce, this would imply, among other measures, removing the damming and afforestation of the coastal dune system or the rest of the basin. Returning to a historical conFiguretion, characteristic of natural resource management or ecosystem management (Chapin et al., 2009), poses significant challenges: a substantial reduction in the water reserve; substantial modifications to raw water pumping systems; modifications to the coastal dune system (and associated real estate development) and to productive systems. Therefore, it is advisable to explore rehabilitation strategies within a framework of ecosystem management and care based on resilience (Chapin et al., 2009). Within this theoretical framework, the goal is to achieve a system conFiguretion that ensures the set of ecosystem services identified as crucial and the portfolio of development options from the present into the future. From this perspective, management is not focused solely on natural systems but also on socioecological systems.

The rehabilitation of Laguna del Sauce requires, first and foremost, the control or elimination of the factors that deteriorate water quality. The first step involves controlling point and non-point nutrient inputs. Advances in the construction of sanitation systems in the department of Maldonado, particularly in the Laguna del Sauce basin, will allow for the short-term control of a significant portion of point-source nutrient inputs. However, controlling non-point source inputs represents the major challenge in the rehabilitation processes of eutrophic systems globally (Moss, 2008). This requires the adoption of best practices and the abandonment of certain traditional management practices, both in agriculture and

Chacras turísticas localizadas en la margen E de Laguna del Sauce.

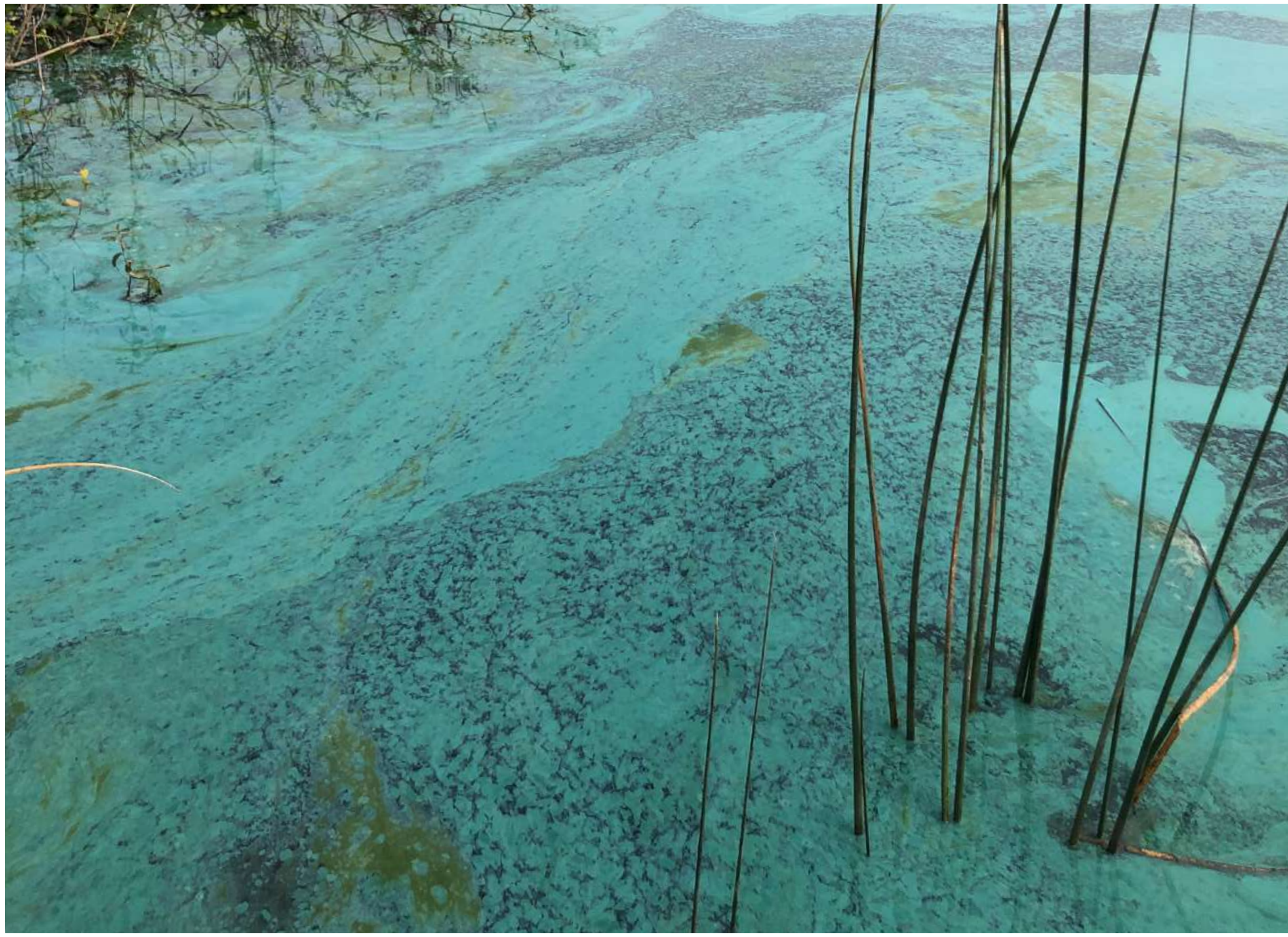
livestock farming. It involves implementing fertilization in line with soil nutrient levels and crop demand, restricting direct livestock access to watercourses, and ultimately, the proper management and conservation of riparian vegetation and wetland areas.

The historical accumulation of nutrients contributes to a significant resilience of the system. In simple terms, the system can maintain elevated nutrient levels for an extended period, even decades, despite effective control of point and diffuse sources. Therefore, it is highly advisable to analyze and implement internal management strategies: controlling the internal nutrient load, managing excess biomass of aquatic plants, applying biomanipulation techniques, and controlling the fishing of top predators. Some of these measures can be used additionally as shock strategies in very adverse circumstances, such as chemical phosphorus sequestration. However, it is important to respect the indicated sequence of actions to implement successful and economically sustainable rehabilitation programs: 1) controlling external nutrient input; 2) controlling internal nutrient input; and 3) biomanipulation.

Successful rehabilitation programs require proper functioning, significantly different from the current conFiguretion of the water governance system (see item 5). Finally, changes in climate variability will amplify eutrophication processes and increase their adverse consequences. Therefore, increasing adaptation capacity to climate change involves controlling the causes of eutrophication and careful water use management.

KEY MESSAGES FOR RISK ANALYSIS

The main environmental issue of the Laguna del Sauce system (interference in the supply of drinking water) is solvable. To achieve this, substantially greater interinstitutional collaboration and cooperation, as well as involvement of the entire society, are required compared to what is currently observed. The economic resources needed for effective progress in this matter have not been fully estimated, but it is likely to involve significant financial investments.



Flowering of *Dolichospermum* spp. at the mouth of Arroyo Sauce.

The mismatch in prioritizing the recovery of Laguna del Sauce between the national and departmental levels in recent government periods has hindered progress. The historical trajectory shows that changes, for the time being, occur in association with crises in the water supply and with limited capacity for anticipation.

Changing the dynamics mentioned earlier involves significant political and cultural transformations. Therefore, anticipating a substantial inertia in the absence of major crises is conceivable. It is advisable to build endogenous anticipatory capabilities and competencies within the organizational structure related to water management, overcoming the reactive culture.

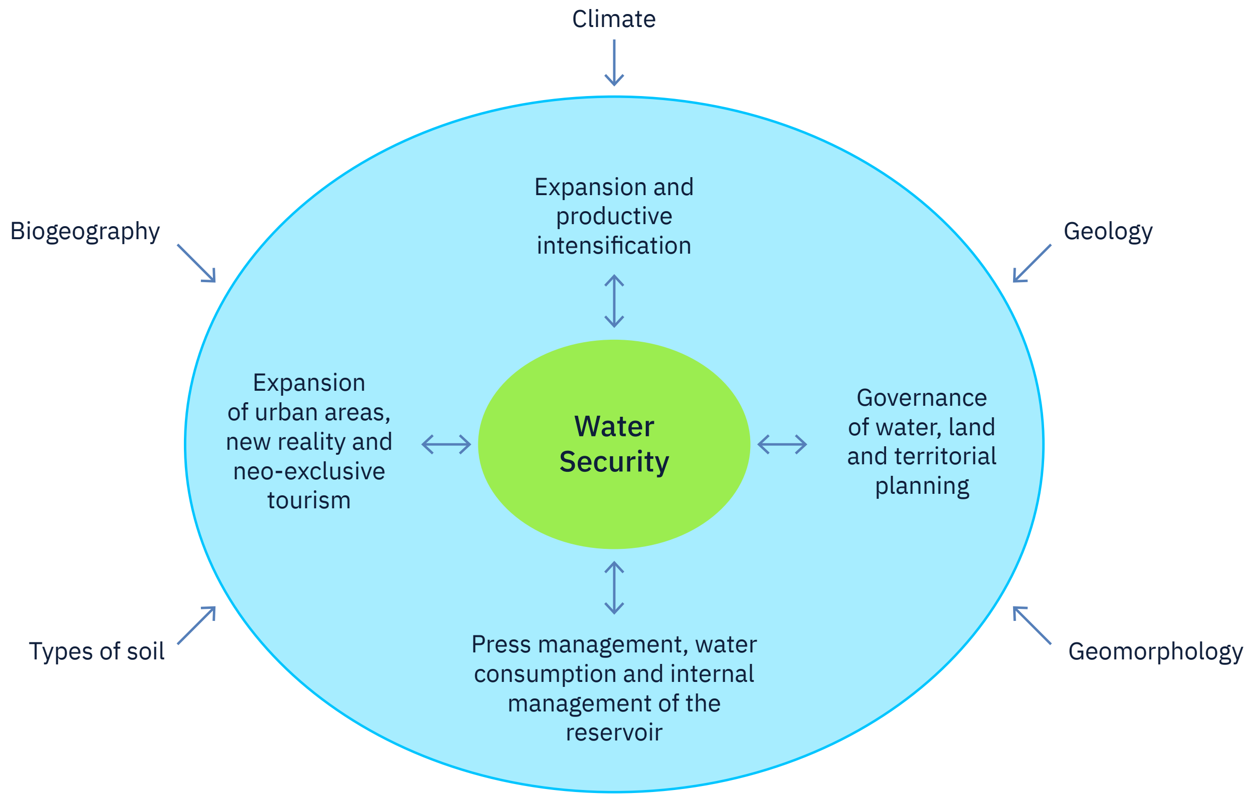


Figure 15.Synthesis of factors and processes that determine water security. The factors outside the light blue circle are called state factors and show changes that operate on considerable time scales (e.g.thousands of years). The factors inside the circle, on the other hand, show changes on smaller time scales and are called interactive. For example, water security affects socio-economic development, and development affects water security.

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