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Environmental Science and Policy

Mazzeo, Néstor; Ciganda, Ana Lía; Fernández Nion, Camila; Peñas, Francisco J.; González-Ferreras, Alexia María et al

https://doi.org/10.1016/j.envsci.2024.103699

Environmental Science and Policy 154 (2024) 103699

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Inter and transdisciplinarity strategies for evaluating and improving water quality monitoring systems: Uruguay as a study case

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ARTICLE INFO

Keywords:
Water resources
Water governance
Eutrophication
Virtual watersheds

ABSTRACT

Developing robust systems for monitoring and evaluating water quality is crucial for assessing ecosystem integrity and the impacts of human activities on nature. It also enables the assessment of water management effectiveness, governance systems, and the design and evaluation of public policies. However, designing such monitoring programs is complex due to multiple constraints like eco-hydrological knowledge, economic resources, human capital availability, and governance dynamics. This study combines quantitative and qualitative analyses (virtual watershed methodologies, empirical modeling, and theoretical frameworks of water governance) to evaluate the robustness of water quality monitoring systems and identify strengthening alternatives (including institutional design and public policy). The inter and transdisciplinary strategy is tested in the evaluation of eutrophication processes in Uruguay. Major spatial patterns of water quality at a national scale were identified, highlighting the influence of land use, soil types, point sources of pollution, and livestock on nitrogen and phosphorus concentrations. Current monitoring efforts and spatial coverage fall short of adequately addressing water management needs, especially in Uruguay's socio-economic context. Based on the weaknesses identified, an increase in the number of stations (and their spatial distribution) is proposed to have a better representation of biogeophysical and socio-economic conditions diversity. The challenge involves an important transformation (i.e. establishing a network system of public institutional nodes at national and regional levels) due to the country's centralism, fragmented water governance system, and scarce economic assets.

1. Introduction

Social-ecological resilience from the local to the global scale depends on a set of interactions between water, land, and climate that generates considerable challenges in water governance (Falkenmark and Wang-Erlandsson, 2021). The analysis of these interactions (also with energy as a key sector) is crucial to achieve Sustainable Development Goals in the context of intensive use of natural resources and climate change (Vinca et al., 2021). Globally, advancements in assessing anthropogenic impacts on aquatic ecosystems have emerged through a complex set of water quality properties, ecosystem and landscape attributes, and refined sampling strategies and statistical analyses (Estévez et al., 2019; Geissen et al., 2015; Peñas et al., 2023; Schäfer et al., 2022). Machine learning, artificial intelligence (Estévez et al., 2019; Fernández et al., 2014, 2012; Huang et al., 2021; Khan et al., 2021), and natural experiment frameworks (Craig et al., 2017; Dunning, 2012; Layzer,

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https://doi.org/10.1016/j.envsci.2024.103699
Received 6 October 2023; Received in revised form 24 January 2024; Accepted 5 February 2024
Available online 22 February 2024
1462-9011/

2008; Penny et al., 2020) offer valuable tools for comprehending the impacts of land use, production practice, and water management effects. Attaining a comprehensive understanding requires robust water quality monitoring systems that have broad spatial coverage, adequate temporal frequency, a set of relevant water quality features (physical, chemical, and biological attributes), several basin characteristics (i.e type and use of soils, geology, topography, hydrological dynamics), finally, databases and statistical capacities connected with key decision-making processes.

Uruguay, an agro-exporting country, has witnessed significant changes in land use in recent decades. The area covered by exotic forest expanded by 1.3 million hectares from 1990 to 2020, and soybean agriculture grew by 1 million hectares between 2000 and 2022, accounting for 15% of the country's productive area (Díaz, 2023; DIEA, 2022). Concurrently, the use of fertilizers experienced a substantial increase in the early 20th century, with Uruguay ranking among the South American countries with the highest intensification of use (FAO, 2023; Heffer et al., 2013). These shifts have posed challenges to managing the nation's natural assets, particularly water resources. Uruguay's water governance system has changed, transitioning from a hierarchical, fragmented model (command-control) to an integrated water resource management promoted by civil society and academia through a constitutional plebiscite in 2004 (Mazzeo et al., 2021; Trimble et al., 2021). Despite these institutional changes, in the recent historical trajectory, critical situations in the supply of drinking water have been faced. They generated problems of both quantity and quality in several regions of the country, including a recent crisis that affected more than 60% of the population in the capital and the metropolitan area (Goyenola, 2023; Trimble et al., 2022). Beyond agricultural impacts, challenges stem from limited wastewater treatment capacities, and altered precipitation patterns. Addressing these challenges requires enhanced stewardship capabilities in managing ecological components, processes, and territorial planning of human activities.

Despite these challenges, significant strides have been made in implementing empirical models to predict water quality variables in aquatic systems in Uruguay. For instance, Díaz et al. (2021) successfully identified primary drivers (e.g., soil type and use, geomorphology, geology, vegetation cover) influencing phosphorus and nitrogen concentrations at watershed and departmental scales. Such approaches can complement empirical models like virtual watersheds, which have yielded promising outcomes across diverse geographic contexts (Barquín et al., 2015; Benda et al., 2016, 2011; Peñas et al., 2011). Improving water quality monitoring and assessment requires an effective capacity for deploying various environmental impact analysis strategies (e.g., Control-Impact-CI-, Before-After Control Impact-BACI-, Randomized Control Impact-RCI-, Randomized Before and After Control Impact-RBACI-) supported by random selection of control and impacted monitoring stations (Christie et al., 2020). This challenge holds great significance for regions lacking or early in the development of monitoring and evaluation systems (Kirschke et al., 2020). Dealing with this complex issue requires a multidimensional analysis, integration of diverse disciplinary domains (i.e. social and political sciences, natural and geosciences), and collaboration between academic and non-academic stakeholders (from public management or civil society organizations engaged in water governance) In other words, it requires inter- and transdisciplinary constructions (Chambers et al., 2021; Norström et al., 2020).

According to the background, strengthening the analysis and decision-making processes linked to water management and its interactions with soil, energy and climate is a key challenge. To this end, this research combines quantitative (virtual watershed methodologies and empirical modeling) and qualitative approaches (semi-structured and in-depth interviews, workshops and focus groups with the network of actors involved in the Basin Commissions and Regional Councils, non-binding spaces of the current water governance system). The main objective is to evaluate the capacity for integrated analysis and processing of multiple sources of information, some with complex databases (i.e. high resolution land use/land cover and climatic data). At the same time, the governance system's capacity for change is evaluated to overcome the identified limitations and implement new strategies. This study combined interdisciplinary and transdisciplinary approaches to achieve the following specific objectives: i) identify spatial patterns of water quality and their underlying causes, especially the interactions with the soil types, uses of land and main climatic gradients; ii) assess the strengths and limitations of the current water quality monitoring network; iii) analyse the capabilities and limitations of the governance system to overcome the identified weaknesses; iv) propose strategies to overcome current limitations of the governance system. The final goal of this research is to promote effective fluvial ecosystems stewardship. The water quality assessment focuses on nitrogen and phosphorus levels in fluvial systems due to: their significance in the country's eutrophication issue (Goyenola et al., 2021), the public policy challenges associated with, and data availability within the National Environmental Observatory (OAN)[1] provided by the Ministry of Environment (MA).

2. Methodology

2.1. Study case

Uruguay's territory covers 176,215 Km^2 and is situated in the temperate zone of South America, spanning from 30° to 35° 05'' south latitude and 53° to 58° west latitude. The climate is characterized as humid temperate, lacking a distinct dry season. Mean annual cumulative rainfall ranges between 1000 mm and 1500 mm, following a southwest-to-northeast gradient. Mean annual temperatures fluctuate between 16.5 and 20 °C, with a southeast-northwest gradient. The predominant geographical features consist of plains, ridges, and hills, exhibiting gentle to moderate slopes, with an average elevation of 140 m above sea level (m.a.s.l). The dominant ecosystems are grasslands, with over 80% of the country's surface suitable for pastoral use and 30% suitable for agriculture (Achkar et al., 2016).

2.1.1. Main land uses

The most extensive territorial activity is cattle ranching, conducted on natural fields (~11 million hectares) and improved or artificial pastures (~2 million hectares). Over the last three decades, two intensive activities have gained prominence: forestry (*Eucalyptus* spp *and Pinus* spp), primarily for cellulose pulp production (~1,3 million hectares); and rain-fed agriculture (~1,2 million hectares), with soybean cultivation being the prominent feature (DIEA, 2022). Irrigated crops encompass 170 thousand hectares, with rice being the predominant crop (~95%) (DIEA, 2022). Rain-fed agriculture dominates the littoral zone, while irrigated crops thrive in the eastern zone. Forestry activities are distributed across four regions (littoral, north center, and east), livestock farming spans the entire country, and in the southern region, dairy and horticulture are notable (Gazzano et al., 2019). The population of Uruguay stands at 3,4 million inhabitants, with a primarily urban distribution (95%), concentrated mainly along the coastal and littoral areas (80%). Point source pollution (industrial, domestic, and agricultural) are more concentrated in the southern part of the country (Achkar et al., 2016).

2.1.2. Water management

Aquatic systems within Uruguay exhibit a concerning trend towards degradation, primarily driven by eutrophication processes (Díaz et al., 2021; González-Madina et al., 2019; Goyenola et al., 2021). This challenge is deeply intertwined with the country's socio-economic structure, centered on agricultural production, and exacerbated by the limitations of sanitation infrastructure in population centers. The strategies

[1] https://www.ambiente.gub.uy/oan/

implemented by Uruguayan institutions have largely been reactive, focusing on managing consequences rather than addressing underlying causes (Mazzeo et al., 2021; Trimble et al., 2022).

In terms of monitoring systems for inland aquatic ecosystems, spatial coverage remains limited, and the frequency and temporal scope of sampling hinder the availability of consistent and up-to-date data series for critical areas of the country. A recent effort led by MA through OAN aims to provide water quality information by integrating data from various public institutions and governmental levels. However, the compiled information in the OAN is constrained to a limited set of physicochemical variables, including temperature, pH, conductivity, turbidity, phosphorus, and nitrogen concentration. Hydrological data present a more favorable outlook, with monthly measurements of hydrological variables, although notable gaps in spatial coverage exist in certain regions and lower-order streams (Mazzeo et al., 2022). Conversely, Uruguay boasts comprehensive information on land types and use, vegetation cover, geology, digital terrain models, and recent assessments of land use changes (DINOT, 2018, 2015; MGAP, 1994; Panario et al., 2011). The potential for generating and analysing data from land use [2] and management plans, as well as livestock traceability,[3] is substantial.

2.2. Research strategy

The research strategy included five distinct stages, drawing upon a fusion of techniques, including virtual watershed construction (Benda edst al., 2016), empirical modeling (Álvarez-Cabria et al., 2016; Díaz et al., 2021; Estévez et al., 2019; Fernández et al., 2014), and theoretical frameworks concerning water and environmental governance (Pahl--Wostl, 2015; Partelow et al., 2020; Zurbriggen et al., 2022). All the spatial information was managed in a Geographic Information System (GIS), using free and open-source software QGIS Version 3.22 (QGIS.org, 2022). The GIS allowed to generate and manage: the geophysical and land use variables of the study area; the predictor variables of the water quality model; spatial distribution of the monitoring stations evaluation (according to the geophysical and land use diversity of the basins); a proposal for new monitoring stations; and cartography. The GIS was transversal to all the stages of the project and was combined with the previously described methodologies to achieve the outlined objectives (Fig. 1).

2.2.1. Database construction

This phase entailed the collection and systematic arrangement of geophysical information (geology, geomorphology, edaphology, hydrology, and climatology), point source of water pollution (industrial, urban, and agricultural discharges), and diffuse sources (agricultural uses and livestock stocking density) (refer to supplementary material, Table A.1). Water quality information was also integrated, with a focus on response variables: total phosphorus (TP) and total nitrogen (TN). The TN and TP data used are public and available official information. This analysis involved TP and TN data from fluvial systems within the OAN database, drawn from sampling stations with data series spanning at least three years between 2016 and 2020, with a minimum of three points annually. Fluvial systems featuring significant upstream dams were excluded due to their propensity to induce hydrological and nutrient cycling changes, thereby enhancing the ability to identify water quality drivers related to geophysical, soil and land use attributes. The study engaged 59 monitoring stations for TP during summer (December-March) and 57 during winter (June-September), and 54 monitoring stations for TN during summer, alongside 52 during winter (Fig. 2). The developed GIS facilitated the integration of variables influencing water quality (refer to supplementary material, Fig. B.1).

2.2.2. Creation of a synthetic fluvial network

By following the model outlined by Benda et al. (2016) and utilizing NetMap software (Benda et al., 2011, 2009), a synthetic fluvial network was generated. The process commenced with the ALOS-PALSAR Digital Elevation Model (DEM) of 12.5 m resolution (NASA, 2011) and mean annual precipitation data (Chelsa V1.2; https://chelsa-climate.org/downloads). To refine the generated network, a reference fluvial network compiled from IDEuy (2017–2018)[4] and Agência Nacional de Águas e Saneamento Básico- ANA (https://www.gov.br/ana/pt-br) was employed. The outcome yielded approximately 2 million synthetic segments, with an average length of 285 m. Subsequently, 418 variables comprising climatic, morphometric, geophysical, land use, and anthropic pressure parameters were attributed (Appendix A).

2.2.3. Predictor variables of water quality

To establish statistical associations between water quality variables (median TP and TN for winter and summer) and environmental drivers of the synthetic network defined in 2.2.2, empirical models were formulated. The study employed Generalized Linear Models (GLM), Generalized Additive Models (GAM), and Random Forest (RF). Model performance was assessed using the proportion of response variable variance explained by predictor variables (R^2) and by gauging predictive capability through independent sample analysis, using the root mean square error (NRMSE) (Crawley, 2007; Wood, 2004). Subsequent findings revealed that the RF model exhibited the lowest NRMSE, while the GAM models yielded the highest R^2. Based on these results and considering that GAMs tend to over-adjust data, a hybrid approach was adopted, integrating the predictive potential of the RF model and the explanatory insights of GAMs. The increase in mean squared error (% IncMSE) was used to evaluate the importance of the predictor variables on each RF model. R software, version 2023.06.1 (R-Development Core Team, 2023), was utilized for these analyses, with key libraries including 'mgcv' (Wood, 2011, 2004) and 'randomForest' (Liaw and Wiener, 2002).

2.2.4. Prediction of water quality patterns at the fluvial network scale

With predictor variables and their statistical relationships with TN and TP medians identified, the RF model was leveraged to forecast TP and TN values across fluvial segments falling within the interpolation range. The interpolation range is defined by segments with predictor variable values within the interval spanned by sampled segments.

2.2.5. Evaluation of the current distribution of monitoring stations

An assessment of the spatial distribution of the chosen monitoring stations in 2.2.1 was undertaken in alignment with the environmental attributes of the draining basin. To achieve this, fluvial segments were classified via the K-means method, employing Euclidean distance as the distance measure, while standardizing data (x-mean/deviation). The analysis encompassed both geophysical variables (drainage surface, lithological material, soil depth, mean annual precipitation, mean annual evapotranspiration, altimetry, and mean slopes) and use variables (relative agricultural area, relative forest area, point source

[2] Under the provisions of Act No. 15.239 and its accompanying regulatory decrees, the Ministry of Livestock, Agriculture, and Fisheries (MGAP) has mandated that agricultural producers must furnish a Responsible Soil Use and Management Plan. These plans should encompass property-specific soil considerations, management methodologies, crop rotation sequences, and permissible erosion levels. The General Directorate of Natural Resources possesses a significant repository of edaphic and productivity-related data pertaining to Uruguay's agricultural producers. You can access this database at https://planesdeuso.mgap.gub.uy

[3] https://www.snig.gub.uy/

[4] Project: Production, control, and dissemination of orthoimagery, digital elevation models, and cartography: https://www.gub.uy/infraestructura-datos-espaciales/programas-proyectos-ideuy

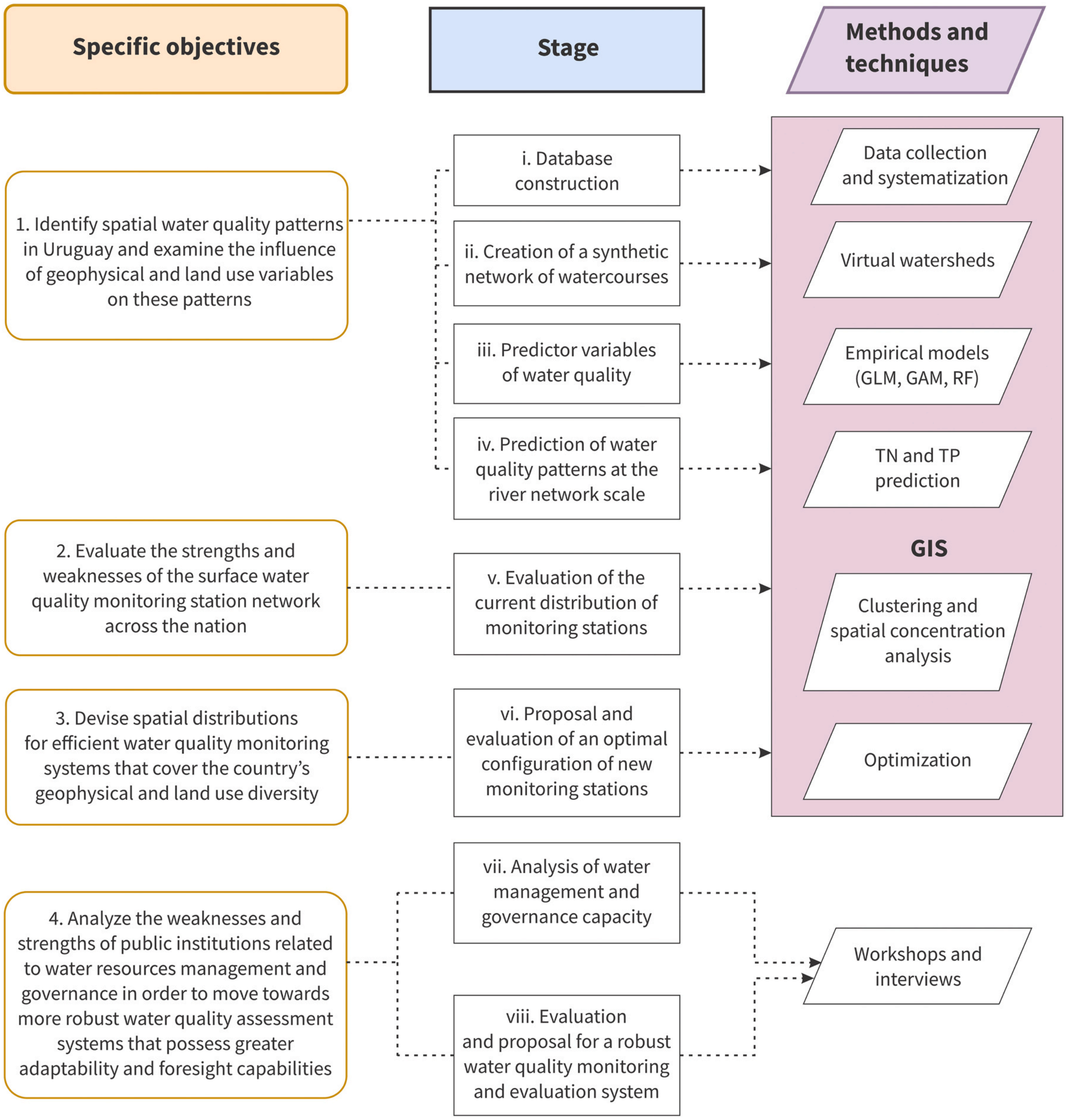

Fig. 1. Flowchart of the research strategy. Specific objectives are connected with the different stages of the project and the latter to the methods and techniques applied to achieve the objectives (dotted arrows). The violet rectangle indicates those methods which relied on spatial data and that were implemented through a Geographical Information System (GIS) and R software (R-Development Core Team, 2023).

pollution, and livestock stocking density). Streams exceeding order 3 (Strahler and Strahler, 1987) were incorporated, as quality monitoring stations were absent in lower-order streams. Consequently, the study focused on 514,222 segments, a subset of the initial 2 million. Subsequently, the Lorenz curve and the Global Spatial Concentration Index (ICEG) (Buzai and Baxendale, 2019) were harnessed to quantify station distribution equity based on stream typologies and associated basins. The ICEG index, ranging from 0 to 100, delineates the percentage-based concentration of a variable within an archetype, reflecting the extent of effort necessary to achieve an equitable distribution among archetypes.

2.2.6. *Proposal and evaluation of an optimal configuration of new monitoring stations*

Various configurations were scrutinized to advance the design of a monitoring network featuring new stations, thereby enhancing territorial coverage. Initial estimation of the new 59 monitoring station distribution among segment groups was based on the ICEG assessment conducted in (2.2.5), doubling the existing number of monitoring for this scenario. An optimization approach using the Generalized Reduced Gradient (GRG) method was employed. The results were contextualized through strategic planning, enabling consideration of spatial segment group distribution and their significance within the Uruguayan society.

2.2.7. *Analysis of water management and governance capacity*

This phase integrates findings from four distinct research projects, as outlined in Table 1. The projects entailed diverse strategies engaging stakeholders within the governance system during the period spanning 2004–2022. Examination of strengths, weaknesses, and challenges related to integrated aquatic system management was undertaken, including the capacity for agreement generation (plans, strategies, and actions) within existing bridging structures (Basin Commissions and Regional Councils). Bridge structures are multi-actor, multi-institutional, multi-level and non-binding spaces of government within the current water governance system. The co-production mode, in line with

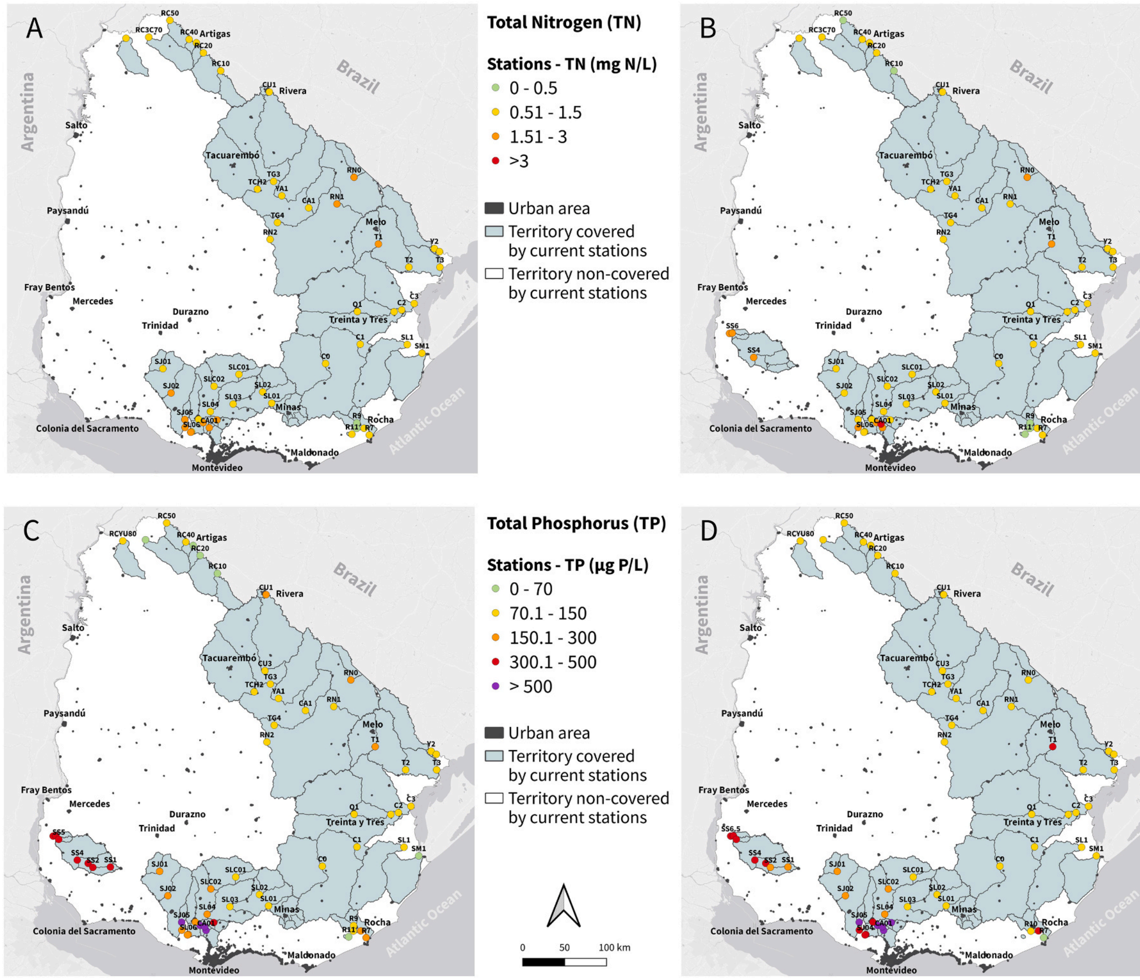

Fig. 2. Spatial distribution of median TN in winter (A) and summer (B), and TP in winter (C) and summer (D), and territorial coverage of current monitoring stations. The territory covered by current monitoring stations corresponds to the area draining into the monitoring stations (station drainage basins). The territory uncovered by current monitoring stations corresponds to the areas of the country that do not drain into monitored water courses. The covered area does not include the basins of monitoring stations located on water courses with upstream dams. The uncovered area includes the country's main agricultural region and important cities on the western part of the country.

Chambers et al. (2021), was employed alongside the evaluation of implementation and follow-up capacities for agreements.

2.2.8. Evaluation and proposal of a robust water quality monitoring and evaluation system

Ultimately, the paper proposes a strategy to construct a robust water quality system, including broader spatial coverage of sampling stations and the incorporation of water quality attributes presently unmeasured. The strategy integrates monitoring capabilities, infrastructure, and laboratories across the country. This aspect was investigated via semi-structured interviews as part of the Virtual Watersheds project (Mazzeo et al., 2022).

3. Results

3.1. Water quality monitoring stations in Uruguay

The distribution of monitoring stations providing nutrient information reveals limited coverage across the national territory, with notable information gaps, especially in the central and western regions (Fig. 2). Uruguay exhibits medium to high nutrient values, which can lead to eutrophication processes. Records for total phosphorus (TP) and total nitrogen (TN) indicate higher concentrations in the southwestern area and lower concentrations in the northern and eastern areas (Fig. 2). Average TP values are higher during the summer period, with greater spatial heterogeneity (Table 2). While the temporal pattern of TN and TP between periods remains relatively stable, there is significant spatial heterogeneity with substantial coefficients of spatial variation in both cases and seasons (Table 2). TP exhibits higher heterogeneity compared to TN.

The assessment of sampling station distribution unveiled limited diversity concerning the value ranges of geophysical and land use variables (Table 3). The scarcity of stations in fluvial segments with drainage basins featuring over 10% relative forestation, exceeding 80% in agriculture, situated at altitudes surpassing 250 m.a.s.l., and within basins marked by high livestock stocking density (LU/Hectare - livestock units per unit area), emerges as a relevant observation.

3.2. Drivers and spatial patterns of water quality in Uruguay

The three models (GLM, RF, and GAM) demonstrated acceptable performance, featuring minimal NRMSE values in the RFs and corresponding R^2 values. GAMs displayed the highest R^2 values, alongside the highest NRMSE values, exceedingly twice the NRMSE of the RFs in three out of four cases (Tables 4 and 5). For the elaboration of RF and GAM models for TP, the four selected variables remained consistent across both periods of the year, ordered uniformly based on their significance in explaining TP for both seasons (Table 4). In contrast, for TN, the

Table 1
Research projects, methodologies, and participating stakeholders in the assessment of water management capacity across departmental and national levels.

Projects	Approaches	Stakeholders
-Dynamics and management of socio-ecological systems. The Laguna del Sauce watershed as a case study. (CSIC-Udelar). 2015–2018	-Semi-structured interviews. -Workshops and discussion groups organized jointly with the Laguna del Sauce Basin Commission on the following topics: strengths and weaknesses of the Laguna del Sauce Basin Commission's performance; communication platform of the Basin Commission's agenda and work; incentive strategies for adequate land and productive systems management; analysis of the basin's land use plan.	-Public institutions at national, departmental and municipal level -Civil society organizations -Academia
-Adaptive co-management of social-ecological systems: challenges for water resources management in Uruguay. Stockholm Resilience Center (Sweden) and SARAS Institute (CSIC, 2017)	-Workshops with Laguna del Sauce and Laguna del Cisne Basin Commissions in order to strengthen the institutional spaces for shared management and make visible existing power dynamics in the governance of socio-ecological systems from a network perspective.	
-The process of building integrated water resources management in Uruguay, state of affairs and controversies. Global Water Partnership (GWP). 2020	-Semi-structured interviews conducted during the COVID-19 pandemic via Zoom. The duration of most interviews was 1 hour 30 minutes, some were in several sessions due to the particular context and reached a total duration of 6 hours.	
-Basis for the design of a national water resources monitoring system from a virtual watershed perspective (ANII- FSDA 1 2018 1 154610). 2020–2022	-Training and information exchange workshops with technical staff of the Ministry of Environment (MA), Ministry of Livestock, Agriculture and Fisheries (MGAP) on databases and statistical tools used in this article. -Semi-structured interviews on strategies for the construction of the national water resources monitoring system in network format. For this last component, semi-structured interviews were conducted with representatives of research groups from Universidad de la República, Pasteur Institute and Clemente Estable Institute.	-Public institutions at national, departmental and municipal level -Academia

contribution of each driver varied between periods. TP models exhibited lower error and a higher degree of fit compared to TN models (Table 5). The importance of each driver in the explanation of the response variable was concordant between RF models and GAMs models.

Table 2
Statistical descriptors for median TP and TN at each sampling site. Units: mg/L = concentration of total nitrogen in milligrams per liter; µg/L = concentration of total phosphorous in micrograms per liter.

	TN (mg N/L)		TP (µg P/L)	
	Summer	Winter	Summer	Winter
n	54	52	57	59
Min	0.3	0.3	60.0	56.0
Max	3.0	5.4	1500.0	875.0
Mean	1.1	1.2	261.7	214.2
Std. error	0.1	0.1	36.7	26.6
Stand. dev	0.5	0.8	277.0	204.5
Median	0.9	0.9	140.0	120.0
25 prcntil	0.7	0.7	100.3	84.5
75 prcntil	1.4	1.5	332.5	280.0
Coeff. Var (%)	50.2	66.4	105.8	95.5

3.3. *Water quality prediction at the scale of fluvial networks*

The prediction of nutrient values within unmonitored fluvial segments, encompassing explanatory variables within the interpolable range, revealed a northeast-southwest gradient increase during both periods (Fig. 3). Elevated TP and TN values were concentrated in coastal and southern regions, intensive agriculture zones, and the eastern rice-growing area. In contrast, the central, northern, and non-rice-growing eastern zones, dominated by extensive livestock farming, exhibited nutrient values below the average.

3.4. *Generation of a classification of fluvial typologies*

Utilizing cluster analysis, twelve distinct groups were identified (Fig. 4, Table 6), effectively distinguishing fluvial segments based on the geophysical and land use characteristics of the associated watersheds (Table 7). These clusters represent the most representative scenarios of the country within the context of environmental impact assessment.

3.5. *Territorial diversity of monitoring stations*

Beyond the absence of monitoring stations in the central and western regions of the country (Fig. 2), the distribution of monitoring stations demonstrates inequity based on stream typology (Fig. 5a). Notably, 56% of monitoring activities concentrate within three segment groups (4, 3, and 9), covering 30% of the drainage area. The distribution of monitoring stations reflects an ICEG of 30%, indicating underrepresentation of nine groups and overrepresentation of groups 3, 4, and 9 (with relative monitoring values exceeding the relative surface area occupied by their drainage basins) (Fig. 5b). Regrettably, segment groups 2 and 10 remain devoid of water quality sampling.

3.6. *Proposal for a robust water quality monitoring and evaluation system with territorial coverage*

A spatial distribution scenario for an enhanced monitoring system, doubling the current number of stations and minimizing distribution inequities, would result in ICEG values of 6.4% (Table 8). However, this proposed scenario does not account for the sampling needs of strategic watercourses and basins, such as those designated for drinking water supply, a factor that can be swiftly integrated into the existing databases and statistical tools.

Fig. 6 illustrates an exercise aimed at strengthening the spatial configuration of the water quality monitoring network based on the study's findings. This exercise contemplates station duplication and distribution, taking into consideration watershed diversity (including natural characteristics and productive activities).

Table 3

Statistical descriptors of geophysical and land use variables for both sampled segments and those meeting the criteria defined in this study, thereby forming the data series. Standard Error (SE), Standard Deviance (SD), Coefficient of variation (COV). * Only segments of order 3 or higher, digitized from satellite images with a geometric resolution of 0.32 m, were included. Units: Km^2= Square kilometers; m.a.s.l= meters above sea level, %= Percentage (used for slopes and for relative surfaces), °C= Degrees Celcius; mm= millimeters, LU/Hectare= livestock units per unit area (hectare), n = number.

	Sampled fluvial segments					Fluvial segments of Uruguay*				
	Mean (min- max)	SE	SD	Median	COV	Mean (min- max)	SE	SD	Median	COV
Stream order	**6.9** (3–10)	0.3	1.8	7.0	26.0	**3.3** (3.0–10.0)	0.0	0,6	3.0	18.8
Area (Km^2)	**5567** (1–71017)	1943	11976	2192	215	**15** (1–71017)	2	366	2	2461
Altimetry (m.a.s.l)	**119** (12.7–243.8)	9.9	61.0	133.2	51.2	**153.0** (9.6–451.5)	0.3	70.5	145.6	46.1
Stream gradient (%)	**0.1** (0.0–0.1)	0.0	0.0	0.1	20.8	**0.1** (0.0–0.4)	0.0	0.0	0.1	38.7
% of Deep soils	**0.5** (0.0–1.0)	0.0	0.3	0.5	52.3	**0.4** (0.0–1.0)	0.0	0.4	0.2	104.5
% of clayey lithology	**0.2** (0.0–1.0)	0.0	0.3	0.1	142.8	**0.1** (0.0–1.0)	0.0	0.3	0.0	241.0
Conductivity of rocks (1 – 5)	**2.2** (1.8–2.9)	0.0	0.2	2.2	10.6	**2.2** (1.0–4.0)	0.0	0.5	2.0	23.8
Medium temperature (°C)	**17.3** (16.2–19.2)	0.1	0.8	16.9	4.6	**17.4** (14.3–19.7)	0.0	0.9	17.5	5.0
Evapotranspiration (mm)	**1473** (1277–1698)	19	116	1487	8	**1520** (1234–1717)	0.5	120	1543	7.9
% of agriculture	**0.3** (0.0–0.8)	0.0	0.2	0.2	77.7	**0.2** (0.0–1.0)	0.0	0.3	0.0	146.6
% of forestry	**0.1** (0.0–0.3)	0.0	0.1	0.0	97.2	**0.1** (0.0–1.0)	0.0	0.2	0.0	238.6
Livestock stocking density (LU/Hectare)	**0.70** (0.29–1.92)	0.04	0.03	0.69	37	**0.68** (0–7.35)	0	0.04	0.65	57
n of point source pollution	**14** (0–165)	5	30	3	218	**0** (0–165)	0	1	0	2568

Table 4

Drivers (x) included in the Generalized Linear Model (GLM), Random Forest (RF) and Generalized Additive Model (GAM) models of Total Phosphorous (TP) and Total Nitrogen (TN) (response variables = y) in order of importance of the predictor variable according to %IncMSE (RF). AG = Surface occupied by agricultural land upstream the fluvial system; DP= Surface occupied by deep soils) upstream the fluvial system; CL= Area occupied by clay soil upstream the fluvial system; PSP= number of point source pollution upstream the fluvial system; RW= Average capacity of the soil to retain water upstream the fluvial system; NG = Surface occupied by natural grasslands upstream the fluvial system; LSD= livestock stocking density upstream the fluvial system.

	Summer				Winter			
	TP		TN		TP		TN	
Importance (% IncMSE)	**Driver (x)**	**Relationship between x and y**	**Driver (x)**	**Relationship between x and y**	**Driver (x)**	**Relationship between x and y**	**Driver (x)**	**Relationship between x and y**
	AG	Positive	RW	Positive at high values of x	AG	Positive	RW	Positive. Then, at high values of X, negative become negative
	DP	Positive at high values of x	NG	Positive	DP	Positive at high values of x	AG	Positive
	CL	Negative	AG	Positive	CL	Negative	LSD	Positive
	PSP	Positive	LSD	Positive	PSP	Positive	NG	Positive

Table 5

Generalized Linear Model (GLM), Random Forest (RF) and Generalized Additive Model (GAM) for median total nitrogen (TN, mg/l) and total phosphorus (TP, μg/l) in summer and winter . Correlation between predicted and response values (R^2) and normalized root mean square error (NRMSE) as a percentage (%) are presented.

	Summer TP			TN		
	GLM	RF	GAM	GLM	RF	GAM
R^2	0.64	0.64	0.80	0.50	0.50	0.76
NRMSE	8.3	4.3	8.3	26.8	11.5	27.2
	Winter TP			**TN**		
	GLM	RF	GAM	GLM	RF	GAM
R^2	0.83	0.79	0.89	0.58	0.55	0.65
NRMSE	6.3	3.5	5.4	28.4	14.0	26.4

3.7. Evaluation of water management and governance capacities, and potential strategies to be pursued in the development of a national monitoring system for inland water resources

The compilation of insights from four projects concerning key capacities and challenges in establishing a robust national water quality monitoring system incorporates inputs from a network of public and private stakeholders within the current governance framework. Since 2004, Uruguay has embarked on a gradual shift from a fragmented and hierarchical water management model (command-control) towards a more integrated and participatory configuration (integrated water resources management). The present landscape comprises 11 basin commissions and 3 regional councils, serving as multiactoral (organized civil society, users, government and academics) for proposing water management solutions at various scales. However, despite regulatory uniformity, each commission's uniqueness hinges upon stakeholder network capacities and limitations. Notably, a dearth of specific support mechanisms impedes interaction facilitation, divergence analysis, and conflict resolution. While overcoming fragmentation in analysis and decision-making is evident in certain watershed commissions, it remains largely unchanged in terms of implementation and monitoring of agreements (plans, strategies, actions) across all of them. Agreement co-production primarily involves interactions between technical and academic stakeholders, corresponding to mode 1 (identifying solutions) as defined by Chambers et al. (2021). Some watershed commissions, such as Laguna del Sauce, exemplify interdisciplinary construction processes, mirroring the attributes of mode 2 (empowering voices).

Public institutions responsible for agreement implementation and follow-up encounter difficulties in adapting to changes since 2004 within the analysis and decision-making processes. These institutions lack consistent reporting on the progress and challenges faced during the implementation of defined measures. Consequently, the system lacks a vital feedback mechanism essential for engaging predominantly volunteer-based stakeholders (e.g., civil society representatives). The bridging structures within Uruguay's system operate as non-binding entities, grounded in social control. Nonetheless, this critical component remains weak due to limited communication capacity. As a result,

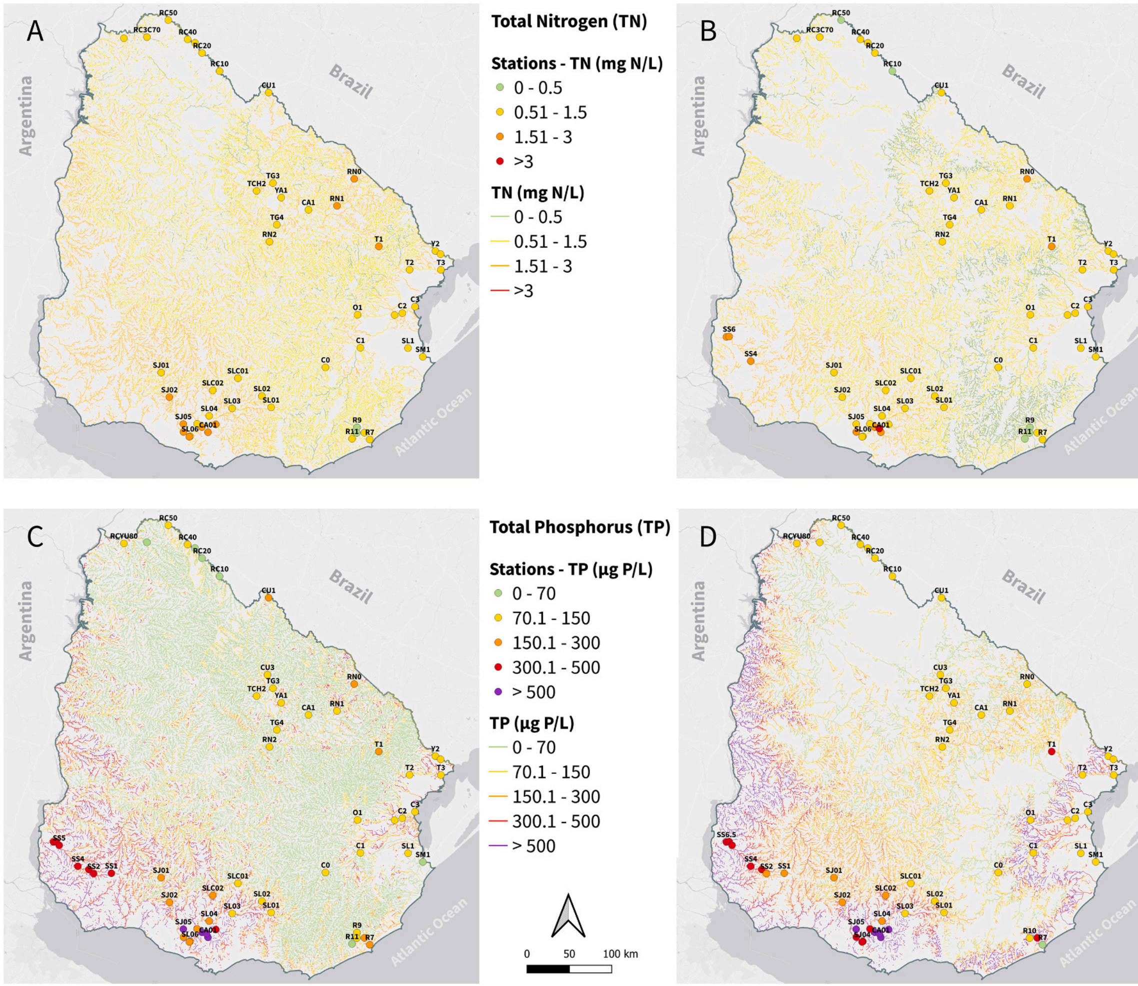

Fig. 3. Predictions of TN in winter (A) and summer (B), and TP in winter (C) and summer (D), using GAM modeling for the segments belonging to the interpolation range. Units: mg/L = concentration of total nitrogen in milligrams per liter; µg/L = concentration of total phosphorous in micrograms per liter.

society remains unaware of work agendas, agreements, and their implementation status. The system's potential hinges on forging new associations among stakeholders, facilitating co-production and co-design of problem-solving solutions, ultimately strengthening response capacities. The main challenge lies in establishing new political interfaces to amplify the influence of water management system stakeholders. Effective participation strategies, fostering commitment, dialog, and trust, are needed for currently unarticulated stakeholders (users, producers, citizens, etc.). Overcoming relational difficulties and joint efforts to devise innovative solutions pose specific weaknesses in the transformational path. Institutional vulnerabilities, such as the lack of dedicated personnel for monitoring and information analysis, are particularly pronounced in two critical nodes of the network: the Ministry of Environment (MA) and OSE (the state water supply and sanitation company). While the outlook is somewhat more promising, challenges persist, especially within the Ministry of Livestock, Agriculture, and Fisheries -MGAP. At the national level, installed capacities at the departmental and municipal tiers remain notably limited. In a hypothetical scenario of robust inter-institutional cooperation, which is yet to be realized, the human, infrastructure, and economic resources remain inadequate to meet the challenge of establishing a comprehensive national water quality system. The inclusion of this challenge is virtually absent from the national budget, with a fragmented approach struggling amid resource competition among ministries, governmental levels, and economic sectors. The transition towards a systemic strategy or the inclusion of a national perspective on this matter remains elusive.

Encouragingly, Uruguay possesses a wealth of spatial data that can facilitate the design of a robust water quality and quantity monitoring system, given genuine inter-institutional and inter-level cooperation and interaction. The country's scale and available economic resources create a conducive environment for constructing a network of monitoring programs that interact and complement each other, combining both decentralized and centralized strategies. Addressing sample collection, spatial distribution, and periodicity requires agreements surpassing specific ministry or governmental level needs. Such a new system calls for the support of regional teams, furnishing field information, and samples to multiple institutions and governmental tiers. This decentralized approach must harmonize with centralized strategies, particularly for resource-intensive analyses, such as pesticide residues, emerging contaminant detection, and environmental metagenomics. In accordance with the aforementioned contributions, a set of monitoring centers is proposed whose final selection took into account spatial connectivity (location and roads), the size and infrastructure of the population centers and the technical capacities installed. Regional nodes, encompassing sample collection, primary analysis, sample preparation for transfer, database generation, and analysis, include locations like Colonia, Maldonado, Montevideo, Paysandú, Tacuarembó and Treinta y Tres. Furthermore, specific analysis centers are designated for tasks like pesticide residue analysis, bioindicators, virology, environmental metagenomics, and bioassays. A network interwoven with decentralized nodes and specialized centers is envisioned (Fig. 6), with OAN proposed as the coordinating entity.

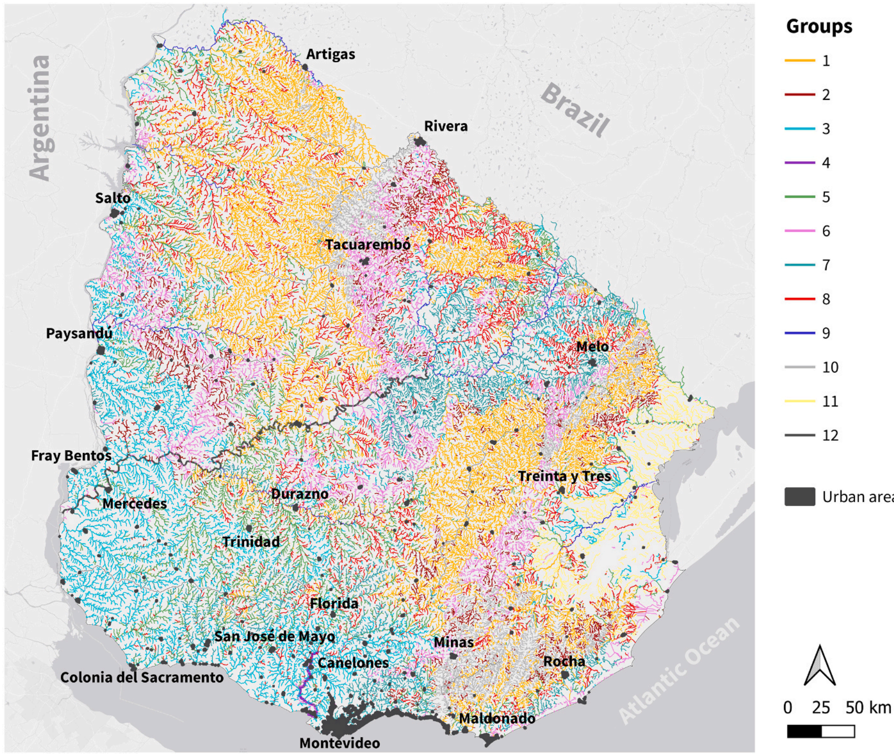

Fig. 4. Groups of watercourse segments according to geophysical and land use conditions.

4. Discussion

The combination of approaches considered allowed us to achieve all the objectives initially set. In order to facilitate the analysis of the results, they are grouped in three subsections according to the order of the specific objectives.

4.1. Spatial patterns and drivers of water quality

Through the research strategy approach, emerging spatial patterns of water quality and the corresponding spatial gradients of environmental drivers, such as soil types, productive land uses, and discharges from point source pollution, were identified. Some of these relationships are rooted in well-established causal mechanisms within the field of limnology (Moss, 2008), such as the impact of diffuse inputs from fertilization or punctual inputs from domestic or industrial effluents on eutrophication processes (Álvarez-Cabria et al., 2016). In some instances, causality involves multifactorial mechanisms, where deep soils naturally exhibit greater nutrient exchanges with aquatic systems compared to shallow and less fertile soils, coinciding (simultaneously) with the spatial distribution of agricultural activities and associated fertilization (Díaz et al., 2021; Hering et al., 2015). No key role for precipitation and evapotranspiration gradients was identified from the database analysis (Bidegain et al., 2013), although they are globally recognized as key attributes that condition the discharge, the dilution capacity of river systems, and the transport of nutrients from terrestrial to aquatic systems. It can be hypothesized that the spatial distribution of agricultural activities, with a greater concentration in the south and south-west of the country, masks this interaction.

The empirical approach enabled the identification of spatial patterns with partially known or unknown causality, shedding light on the relative significance of different predictor variables within distinct biogeographic and socio-economic contexts. This analytical framework not only assists in identifying fundamental research directions across various domains, including Limnology, Landscape ecology, Geostatistics, and Machine Learning, but also facilitates the identification of impacted, control, and reference zones for assessing environmental impacts stemming from land use and human activities. Sound scientific evidence plays a pivotal role in water management and land use planning, as exemplified by Uruguay's recent history, which showcases the potential pitfalls resulting from the absence of robust databases (Alcántara et al., 2022). The generated information holds immense value for multisectoral watershed planning (specially food-water-energy nexus) and the design of multifunctional landscapes that sustain vital ecosystem processes. These potential applications are particularly pertinent to address strategic challenges confronting the country, including the sustainability of productive systems and fulfilling Uruguay's commitments within its climate and biodiversity agendas. Achieving more sustainable production transitions necessitates both predial and multipredial strategies implemented at watershed, landscape, and regional scales. The constructed databases and modeling tools significantly contribute to advancing these goals.

4.2. Current capacities and weaknesses

Uruguay's existing monitoring systems exhibit limited scope, both spatially and temporally, encompassing only a fraction of water quality attributes and a narrow selection of biological and ecosystem indicators, supporting a previous qualitative analysis by Mazzeo et al. (2019). The country lacks a cohesive, systematic approach to water quality management at a national scale. Programs in place cater to specific requirements, often tied to industrial installations (e.g., pulp and paper mills) or watershed management for drinking water supply. Additionally, organizational fragmentation within the State hampers cooperation and synergy among monitoring efforts spread across different ministries and government tiers (Mazzeo et al., 2021). Given the substantial land use changes over the past two decades (Díaz, 2023; Gazzano et al., 2019) and the projected intensification of production models, sustainable water resource management has become an imperative. In short, the existing water quality information generation systems fail to ensure the provision of essential data necessary to sustain anthropic activities without inflicting notable degradation upon inland aquatic ecosystems.

Table 6
General description of watercourse segments' groups. *The total number of segments is reduced to 55,369 because continuous segments of the same group are merged.

Group	N° stream segments*	Brief characterization of segment groups
1	16838	Low-order segments in shallow basalt and upland areas. Segments with small, medium slope drainage basins, on low conductivity, non-argillaceous lithologies and on shallow soils. In addition, their drainage basins register low agricultural and forestry area, with medium livestock stocking density and medium to low number of point source pollution.
2	3862	Low-order segments in upland areas. Segments with small, medium to steep slope drainage basins, on medium conductivity and non-argillaceous lithologies, and on medium or deep soils. Their drainage basins register low agricultural and high forestry area, with low livestock stocking density and medium to low number of point source pollution.
3	6173	Low-order segments located in the south and south-west coastal zone and marginally in Merín Lagoon and Tacuarembó river basins. Segments with small, low-slope drainage basins, on low conductivity and non-argillaceous lithologies, and on deep soils. They register very high agricultural and low forestry area, with low livestock stocking density and a very high number of point source pollution.
4	1	Lower segment of the Santa Lucía river. Segment of an extensive drainage network, with medium to low slope, on low conductivity and non-argillaceous lithologies and on deep soils. Located in basins with high agricultural and low forestry area, with medium livestock stocking density and a very high number of point source pollution.
5	4935	Low to medium order segments, located in the center-south and north coast of the country. Segments with medium to small drainage basins, medium slopes, on low conductivity and non-argillaceous lithologies and on deep soils. They register very high agricultural and low forestry area, with low livestock stocking density and a very high number of point source pollution.
6	5734	Low-order segments, with medium to small, medium slope drainage basins, on high conductivity and non-argillaceous lithologies and on deep soils. In addition, they register agricultural and forestry area of around 10% (average values), with medium livestock stocking density and a high number of point source pollution.
7	4436	Segments located in the upper Río Negro and Santa Lucía river basins and in eastern areas of Río de la Plata and Atlantic Ocean basins. Low-order segments, in medium to small drainage basins with moderate mean slopes, on high conductivity and clayey lithologies and on deep soils. They register high agricultural and low forestry area, with medium livestock stocking density and a very high number of point source pollution.
8	6385	Segments located in several areas of the country. Low-order segments in medium to small drainage basins, with gentle slopes, on low conductivity and non-argillaceous lithologies and on deep soils. Their main land use is livestock and, in some areas, agriculture. They present a very high livestock stocking density and medium to low number of point source pollution.
9	9	Lower segments of large rivers, such as Yí, Queguay Grande, Arapey Grande and Tacuarembó rivers. Segments with large drainage basins, with slight average slopes, on clayey and low conductivity lithologies. They show high agricultural and forestry area, medium livestock stocking density and medium number of point source pollution.
10	6065	Segments in small drainage basins located in northern and eastern uplands. Low-order segments with steep slopes, on low conductivity and non-argillaceous lithologies and on superficial soils. They register low agricultural and forestry area, low livestock stocking density and a low number of point source pollution.
11	930	Segments of Laguna Merín basin watercourses. Segments with small drainage basins, with very low slope, on clayey and low conductivity lithologies, and on deep soils. They show medium irrigated agriculture area, forestry is marginal, livestock stocking density and point source pollution. are low.
12	1	Lower segment of the Río Negro river basin. Segment with a large drainage basin, of moderate slope, on clayey and high conductivity lithologies and deep soils. Agricultural and forestry are the major land uses. Livestock stocking density is medium, and the number of point source pollution is low.

The main results also yielded insight into optimizing the spatial configuration of monitoring stations, leading to proposals for their enhancement. The final proposition envisions the optimization of new stations, considering both geographic diversity and the strategic needs of the country. However, it is probable that the incorporation of key water quality variables (currently not monitored) into the new monitoring network will require the identification of reference zones and the addition of new sampling stations. Similarly, evaluating fluvial systems impacted by large dams, both in terms of modeling and spatial pattern identification, as well as in assessing new stations, presents a crucial avenue for future exploration (aspects not addressed in this study). Additionally, the inclusion of lentic water ecosystems, such as lakes, reservoirs, and coastal lagoons, will necessitate tailored analyses and the establishment of new monitoring stations. An equally vital challenge for the country pertains to its emerging System of Protected Areas (SNAP),[5] which currently lacks the foundation for establishing reference or control zones. The design of protected areas must confront this challenge, with the databases and statistical tools developed herein serving as essential contributions in this context.

4.3. Opportunities for change

Uruguay's socioeconomic foundation is intricately tied to the sustainability of its primary production systems, including agriculture, livestock, and forestry. Assessing the impacts of these production systems, understanding fluvial ecosystem responses to changes in land use and production practices, and evaluating system reactions to sanitation infrastructure development, all require robust monitoring and evaluation systems. Although the existing water quality monitoring system is frail, its rapid reinforcement is feasible using spatial information from watersheds, given the country's size and road connectivity. In this trajectory, enhancing connectivity and complementarity among existing monitoring programs is essential to achieve objectives that extend beyond their original scope or the responsibilities of supporting institutions. Incorporating new water quality attributes into monitoring programs led by entities responsible for drinking water supply and sanitation (such as OSE) or subnational environmental directorates represents a potent leverage effect. Nevertheless, this endeavor requires cooperation and resources that are currently scarce.

The envisioned network of centers (Fig. 6) serves as a preliminary proposal, inviting further discussion. The ultimate challenge lies in the political, economic, and social realms, particularly in formulating a long-term strategy grounded in broad consensus. These centers, beyond meeting institutional information demands at national and sub-national levels, can fulfill other state roles, including oversight of measures and plans, educational and outreach initiatives associated with their design and implementation. Such shared physical spaces and resources surmount the traditional fragmentation often encountered within the State

[5] https://www.gub.uy/ministerio-ambiente/areas-protegidas

Table 7
Groups of watercourse segments and description of variables that determine the groups. Units: Km^2= Square kilometers; m.a.s.l= meters above sea level, %= Percentage (used for slopes and for relative surfaces), mm= millimeters, n = number; LU/Hectare= livestock units per unit area (hectare). * The area calculated is greater than the group watercourses' drainage area. Many watercourses drain towards higher hierarchy ones from the same group and therefore, their drainage area is overestimated.

Group	Area (Km^2)			Slope (%)		% of clayey lithology		Conductivity of rocks (1–5)		% of deep soils		% of agriculture		% of forestry		n of point source pollution		Livestock stocking density (LU/Hectare)	
	total*	$\bar{x}$	range	$\bar{x}$	range	$\bar{x}$	range	$\bar{x}$	range	$\bar{x}$	range	$\bar{x}$	range	$\bar{x}$	range	total		$\bar{x}$	range
1	172459	10	(0.1–5298)	7.0	(3–13)	0.01	(0–0.7)	1.85	(1–2.7)	8.2	(0–80)	2.6	(0–50)	2.3	(0–50)	78	–	0.75	(0–1.7)
2	16684	4	(0.1–309)	8.0	(4–19)	0.06	(0–1)	2.43	(1–4)	28	(0–100)	2.3	(0–60)	71.7	(30–100)	6	–	0.25	(0–1.0)
3	94080	15	(0.1–5145)	5.0	(2–10)	0.06	(0–1)	2.22	(1–4)	81.9	(0–100)	79.3	(10–100)	1.9	(0–50)	899	–	0.37	(0–1.5)
4	13446	13446	(13446–)	5.0	(5)	0.20	(0.2)	2.18	(2.2)	52	(50)	49.7	(50)	4.8	(4.8)	165	–	0.78	(0.78)
5	120449	24	(0.1–7324)	6.0	(3–12)	0.04	(0–0.6)	2.04	(1–3.2)	38.3	(0–100)	50.9	(0–100)	2.7	(0–40)	228	–	0.58	(0–1.5)
6	70188	12	(0.1–3522)	7.0	(1–13)	0.03	(0–0.7)	3.04	(2–4)	46	(0–100)	12.7	(0–100)	8.9	(0–60)	109	–	0.68	(0–2.24)
7	48806	11	(0.1–1074)	6.0	(3–14)	0.81	(0.3–1)	2.36	(1–4)	65.6	(0–100)	32.5	(0–100)	4.7	(0–80)	289	–	0.78	(0–2.7)
8	55107	9	(0.1–2889)	6.0	(0–14)	0.08	(0–1)	2.09	(1–3.5)	55	(0–100)	11	(0–100)	1.5	(0–60)	62	–	0.124	(43–7.3)
9	118041	13116	(9024–18746)	6.0	(6–7)	0.16	(0–0.4)	2.21	(2.1–2.4)	43	(30–60)	19.8	(10–40)	6.1	(0–10)	93	–	0.66	(0.5–0.8)
10	28241	5	(0.1–747)	13.0	(9–39)	0.01	(0–1)	2.14	(1–4)	3.2	(0–100)	1	(0–80)	5.5	(0–80)	33	–	0.50	(0–1.5)
11	15713	17	(0.2–743)	4.0	(2–8)	0.79	(0–1)	2.15	(1.8–3)	91.8	(0–100)	60	(0–100)	1.2	(0–60)	8	–	0.56	(0–2.8)
12	71017	71017	(71017)	6.0	(6)	0.16	(0.2)	2.31	(2.3)	52.6	(50)	24.4	(20)	8.5	(10)	76	–	0.63	(0.6)

concerning cross-cutting environmental issues. This approach also offers substantial resource savings.

Constructing a robust national water quality monitoring system entails a significant economic endeavor for Uruguay's scale. Consequently, the strategy must effectively cater to information needs across multiple ministries and governmental tiers. This represents a considerable challenge for a nation historically inclined towards centralization. Nevertheless, the decentralization processes witnessed within the Instituto Nacional de Investigación Agropecuaria -INIA, the Universidad de la República-Udelar, and the Universidad Tecnológica del Uruguay-UTEC, coupled with their interaction and shared campus initiatives, illustrate potential pathways for incorporation. To chart a successful course in water management and avert crises like those in the drinking water supply sector, Uruguay must draw from past lessons (CIDE-PNDES, 1966). Integrating public policies for monitoring and management purposes, the country boasts a global example of early soil classification and mapping system development in the late 1960 s and early 1970 s. Leveraging this foundation, Uruguay established a taxation system linked to soil productivity (CONEAT productivity index, MGAP, 1994), facilitating land use and management plan implementation in the present era (DGRN-MGAP, 2013; Zurbriggen et al., 2020). In a similar vein, aligning information generation from land use and management plans, livestock traceability, and the National Agricultural Research System (SNIA) serves as another pivotal lever for transforming the national water quality monitoring and evaluation system. Uruguaýs trajectory of soil management and energy matrix transformation offers insights into the power of technical-academic collaboration and support alongside political backing. While these synergies have expedited progress in the energy matrix during the past decade (Méndez, 2021), water management has yet to benefit fully from such virtuous interactions

In the realm of contemporary environmental governance systems (Pahl-Wostl, 2015; Partelow et al., 2020; Zurbriggen et al., 2022), networks of public and private stakeholders, comprising participatory spaces like basin commissions, serve as foundations for robust and transparent inland aquatic resource monitoring and management. These mechanisms promote effective, well-informed participation and a deeper understanding of pertinent issues. Embracing management grounded in scientific evidence constitutes an essential stride, enabling a better grasp of the resources at hand, and comprehending the impacts of human activities, including water management systems and public policy implementation. This capacity to navigate change, anticipate shifts driven by climatic and non-climatic factors, and manage associated uncertainties necessitates learning, failure detection, and continuous improvement (Boyd and Folke, 2011), all underpinned by robust scientific evidence. The current study's contribution is a primary step, responding to challenges that mandate the active engagement of a network of public and private stakeholders. These stakeholders must comprehend and leverage monitoring system information, acknowledge the significance of allocating resources and efforts to system construction. It is essential to remember that environmental challenges fundamentally stem from social and political factors (Alcañiz and Gutiérrez, 2022). Uruguay is undergoing significant shifts in water management paradigms. However, the varying perspectives on different worldviews regarding the human-nature relationship, water as a fundamental human right, and the role of the state in water management, currently hinder the creation of constructive frameworks that could effectively drive and support transformative processes. Recent crises in Montevideo's drinking water supply and water quality concerns over the past 15 years (Goyenola, 2023; Goyenola et al., 2021; Trimble et al., 2022) underscore the urgency of transformative measures to bolster short-term resilience (via adaptation and transformation).

5. Conclusions

Developing a robust water quality monitoring system presents a profound environmental management challenge. The approach

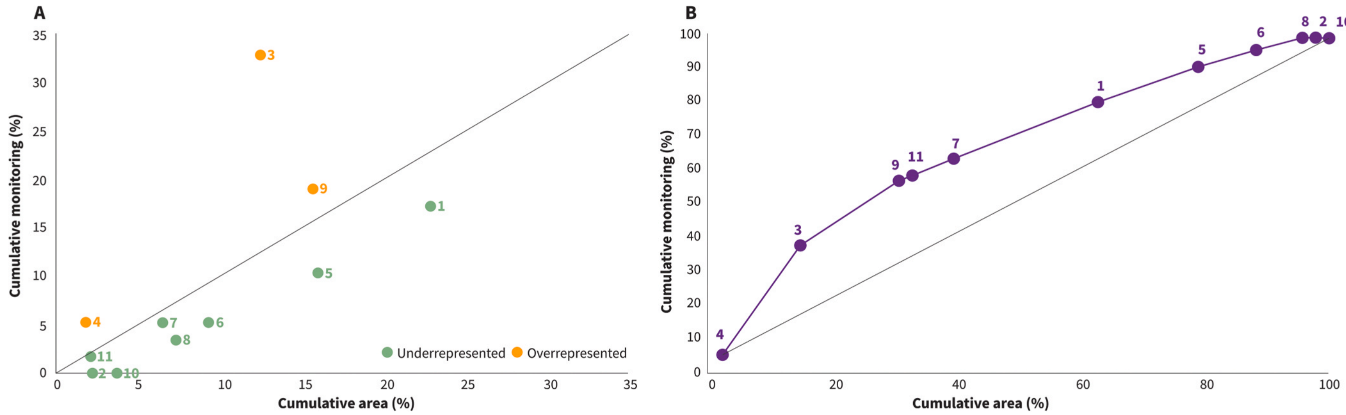

Fig. 5. A) Relationship between stations distribution (%) and the relative area of drainage basins across various watercourse segment groups. "underrepresented" and "overrepresented" are terms that express a relative assessment, based on the %area/%monitoring ratio. B**) Lorenz curve showing the distribution of stations based on the surface area covered by the drainage basins from different watercourse segments groups.**

Table 8
Distribution by group of current monitoring and the scenario of a 100% increase in the number of monitoring instances.

Group	No current monitoring	No monitoring in the scenario of a 100% increase
1	10	23
2	0	3
3	19	20
4	3	3
5	6	18
6	3	10
7	3	7
8	2	8
9	11	17
10	0	4
11	1	3

employed here, founded on inter and transdisciplinary perspectives, offers a robust avenue for assessing current capacities and to formulate overcoming strategies. The study's main conclusions show that Uruguay's water quality monitoring program is deficient and requires enhancing spatial coverage, improving temporal scale, and including new attributes; a public institutional nodes network, combining decentralization and centralization strategies, is crucial to improve the water monitoring and management system; and the solutions should incorporate the transition towards an effective integrated and participatory water management model. A solid design and robust evaluation of public policies linked to water (as well as water-food-energy interactions) are built on good databases, an essential and urgent step in the context of transformation that Uruguay is navigating.

The improvement strategies involve the redesign of the current water quality monitoring system, considering the national scale and the interactions with the types and uses of land, as well as the agricultural development trends of the country. The incorporation of key water quality attributes, currently not surveyed, can be analysed and designed on the same conceptual-methodological bases. The main challenges lie in the current functioning of the governance system. Strengthening the national water quality monitoring system requires solid intra- and inter-institutional interactions and between levels of government, very limited to date. The proposed change constitutes a fundamental pillar to promote an effective capacity for adaptation and anticipation, and greater traceability of land use changes and their effects.

Uruguay's scale and existing capabilities suggest that swift progression from lagging behind to a leading example is feasible. However, simplistic extrapolations of our strategy must be avoided, particularly the combination of centralized and decentralized approaches. Historically, examples of virtuous transformation in Uruguay were based on close interaction between political-technical-academic actors (i.e. soil policy and energy matrix). Moving forward on the proposed path has the potential to consolidate the country's transition to an integrated and participatory water management model.

Funding

This research was funded by ANII (ANII_FSDA_1_2018_1_154610) and FTPA INIA-SARAS (Plataforma para la construcción de herramientas y capacidades para el diseño de transiciones productivas sostenibles en Uruguay). Additionally, NM, CZ, CC and ID were supported by the National Researchers System (SNI-ANII-Uruguay) and FJP by the I+D+I project RIFFLE PID2020-114427RJ-I00 funded by MCIN/AEI/10.13039/50110001103.

CRediT authorship contribution statement

Mazzeo Néstor: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ciganda Ana Lía:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fernández Nion Camila:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Peñas Francisco J:** Writing – original draft, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **González-Ferreras Alexia María:** Writing – original draft, Software, Formal analysis, Data curation. **Crisci Carolina:** Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation. **Zurbriggen Cristina:** Writing – original draft, Supervision, Investigation, Formal analysis. **Pérez Daniel:** Writing – original draft, Investigation, Formal analysis. **Barquin José:** Writing – original draft, Supervision, Methodology, Conceptualization. **Díaz Ismael:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

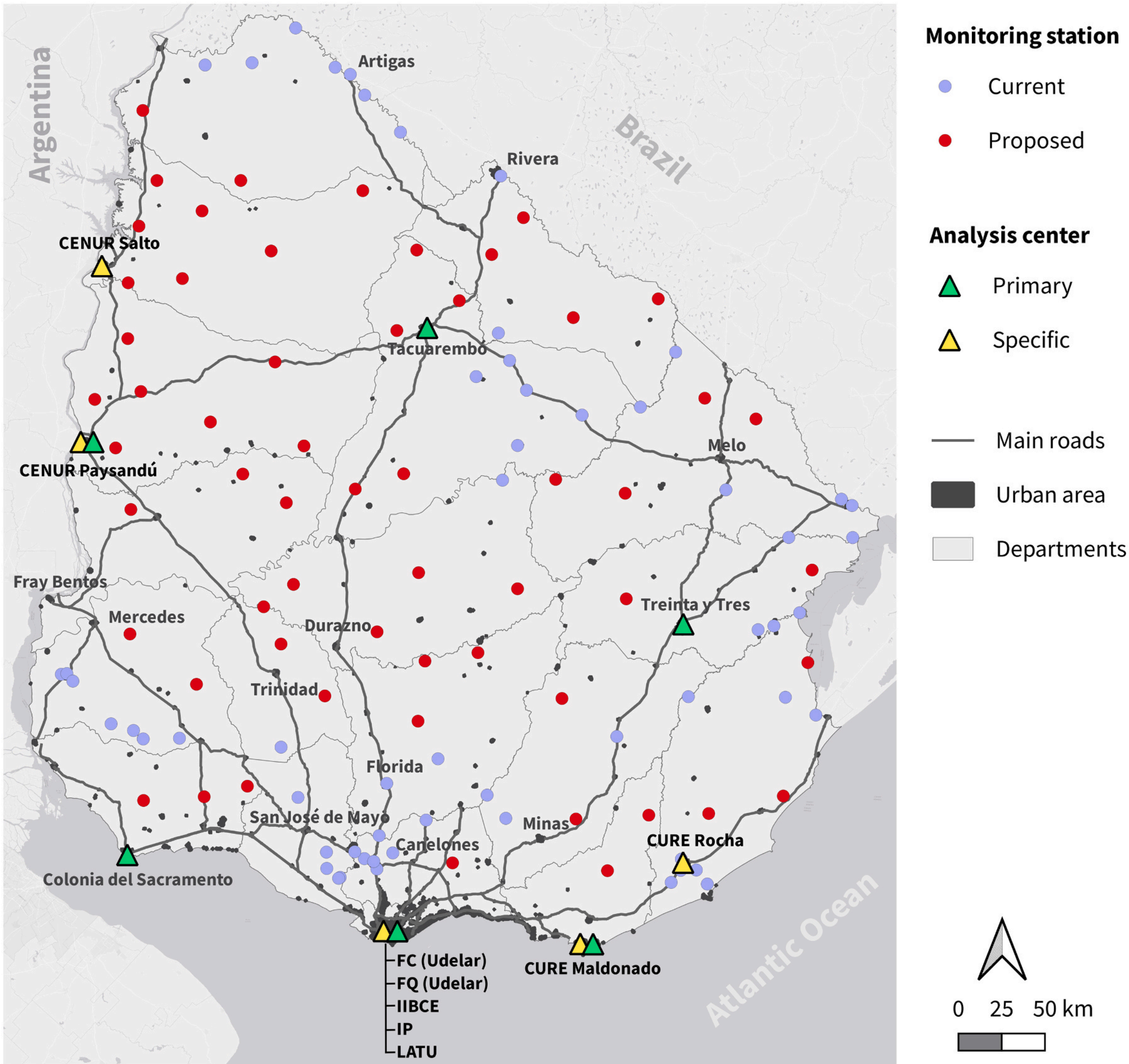

Fig. 6. Water quality monitoring stations, and primary sample analysis centers, along with specialized analysis centers. Current spatial distribution of monitoring stations in fluvial systems and proposed distribution for the scenario of doubling the number of monitoring stations. The stations considered for the current distribution are those with: a) submitted data series spanning at least 3 years between 2016 and 2020 and b) a minimum of 3 samples per year. Cities with specific analysis centers also include primary analysis. Montevideo: Facultad de Ciencias (FC-UdelaR, bioindicators and biomarkers at different levels of organization, land use cover), Facultad de Química (FQ-UdelaR, pesticide residues), Instituto de Investigaciones Biológicas Clemente Estable (IIBCE, metagenomics), Instituto Pasteur de Montevideo (IP, metagenomics and virology), Laboratorio Tecnológico del Uruguay (LATU, water quality bioassays). Rest of the country: CENUR-Salto UdelaR (virology), CENUR-Paysandú UdelaR (pesticide residues), CURE-Rocha UdelaR (metagenomics), CURE-Maldonado UdelaR (bioindicators and biomarkers at different levels of organization). The centers in charge of sample collection and primary analysis of physical-chemical properties are: Paysandú, Tacuarembó, Colonia, Montevideo and Maldonado. The spatial distribution of these centers took into account the territorial connectivity and the installed capacities of institutions.

Data availability

Data will be made available on request.

Acknowledgments

The authors express their gratitude to: the specialists who participated in the initial project planning interviews; the scientists and technicians who participated in the workshops; and the institutions that provided data and information (IDEuy and Ministerio de Ambiente) . Additionally, we thank Guzmán López for his help with the R scripts, Leticia González Carreira for the litological reclassification and Lee Benda and Daniel Miller from Terrainworks for the support with the Netmap software.

Author Agreement Statement

On behalf the authors, I declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

The manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. I further confirm that the order of authors listed in the manuscript has been approved by all.

I am responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2024.103699.

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