Water Quality Assessment in Urban Watersheds of Tierra del Fuego: A Perspective from the Integrated Water Resources Management

Soledad Diodato, Yamila Nohra, Gerardo Noir, Julio Escobar, Romina Mansilla, and Alicia Moretto

Abstract Water quality deterioration is one of the most challenging environmental problems in the world. Land use change like urbanization has several impacts on the presence, utilization and management of water resources. The Province of Tierra del Fuego, Southernmost Patagonia, Argentina, is not exempt from the challenges that happen at a global scale. Several problems derived from the high pressure that natural resources are subjected to are evident. Therefore, the generation of information is of great relevance within the Integrated Water Resources Management (IWRM) framework with an Ecosystem Approach (EA). Water Quality of five relevant watersheds of Tierra del Fuego from the Río Grande and Ushuaia cities was systematically monitored during the period 2008–2019, assessing physicochemical and microbiological parameters. The Canadian Council of Ministers of the Environment Water Quality Index was applied to simplify and facilitate the transmission of the generated information to diverse actors. Although downstream sampling sites presented fair to poor water quality, headwaters from water intakes remains of good quality. It is necessary to implement IWRM with an EA as a way of preserving environmental and population health.

Keywords Urbanization · Water quality monitoring · Río Grande · Ushuaia · Water sources

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S. Diodato (✉) · J. Escobar · R. Mansilla · A. Moretto
Centro Austral de Investigaciones Científicas, CONICET, Ushuaia, Argentina
e-mail: sdiodato@conicet.gov.ar

S. Diodato · R. Mansilla · A. Moretto
Instituto de Ciencias Polares, Ambiente y Recursos Naturales, Universidad Nacional de Tierra del Fuego, Ushuaia, Argentina

Y. Nohra · G. Noir
Dirección General de Recursos Hídricos, Secretaría de Ambiente, Ministerio de Producción y Ambiente de Tierra del Fuego, Ushuaia, Argentina

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1 Introduction

Water, as a vital resource for the life and the development of the society, must be managed for the benefit of the entire population, since it is a scarce resource in time and space, it has low costs, sometimes does not have legal protection measures and it is subjected to the vulnerability of pollution. This fact implies that the local government authorities have to assume the responsibilities related to its management, conservation, control and regulation of its appropriate use. If there is or will be a water crisis there will also be a development crisis; therefore, water management has to do with how this vital natural resource is managed (Al Radif 1999).

Worldwide, there is a competition for the multiple uses of water due to population, energy and agricultural demands. As the population increases and the economy grows, the need for water provision and the pressure on water resources increases (Giri and Qiu 2016). In essence, water management is a conflict management, which allows focusing on several interests related to the quantity and quality of water; and involving the design and use of practical and effective mechanisms to solve the future conflicts (Martínez Valdes and Villalejo García 2018).

During the recent decades, river water quality and the different problems related to the presence, utilization and management of water resources have been matter of constant concern (Al Radif 1999; Zamparas and Zacharias 2014; Chittoor Viswanathan and Schirmer 2015). Direct and indirect impacts of urbanization and agricultural activities degrade water quality, as the consequence of land use change (Yu et al. 2013; Giri and Qiu 2016; Miller and Hutchins 2017). Agricultural activities involve the use of increasing amounts of fertilizers, pesticides, herbicides, and dairy manures in croplands to fulfill the food demand of human population and some of them enter into the nearest water bodies (Giri and Qiu 2016). Urbanization increases impervious surfaces such as parking lots, roads, and sidewalks, resulting into an increase in runoff which creates an additional pathway for the transportation of pollutants from landscape into water bodies (Wilson and Weng 2010; Glińska-Lewczuk et al. 2016).

As a consequence of urbanization, a great number of rivers and streams are highly contaminated due to the anthropogenic activities such as industrial and sewage disposal (Almeida et al. 2007; Zagarola et al. 2017; Granitto et al. 2021). The problem increases when the depurating capacities of these aquatic systems are significantly reduced in relation to the amount and kind of contaminating substances received (Almeida et al. 2007; Oliva González et al. 2014). In this sense, river pollution endangers water reserves and the ecosystem services related to it. Therefore, every problem associated with the lack of water and the deterioration of its quality constitutes an important issue for the twenty-first century.

The Integrated Water Resources Management (IWRM) is defined as “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner, without compromising the sustainability of vital ecosystems" (GWP 2000). This approach promotes moving from fragmentation to integration, from the mere exploitation of the resource to the conservation and rational use of it, from the management of supply to the management of demand, from paternalism to participation, from centralization to decentralization, from infrastructure management to efficient administration (Martínez Valdes and Villalejo García 2018).

The Province of Tierra del Fuego (TDF), Southernmost Patagonia, Argentina (Fig. 1a), is not exempt from the problems that happen at a global scale. For many years, the Fuegian community has been concerned about local water resources, which led in 2016 to the enactment of the Framework Law for the Integrated Water Resources Management N^{o} 1126. The goal of this regulation is to build and promote an IWRM, in order to overcome threats, and to reduce vulnerability to scarcity or deterioration in water quality. These problems derive from the high pressure that the basins' natural resources are subjected due to the development of activities that impact them. This holistic concept is developed worldwide and is used to explore new forms of relationships between water and society within the Ecosystem Approach (EA) (IPBES 2019; Noir 2019). In this context, the generation of information is of great relevance within the framework of what is established by IWRM with an EA: the forests, peatlands, glacial environments and wetlands of TDF play a fundamental role due to the ecosystem services they provide for the conservation of the quantity and quality of water (Zagarola et al. 2014; Mrotek et al. 2019).

In TDF, 97% of the total population (127,205 inhabitants, INDEC 2010) is concentrated in the urban areas, in the cities of Río Grande, Ushuaia, and Tolhuin. The city of Río Grande is crossed by the largest basin of TDF. The Grande River watershed (GR) is a binational basin located in the southern portion of Argentina and Chile. Its importance lies in its large size and the magnitude of its annual average flow (40 m^3 seg^{-1}), receiving important tributaries in the Argentine sector of TDF (Iturraspe and Urciuolo 2000). Also, it is the basin with the greatest number of uses in the province (drinking water, tourism, animal husbandry, fishing, oil activity, etc.), as well as the one that involves several social actors related to the different water uses. The GR is the drinking water source of Río Grande city, with the water intake located a few kilometers above the city. Also, the touristic and recreational use of water in the middle and lower basins has acquired great importance since numerous ranches have diversified their activities towards agrotourism and the establishment of fishing preserves (Urciuolo et al. 2009). Given its characteristics and ecological importance, this sector of 220 km of coast was incorporated into the Provincial System of Protected Natural Areas through the creation of the "Atlantic Coast Reserve" (1992; https://whsrn.org/es/whsrn_sites/costa-atlantica-de-tierra-del-fuego/), assigning it the category of Coastal Natural Reserve. In addition, since 1992 it constitutes a site of the Western Hemisphere Shorebird Reserve Network and a wetland of international importance declared a RAMSAR site (SAyDS 2009). The GR flows into the protected marine coastal zone constituting an estuary, where the city of Río Grande is located. The significant urban and industrial expansion of the city based on economic promotion laws of the 1970s, has caused changes in land use, as well as situations that altered the water quality of the estuary such as human settlements in the riverside

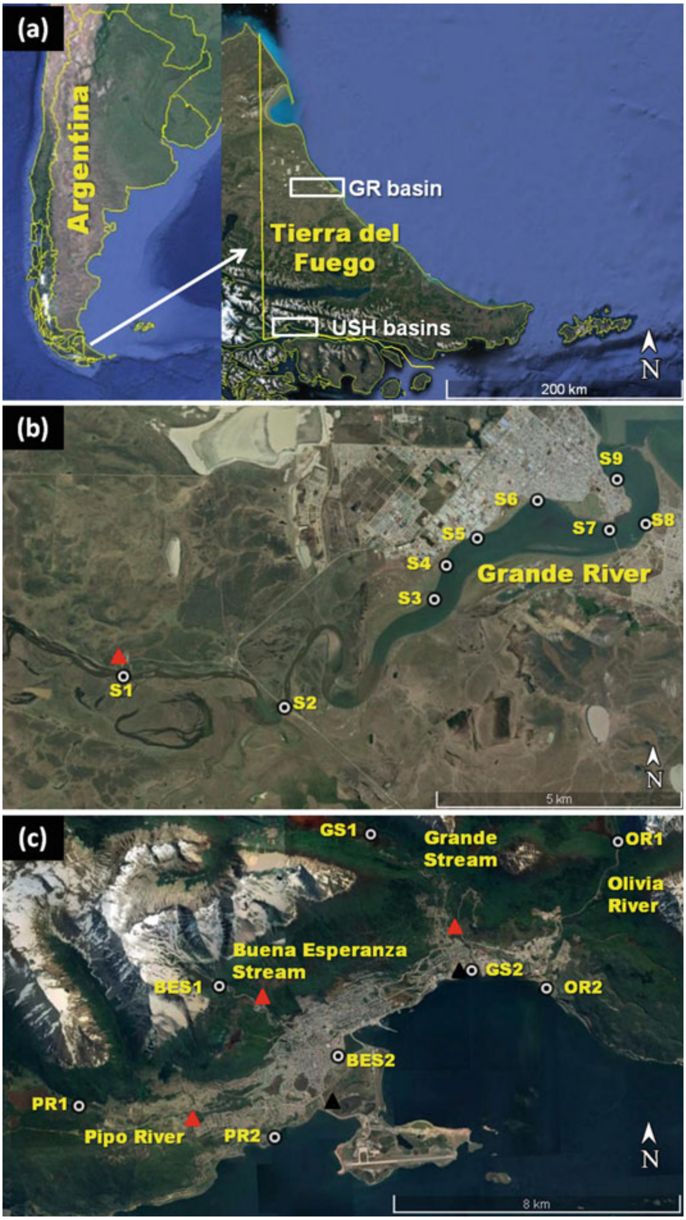


Fig. 1 Maps showing the location of the study area in Tierra del Fuego, Argentina (**a**), and the sampling sites at Grande River basin (**b**; S1–S9), and at four watersheds in Ushuaia city (**c**): Buena Esperanza Stream upstream (BES1) and downstream (BES2); Grande Stream upstream (GS1) and downstream (GS2), Olivia River upstream (OR1) and downstream (OR2), and Pipo River upstream (PR1) and downstream (PR2). Red triangles indicate drinking water treatment plants, and black triangles indicate wastewater treatment plants

and flooded areas, effluent discharges without treatment, and presence of solid wastes on the banks. In this way, the anthropogenic impact on the wetland has generated severe changes in the landscape of this relevant site (Lofiego et al. 2009), which also constitutes an environment of great importance for the inhabitants of Río Grande city.

The city of Ushuaia is defined by four main watersheds: Buena Esperanza Stream (BES), Grande Stream (GS), Olivia River (OR), and Pipo River (PR) (Iturraspe and Urciuolo 2000). Although each water course presents particular characteristics and defined uses, the major problem they have been subjected to is the negative consequences of urbanization. The population has exponentially increased in the last decades (from 7000 inhabitants in 1970 to approximately 60,000 in 2010; INDEC 2010). The main reason for this population growth was the promulgation of the Argentinian National Law N° 19,640 of industrial promotion and customs benefits, which motivated immigration from the central and northern provinces of Argentina. These facts led to substantial changes in land use, mainly due to the need for space for urban and industrial settlements. The urban expansion was not largely accompanied by the development of the necessary infrastructure to provide services such as drinking water and sewers to all the population. Therefore, the degradation of fluvial watersheds that cross the city and consequently, the coastal system of Ushuaia city has been subjected to the impact of raw sewage effluents (Amin et al. 2011; Zagarola et al. 2017; Diodato et al. 2018, 2020; Granitto et al. 2021).

Evaluation of limnological parameters can be considered an essential tool in the study of environmental problems, contributing to the knowledge of the main functioning mechanisms of aquatic ecosystems, assisting in water quality management, with a substantial role in the monitoring and recovery of water bodies, mainly regarding eutrophication control (Almeida et al. 2007; Akkoyunlu and Akiner 2012; Poonam et al. 2013; Oliva González et al. 2014; Glińska-Lewczuk et al. 2016). The information that provides the evaluation of limnological parameters are comprehensible for scientists; however, this type of information should also be meaningful to managers and decision makers who want to know about the state of their local water bodies. For this reason, water quality indexes (WQI) were designed with the aim of creating a mean of communicating water quality issues (CCME 2001).

One of the most commonly used indexes was developed in 2001 by the Canadian Council of Ministers of the Environment (CCME): the CCME Water Quality Index (CCME WQI). This index has been used widely worldwide to evaluate the water quality in rivers and other water bodies (Akkoyunlu and Akiner 2012; Bilgin 2018; Gikas et al. 2020; Hossain and Patra 2020). The CCME WQI offers several advantages over other methods, including compliance with different legal requirements and different water uses, eligibility for water quality assessment in specific areas, flexibility in the selection criteria, and tolerance for missing data. On the other hand, it does not require a huge number of different water quality parameters for its development and validation (CCME 2001). The index incorporates three elements: *scope*—the number of parameters not meeting water quality guidelines; *frequency*—the number of times these guidelines are not met; and *amplitude*—the amount by which the guidelines are not met (CCME 2017). The index produces a number between 0 (worst water quality) and 100 (best water quality) and is divided into five descriptive categories to simplify its presentation: “poor”, “marginal”, “fair”, “good”, and “excellent”.

The CCME WQI can be used to track changes at one site over time and comparisons among sites. If used for the latter purpose, care should be taken to ensure that there is a valid basis for comparison. Sites should be compared when the same parameters and guidelines, time periods and numbers of samples are used. Otherwise, each site should be measured against its ability to meet relevant guidelines (CCME 2001, 2017; Hossain and Patra 2020).

In the present study, the hydrographic basin is the scale of study. Moreover, they are the geographic spaces where groups and communities share activities, socialize and work, based on the availability of renewable and non-renewable natural resources. Based on the foregoing, we can conclude that in hydrographic basins it is possible to identify real-scale solutions to problems to water situations and risks, which is why they constitute the ideal territories to carry out IWRM (Noir 2019).

Although past and current uses of the watersheds differ among them, monitoring physicochemical and microbiological parameters of water quality over time will provide a better characterization of our natural resources. Therefore, the aim of this study was to assess the water quality of five hydrological basins of TDF with different degrees of anthropogenic impact along each watershed and between watersheds. The CCME WQI was applied to compare upstream and downstream sites in each course, providing simplified information to decision makers and stakeholders. On the other hand, and related to water quality and different uses of the basins, a perspective from the IWRM is also provided. These results may be useful for the development of local and regional mitigation and remediation programs regarding the deterioration of water quality with different uses along freshwater courses.

2 Study Area

Tierra del Fuego watersheds can be classified and characterized into four groups of basins or water zones. In the present study, we evaluate water quality from two of them: central or transition basins, and southern or mountain range basins (Iturraspe and Urciuolo 2000).

The GR basin belongs to a transition basin located in the central steppe-forest zone called ecotone (Fig. 1b; Iturraspe and Urciuolo 2000). The total area of the basin is 8580 km^2, but only 3780 km^2 correspond to the Argentine territory (Table 1; Iturraspe et al. 2007). The GR flows from west to east, receiving tributaries from the south and from the north. Before discharging into the Atlantic Ocean and constituting an estuary, the river makes a long bend to the south around gravel beach barriers on which the GR is built (Isla and Bujalesky 2004). In GR’s outer estuary, the mean tidal range is 4.16 m. The climate is semi-arid, and mean annual rainfall varies from 600 mm in the southern springs of the basin to 330 mm in Río Grande city at sea level. Strong winds prevail from the west, which are of great intensity in spring and summer. The floods appear in early spring, which mainly depend on local precipitation, with the lowest water level in autumn and early winter due to freezing temperatures in the soil and riverbeds (Koremblit and Forte Lay 1991). The landscape is highly variable, undulating with low slopes and marked meanders in the river course. Forests that grow in this zone are deciduous; they are represented mostly by *Nothofagus antarctica* (ñire), followed by *N. pumilio* (lenga). These forests take up the hills and the highest places, whereas the low zones and the wide and not very deep valleys are occupied by herbaceous vegetation, predominantly the gramineous one (Iturraspe and Urciuolo 2005). The GR basin stands out for the extension, diversity and uniqueness of its wetlands (Anchorena et al. 2009), which, outside the thaw period, acquire importance as regulatory storages.

The southern or mountain range basins comprise the area delimited between the northern part of the Fuegian Andes and the Beagle Channel. The orography responds to structural features that have resisted the intense glacial activity, basically erosive. The transversal and longitudinal valleys of the Fuegian Andes (Andorra, Cañadón del Toro, Pipo, Olivia, Carbajal-Tierra Mayor, and Beagle Channel) show the effect of Pleistocene glacier erosion (Rabassa et al. 2000). The tributary valleys were occupied by multiple valley glaciers, ranging from 20 to 30 km in length, with smaller, single valley glaciers (Rabassa et al. 2000). Forest is the absolutely dominant vegetation in this mountainous landscape, covering the mountain hillsides until 500–600 m a.s.l. Beyond that height, there are only peat bog patches and high mountain thin vegetation adjacent to the forest, In higher altitudes, it's only possible to find nude rocks, glaciers, semi-permanent snows and little high lakes (Iturraspe and Urciuolo 2005; Strelin and Iturraspe 2007). The main watersheds that cross Ushuaia city are BES, GS, OR and PR, which belong to southern or mountain range basins (Fig. 1c; Table 1).

The BES basin springs in the Martial mountains at 1340 m a.s.l. and it flows into the Encerrada Bay after a 7 km way in which it crosses the urban area of the city (Urciuolo and Iturraspe 2005). Its waters are hyposaline, slightly bicarbonated, of great transparency and with a moderately high Fe content; although its turbidity increases during floods due to sediment drag (Iturraspe et al. 2007). There is no

Table 1 Hydrological characteristics of five watersheds of Tierra del Fuego (Argentina): Grande River (GR), Buena Esperanza Stream (BES), Grande Stream (GS), Olivia River (OR) and Pipo River (PR). Data from Iturraspe et al. (2009), Zagarola et al. (2017) and Granitto et al. (2021)

Watershed	Area (Ha)	Mean annual flow (m^3 s^{-1})	River length (km)	Urbanized area* (%)
GR	868,000	40.00	240.00	2.9
BES	1656	0.37	6.97	68.0
GS	12,538	3.20	18.31	18.1
OR	20,924	5.40	41.59	7.0
PR	15,900	3.70	11.60	28.3

*Percentage of the total river length

agricultural or livestock activity within this basin. A water treatment plant is located at 110 m a.s.l., which contributes 20% of the raw water that is purified there (Huelin Rueda 2008). Above that point, there are small water intakes for tourist settlements such as hotels, cabins and mountain huts, and downflow the treatment plant begins the densely urbanized area. Through the urban area, the stream crosses house settlements with different degrees of consolidation. In its middle and lower sections, the stream receives the majority of pluvial and sewage discharges, urban water runoff and water from urban peat bogs, before draining into Encerrada Bay.

GS is located in the Andorra Valley, where peat bogs, lagoons and glaciers compose the natural landscape (Urciuolo and Iturraspe 2011). In 2009, the middle section of the Andorra Valley basin was declared a RAMSAR site called "Vinciguerra Glacier and associated peatlands" (https://rsis.ramsar.org/es/ris/1886). This condition led to stop urbanization planning in the sector and the exploitation of peat. The RAMSAR site, limits to the west with the Tierra del Fuego National Park where the headwaters of GS are located. These protected areas favor the preservation of the 72% of the GS basin, which is relevant because this stream is the main source of drinking water in the city providing approximately 80% of the raw water in the treatment plants (Huelin Rueda 2008). Moreover, it is a direct water source that supplies some of the precarious houses of the area and the irrigation of crops in small farms in the valley (Urciuolo and Iturraspe 2005). Over the years, the urbanization in this sector has been planned, building social neighborhoods and single-family homes, although untreated domestic discharges have been detected (Amin et al. 2011; Diodato et al. 2018, 2020; Granitto et al. 2021). Crossing the urban area, GS flows into the eastern part of Ushuaia city and discharges in Ushuaia Bay, Beagle Channel. In the lower basin, GS crosses a zone occupied by different industries (plastic and electronic manufactures), a petrol station, and the municipal slaughterhouse, whose spills have been occasionally dumped into the stream during the last years. Close to the outlet, a secondary sewage treatment plant is under construction and would begin operating at the end of 2021.

The OR defines the East boundary of the urban area of Ushuaia city. It occupies the Carbajal bottom Valley, where a large wetland of 672 ha is made up of peat bogs and lagoons, and is influenced by allochthonous drainages (Urciuolo and Iturraspe 2011). There is an active peat extraction. The low slope of the catchment determines a fair runoff regime and marked meanders in the river course, draining into the coast of Ushuaia Bay. The capacity of self-purification of this stream is low, especially in winter when the low temperatures and the reduction of flow rates are combined. In addition, surface freezing hinders water oxygenation during part of the year (Urciuolo and Iturraspe 2005). In its middle section, this course is a possible source of drinking water for the city. Moreover, this basin provides valuable environmental services, especially in terms of hydrological regulation (Noir 2019). In its lower section, the urbanization is reduced, but several economic and productive activities are settled: the current sanitary landfill, a concrete plant, a quarry, a fish farming station, a hazardous wastes treatment plant with a pyrolytic oven, and a small bottled water venture.

The upper section of the PR is away from the principal urban area and belongs to a protected area under the preservation of the Tierra del Fuego National Park.

Leaving this restricted area, the newest drinking water treatment plant of the city is located (recently opened in 2017), supplying drinking water to the western sector of the city. In the 1990s, the middle section of this watershed was used as a quarry for the extraction of solid material for the construction of the international airport and a sanitary landfill operated there without any type of aquifer protection. In the last 10 years, large urbanization projects such as neighborhoods have been developed in this sector, joining the already urban urbanization near the outlet of the PR into Golondrina Bay.

3 Materials and Methods

3.1 Sampling Sites and Experimental Design

Nine sampling sites were selected along the GR (S1–S9; Fig. 1b; Table 2) taking into account different characteristics such as the degree of occupation, the development of socio-economic activities, and the presence of wastewater discharges, among others. Most of the sites were located on the north riverside, because there is where most of the pollutants could accumulate, according to river dynamics. In Ushuaia watersheds, two sites were sampled for each watershed: one site upstream before urbanization (labelled by adding number “1”) and the other site close to the outlet in the coast of Beagle Channel (labelled by adding number “2”) (Fig. 1c; Table 2).

Water samples were collected between 2008 and 2014 in the GR, and between 2009 and 2019 in Ushuaia watersheds (BES, GS, OR and PR) with a frequency between 2 and 4 months, and taking into account the tidal regime for downstream sites, since salinity conditions could influence chemical determinations. In all cases, subsurface water samples were taken and at a distance of about 1.5 m from the river bank with a horizontal Niskin bottle. After collection, samples were kept refrigerated (4 °C) and processed as quickly as possible. In all samples from the GR, 12 parameters were registered to characterize the water quality: pH, electrical conductivity (EC), salinity (SAL), total dissolved solids (TDS), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), turbidity (TURB), orthophosphate (PO_4^{3-}), nitrate (NO_3^-), nitrite (NO_2^-), total coliforms (TC) and fecal coliforms (FC). In water samples from Ushuaia watersheds, 10 parameters were evaluated: pH, EC, TDS, BOD_5, PO_4^{3-}, ammonium (NH_4^+), NO_3^-, NO_2^-, TC and FC. Determinations were performed using the procedures recommended in APHA (2017). The list of the examined parameters with their units, used abbreviations and applied analytical methods are shown in Table 3.

Table 2 General characteristics of the studied sampling sites in Tierra del Fuego watersheds, geographical locations and site descriptions

Watershed	Sampling site	Geographical coordinates		Site description
		Latitude (S)	Longitude (W)	
Grande River (GR)	S1	−53.829605°	−67.843270°	50 m upstream the water intake
	S2	−53.835158°	−67.792277°	Bridge of GR and National route No 3
	S3	−53.814860°	−67.745440°	Old channel from industrial zone
	S4	−53.809104°	−67.741318°	New channel from industrial zone
	S5	−53.804100°	−67.730430°	Pluvial discharge next to industrial zone
	S6	−53.797243°	−67.709829°	Direct discharges from neighbourhoods
	S7	−53.802862°	−67.689083°	Point in the bridge near direct discharges
	S8	−53.802041°	−67.676338°	Small dock in south riverbank
	S9	−53.793543°	−67.685823°	Dock located at the mouth of the GR where small ships moor
Buena Esperanza Stream (BES)	BES1	−54.798361°	−68.371000°	Mountain area (800 m a.s.l.) located before the drinking water treatment plant and surrounded by *Nothofagus* spp. forests
	BES2	−54.819083°	−68.324306°	High degree of urbanization including direct sewage discharges. It discharges into Encerrada Bay
Grande Stream (GS)	GS1	−54.759721°	−68.304928°	Natural area surrounded by *Nothofagus* spp. forests and peatlands; upstream the urbanization
	GS2	−54.795701°	−68.257813°	Next to an industrial area and influenced by urban settlements along its course. It discharges into Ushuaia Bay
Olivia River (OR)	OR1	−54.762667°	−68.194444°	Area surrounded by *Nothofagus* spp. forests

(continued)

Table 2 (continued)

Watershed	Sampling site	Geographical coordinates		Site description
		Latitude (S)	Longitude (W)	
	OR2	−54.799194°	−68.226611°	Low degree of urbanization. Area receiving leaches from the sanitary landfill, an aggregate quarry and a small fish farm. It discharges into Ushuaia Bay
Pipo River (PR)	PR1	−54.829778°	−68.427083°	Area surrounded by *Nothofagus* spp. forests, outside the National Park boundary
	PR2	−54.836333°	−68.352783°	Middle degree of urbanization. It discharges into Golondrina Bay

3.2 Legal Framework

The assessment of surface freshwater quality was based on standards established by national and international guidelines. The implemented national normative derives from the Water Quality Guidelines for the Protection of Aquatic Life in Surface Freshwater established in the resolution No 1333/93 of the Environmental law No 55 from Tierra del Fuego province (https://desarrollosustentable.tierradelfuego.gob.ar/wp-content/uploads/2017/04/Decreto-N%C2%BA1333-93.pdf). Two international guidelines were applied when national regulations did not establish the standards for some of the studied parameters. In this case, guidelines from the Chilean National Commission for Environment (CONAMA-Chile) and the Canadian Council of Ministers of the Environment (CCME) were applied (CONAMA Guide for the Establishment of Secondary Environmental Standards for Surface Continental and Marine Waters, and Canadian Water Quality Guidelines for the Protection of Aquatic Life, respectively).

3.3 Data Analysis

All the data were processed in order to determine mean and median values, standard deviations, and maximum and minimum values and were graphically displayed as boxplots using the software Statistica 7.0.

Table 3 List of physicochemical and microbiological parameters measured in the sampling sites, their units, and the applied methodological techniques. For parameter´s abbreviations see the text

Watershed	Parameter	Unit	Applied analytical techniques
Grande River (GR)	pH	–	In situ measurements with multiparametric probe HORIBA W-23XD and HANNA HI 9813-5
	EC	mS cm^{-1}	
	SAL	PSU	
	TDS	mg L^{-1}	
	TURB	NTU	
	BOD$_5$	mg L^{-1}	SM 5210 D; incubation and respirometric measurements with BODTrak from HACH
	COD	mg L^{-1}	SM5220 D; colorimetric method
	PO_4^{3-}	mg L^{-1}	4500-P E; ascorbic acid method
	NO_3^-	mg L^{-1}	4500-NO$_3$ E; cadmium reduction method
	NO_2^-	mg L^{-1}	4500-NO$_2$ B; colorimetric method
	TC	MPN 100 mL^{-1}	9221 B/C/E; incubation and multi-tube fermentation technique
	FC	MPN 100 mL^{-1}	
Ushuaia watersheds (BES, GS, OR and PR)	pH	–	In situ measurements with multiparametric probes HORIBA W-23XD and HANNA HI 9813-5, and conductivity meter HANNA HI8733
	EC	mS cm^{-1}	
	TDS	mg L^{-1}	
	BOD$_5$	mg L^{-1}	SM 5210 D; incubation and respirometric measurements with BODTrak from HACH
	PO_4^{3-}	mg L^{-1}	4500-P E; ascorbic acid Method
	NH_4^+	mg L^{-1}	SM 4500-NH$_3$ F; phenate method
	NO_3^-	mg L^{-1}	4500-NO$_3$ E; cadmium reduction method
	NO_2^-	mg L^{-1}	4500-NO$_2$ B; colorimetric method
	TC	MPN 100 mL^{-1}	9221 B/C/F; incubation and multi-tube fermentation technique with 24 h-Colitag™ (CPI International) substrate
	FC	MPN 100 mL^{-1}	

3.4 Calculation of CCME WQI

CCME WQI was computed using the method of CCME (2001). This method was developed to protect aquatic life and assess water quality by applying local or international guidelines in order to compare these standard permissible values with the observed values. In this case, the selected guidelines for comparison purposes came from the local and international normative (see Sect. 9.3.2).

The mathematical formulation of CCME WQI is shown in (Eq. 1) (CCME 2001):

$$CCME\ WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{1}$$

where F_1 represents the percentage of variables that do not meet their objectives at least once during the time period under consideration (failed variables), relative to the total number of measured variables (see Eq. 2); F_2 represents the percentage of failed individual tests that do not meet their objectives (see Eq. 3); F_3 is an asymptotic capping function that scales the normalized sum of the departures from objectives (*nse*) to yield a range between 0 and 100, and the constant, 1.732, is a scaling factor (see Eq. 4):

$$F_1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables} \right) \times 100 \tag{2}$$

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests} \right) \times 100 \tag{3}$$

$$F_3 = \left(\frac{nse}{0.01\, nse + 0.01} \right) \tag{4}$$

The *nse* variable is, expressed as:

$$nse = \frac{\sum_{i=1}^{n} departure_i}{\#\ of\ tests} \tag{5}$$

The collective amount by which individual tests are out of compliance is calculated by summing the departures of individual tests from their objectives and dividing by the total number of tests (Eq. 5).

For the cases in which the test value must not exceed the objective:

$$departure_i = \left(\frac{Failed\ Test_i}{Objective_j} \right) - 1 \tag{6a}$$

For the cases in which the test value must not fall below the objective:

$$departure_i = \left(\frac{Objective_j}{Failed\ Test_i}\right) - 1 \tag{6b}$$

For the cases in which the objective is zero:

$$departure_i = Failed\ Test_i \tag{6c}$$

As a result of the calculations, CCME WQI was evaluated as "poor" (0–44), "marginal" (45–64), "fair" (65–79), "good" (80–94), and "excellent" (95–100) (CCME 2001).

4 Results and Discussions

4.1 Spatial Variation of Water Quality Parameters in Grande River

The spatial variation of physicochemical and microbiological parameters in nine sites from the GR is shown in Figs. 2 and 3. Mean pH values in all sites were similar and near the neutrality (mean values between 7.25 and 7.67). Mean values of EC, SAL and TDS showed a similar trend in each site due to its common origin: lower values were found in S1 (means of 0.15 mS cm^{-1}, 0.10 PSU and 87.24 mg L^{-1}, respectively), which were increasing towards the mouth of the river. Maximum values were reached in S9, which corresponded to approximately 100 times those found in S1 (means of 15.70 mS cm^{-1}, 9.93 PSU and 8121.89 mg L^{-1}, respectively). This gradual increase in EC, SAL and TDS can be explained due to the dynamics of the estuary and the intrusion of seawater in each tidal cycle. S9 is the closest site near the coast where the GR inlet is controlled by macrotides and high-energy waves (Bujalesky 2007). Despite the fact that precautions were taken during sampling to avoid the influence of seawater, estuarine parameters fluctuate in relation to the tide. The wind effect is very important during some days and during slack water (Isla and Bujalesky 2004).

BOD_5 mean values were consistently below 10 mg L^{-1} in all sites, although some extreme values were recorded in sites with industrial influence (S3–S5; up to 46 mg L^{-1}) and urban inputs (S6–S9; up to 39 mg L^{-1}). COD mean values varied between 30 mg L^{-1} (S2) and 128 mg L^{-1} (S9), with intermediate values in sites with industrial influence. Maximal COD values were registered in S9, according to the presence of ships that moored in the dock. Extreme values registered in 2012 in almost all sites were related to a devastating fire in the industrial park near the riverbank, where approximately 2000 tanks with disused, highly flammable petroleum, degreasers and

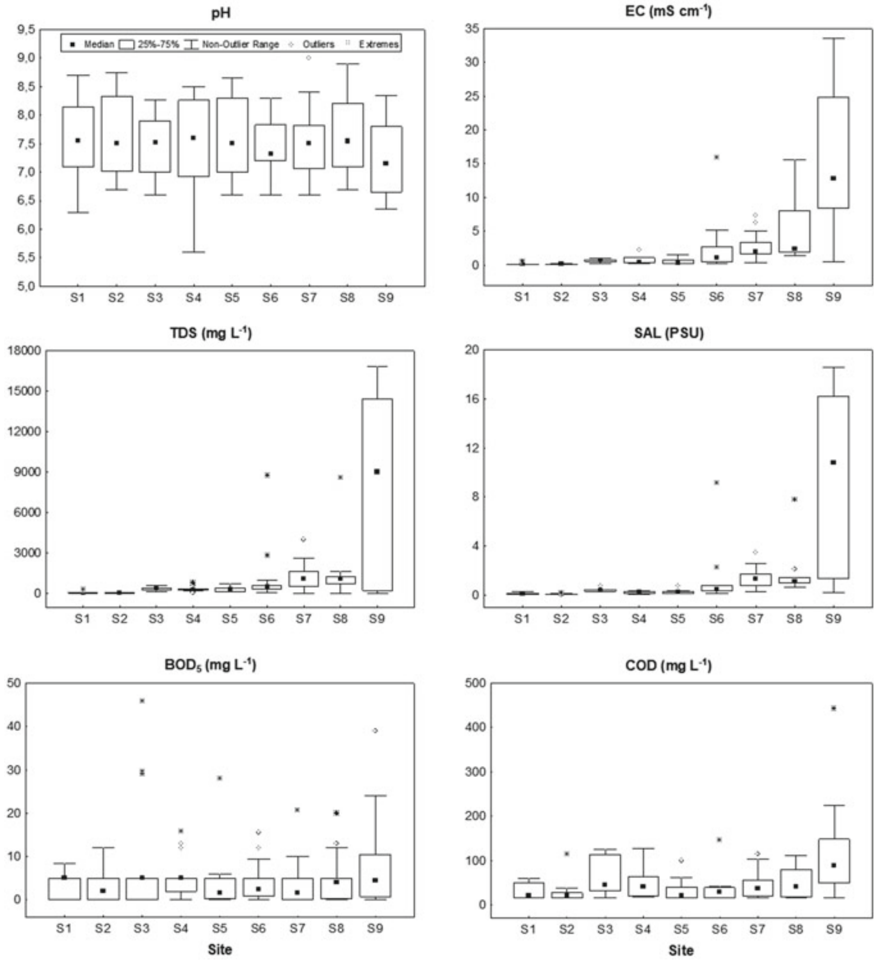


Fig. 2 Boxplots representing the variation of pH, electrical conductivity (EC), total dissolved solids (TDS), salinity (SAL), 5-day biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) in water samples collected in Grande River watershed (S1–S9)

other fuels burned. TURB mean values were higher in sites with urban influence, ranging from 40 to 76 NTU.

The concentration of dissolved nutrients in water samples did not reflect severe problems of N and P contamination. PO_4^{3-} values were close to the detection limit (0.5 mg L^{-1}), although maximal values were registered in sites S5–S9 (2.0 to 2.7 mg L^{-1}), which are associated with urban influence and wastewater discharges. NO_3^- mean values were higher in those sites near the coast (up to 10.4 mg L^{-1}) compared to those sites located upstream with lower seawater influence. Nevertheless, they did not exceed the values established by the international normative (13 mg L^{-1}).

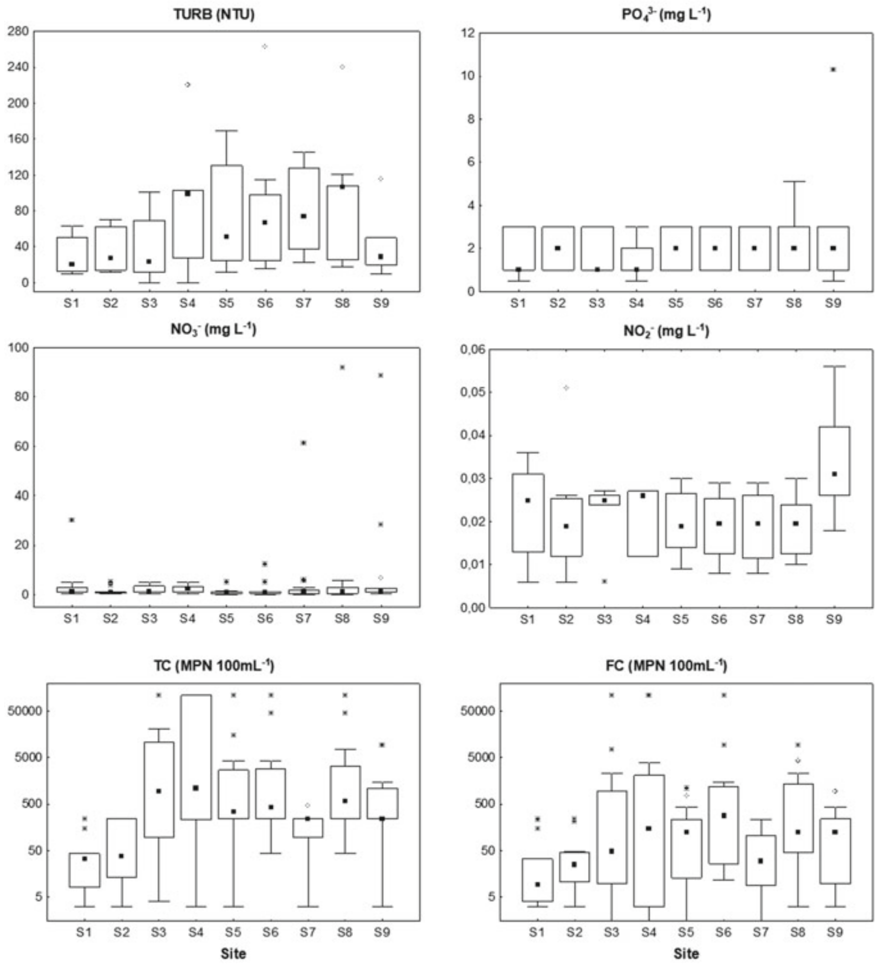


Fig. 3 Boxplots representing the variation of turbidity (TURB), orthophosphate ($PO_4{}^{3-}$), nitrate ($NO_3{}^{-}$), nitrite ($NO_2{}^{-}$), total coliforms (TC) and fecal coliforms (FC) in water samples collected in Grande River watershed (S1–S9). Note the different scale of the y-axis (log scale) in TC and FC

$NO_2{}^{-}$ values recorded in this study (from 0.01 to 0.06 mg L^{-1}) were within the range suggested by the literature (Chapman 1996) and they did not exceed the standard values established by the national normative (0.06 mg L^{-1}). Lower concentrations of dissolved nutrients could be due to the tidal dynamics to which the estuary is subjected. This fact allows the constant dilution of the pollutants that enter the river through wastewater discharges.

The presence of coliform bacteria and especially fecal coliforms is widely used as an indicator of contamination, particularly due to the contribution of human and animal fecal matter (Chapman 1996; Pommepuy et al. 2006). By themselves, coliform bacteria are not a threat to health; however, the detection of *Escherichia coli*, a fecal coliform, is used to indicate the potential presence of other possibly harmful pathogens (viruses, bacteria, gastrointestinal parasites, among others) and transmittable by water (Haile et al. 1999; Pommepuy et al. 2006). In the present study, it was observed that TC and FC concentrations were the lowest in S1 and S2. Those found values (means below 100 and 60 MPN 100 mL^{-1} of TC and FC, respectively) allow inferring the existence of diffuse contamination in the upper basin, probably due to the presence of livestock. From S3 towards S9, TC and FC concentrations increased in agreement with the urbanization gradient. In these sites, high concentrations of *Pseudomonas aeruginosa* and *Enterococcus* spp. were also found in water samples (data not shown).

4.2 Spatial Variation of Water Quality Parameters in Ushuaia Watercourses

Water quality parameters registered in Ushuaia watersheds are shown in Figs. 4 and 5. Mean pH values ranged between 6.68 (PR1) and 7.34 (OR2); remaining near neutrality in all sites. EC values were within the range established for most freshwaters (0.01 and 1 mS cm^{-1}; Chapman 1996), but they were higher in downstream sites respect to upstream sites, mainly in BES and GS. A similar trend was registered in TDS. Both parameters increased as a function of increasing urbanization which is in agreement with the findings of Zagarola et al. (2017), Albizzi et al. (2021) and Granitto et al. (2021). BOD_5 mean values were below 5 mg L^{-1} in all sites except in BES2, where it was 54 mg L^{-1} with an extreme value of 112 mg L^{-1}.

In Ushuaia watersheds, nutrient inputs fundamentally come from two sources: in upstream sites, *Nothofagus* spp. forests contribute through litter-fall (Frangi et al. 2005; Amin et al. 2011); while in the downstream sections of the watercourses, the main nutrient provision comes from untreated sewage discharges (Torres et al. 2009; Gil et al. 2011; Diodato et al. 2018, 2020; Albizzi et al. 2021; Granitto et al. 2021). In general, dissolved nutrients increased its concentrations from upstream to downstream sites, in agreement with the contribution of urban inputs to the watercourses. PO_4^{-3} values ranged between 0.05 and 15.30 mg L^{-1} with the highest mean concentrations in BES2 (2.82 ± 2.23 mg L^{-1}) and PR2 (3.23 ± 5.93 mg L^{-1}), exceeding the level established by the international normative (0.05 mg L^{-1}; CCME). Among N compounds, NH_4^+ mean values exceeded the national normative (0.05 mg L^{-1}) only in BES2 (10.49 mg L^{-1}) and GS2 (0.29 mg L^{-1}). Respect to NO_3^-, BES and GS presented higher mean values than OR and PR watersheds, although they did not exceed allowed values established by the international normative (13 mg L^{-1}; CCME). NO_2^- was higher in BES2 (0.17 mg L^{-1}) than in the other sites, exceeding the national normative (0.06 mg L^{-1}).

It is possible that TC and FC were the most indicative parameters of urban inputs in Ushuaia watersheds. The highest mean values of FC were observed in downstream

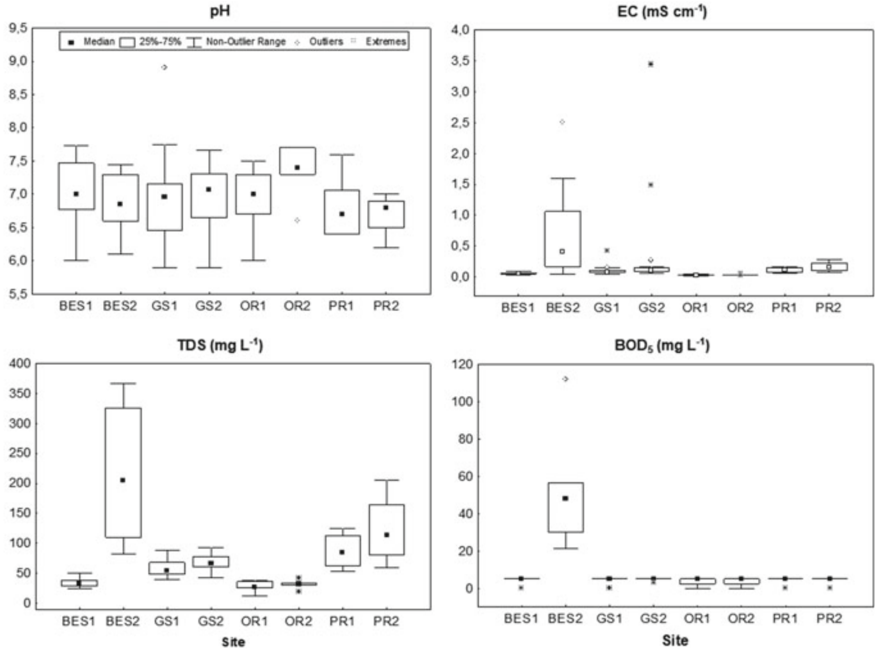


Fig. 4 Boxplots representing the variation of pH, electrical conductivity (EC), total dissolved solids (TDS) and 5-day biochemical oxygen demand (BOD_5) in water samples collected in Ushuaia watersheds: Buena Esperanza Stream upstream (BES1) and downstream (BES2); Grande Stream upstream (GS1) and downstream (GS2), Olivia River upstream (OR1) and downstream (OR2), and Pipo River upstream (PR1) and downstream (PR2)

sites of BES, GS and PR basins (BES2: 211,324 MPN 100 mL^{-1}, GS2: 22,249 MPN 100 mL^{-1} and PR2: 38,506 MPN 100 mL^{-1}), all of them above the national legislation (2000 MPN 100 mL^{-1}), and in agreement with Albizzi et al. (2021) and Granitto et al. (2021). FC values found in upstream sites were detected in small quantities and related to the presence of wild animals like beavers and horses. On the other hand, the total coliform/*Escherichia coli* (TC/EC) ratio has been used to define the origin of coliform bacteria (fecal or natural origin). As the ratio approaches 1, the probability of a fecal origin is higher (Haile et al. 1999; Evanson and Ambrose 2006). In this study, the calculated TC/EC ratios in all sites, except at PR1, were near 1, which indicates an increased probability of human fecal contamination. At PR1, this ratio was approximately 53, indicating a natural origin probably caused by the proliferation of fecal indicator bacteria in sediments (Evanson and Ambrose 2006).

Taking into account all water quality parameters, the most notable differences between upstream and downstream sites within each watershed were observed in the BES basin. The highest amounts of EC, TDS, BOD_5, PO_4^{3-}, NH_4^+, NO_3^-, NO_2^-, TC and FC were registered in BES2, the downstream site that flows into Encerrada Bay. Moreover, the most marked differences in the analyzed chemical properties of fluvial sediments of Ushuaia watersheds have been registered in the same site, which had the

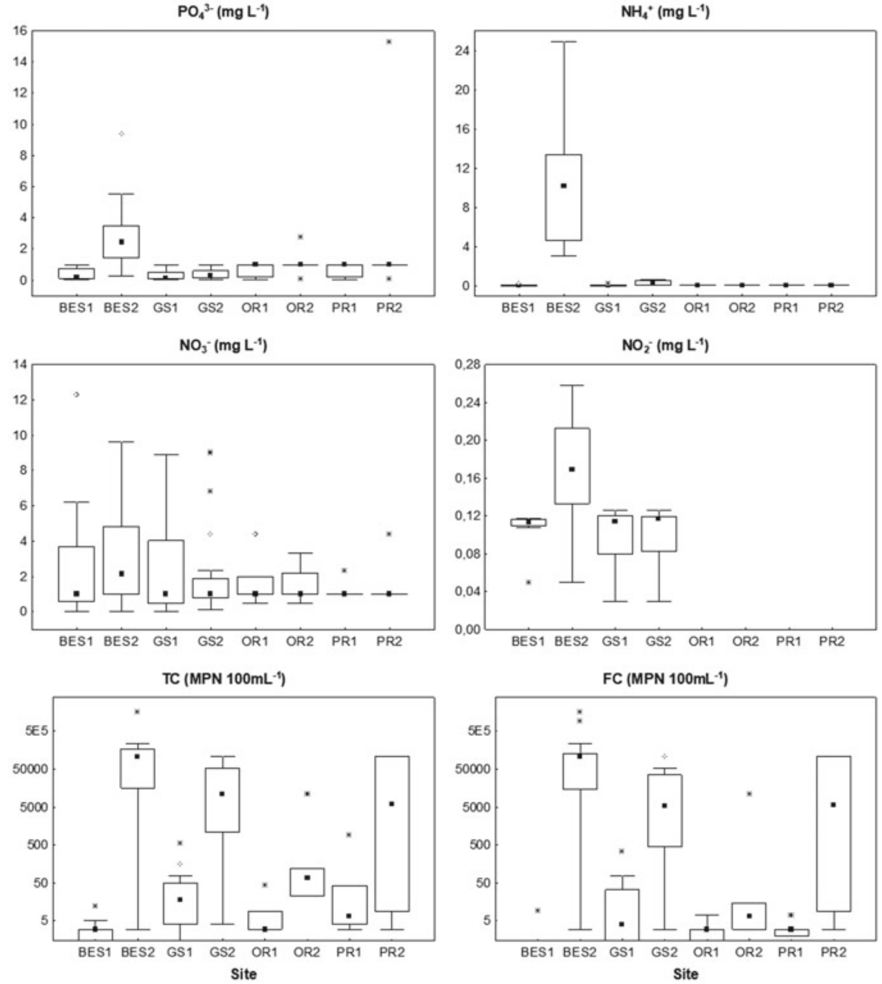


Fig. 5 Boxplots representing the variation of orthophosphate (PO$_4^{3-}$), ammonium (NH$_4^+$), nitrate (NO$_3^-$), nitrite (NO$_2^-$), total coliforms (TC) and fecal coliforms (FC) in water samples collected in Ushuaia watersheds: Buena Esperanza Stream upstream (BES1) and downstream (BES2); Grande Stream upstream (GS1) and downstream (GS2), Olivia River upstream (OR1) and downstream (OR2), and Pipo River upstream (PR1) and downstream (PR2). Note the different scale of the y-axis (log scale) in TC and FC

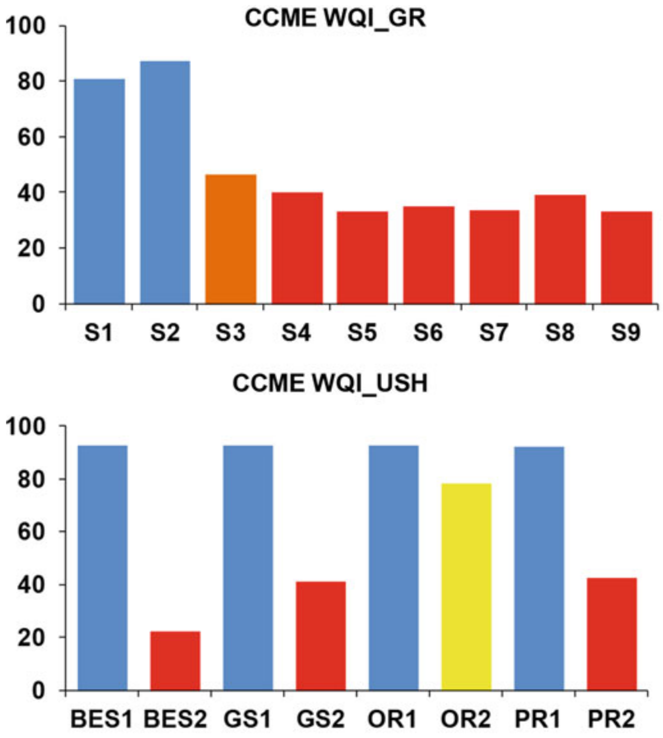
lowest mean pH values and the highest mean concentrations of organic carbon, total nitrogen, and soluble reactive phosphorous (Diodato et al. 2020). Several factors are related to this fact: BES is the watershed most affected by urban discharges and has the least mean water flow (0.37 m^3 s^{-1}), which is aggravated by the fact that it covers a larger urbanized area in comparison to GS, OR, and PR (Table 1). The opposite situation occurs in GS which presents 10 times more water flow and consequently, the dilution effect is more relevant (Diodato et al. 2018). Dilution is a physical process directly related to water discharge, since with lower water discharge, the dilution power of pollutants decreases. The relative influence of the hydrology and morphology of the watersheds must be taken into account since they could explain larger vulnerability to the impacts of urbanization (Granitto et al. 2021).

4.3 CCME WQI Results

The following nine parameters were used for the index calculation: pH, EC, TDS, BOD_5, COD, NO_3^-, NO_2^-, TC and FC for GR ($n = 144$ including all samplings between 2008 and 2014), and pH, EC, TDS, BOD_5, NH_4^+, NO_3^-, NO_2^-, TC and FC for Ushuaia watercourses ($n = 98$ including all samplings between 2009 and 2019). The CCME WQI results are shown in Fig. 6. The water quality ranged between “good” (WQI = 87) and “poor” (WQI = 33) in GR, and between “good” (WQI = 93) and “poor” (WQI = 22) in Ushuaia watersheds.

Specifically in GR, water quality decreased gradually from S1 to S9. S1 is located upstream the water intake of the drinking water treatment plant and presented “good” quality (WQI = 81). S2 is 3.5 km from S1 and also presented “good” quality (WQI = 87). S3, S4 and S5 are sites with high industrial influence, and the estimated water quality was “marginal” in S3 (WQI = 47) to “poor” quality in S4 and S5 (WQI = 40 and 33, respectively). S6–S9 presented “poor” water quality (mean WQI = 35), mainly related to urban influence due to the presence of direct wastewater discharges into the river and the presence of several neighbourhoods in the riverbank without the provision of essential services (drinking water and sewers). Lofiego et al. (2009) calculated for the same sites of GR the WQI proposed by the National Sanitation Foundation (Brown et al. 1970), arriving to similar results in downstream sites of GR. However, they found a worse water quality in S1 and S2, which reinforces the idea of using a unique WQI for comparison purposes between sites and times.

The CCME WQI values estimated for Ushuaia watersheds were in agreement with the results obtained in the spatial variation of physicochemical and microbiological parameters. All upstream sites (BES1, GS1, OR1, and PR1) presented “good” water quality (mean WQI = 92.5), which is of great importance because they are the sources of drinking water to the local population. However, “poor” water quality was found in PR2 (WQI = 43), GS2 (WQI = 41) and BES2 (WQI = 22). OR2 presented “fair” water quality (WQI = 78) showing that there is no marked evidence of degradation of the watercourse by organic inputs. This information is totally relevant because the riverbanks of OR will soon be urbanized owing to the growth need of the city. Granitto et al. (2021) calculated the Fuegian WQI (F_WQI), which includes periphytic chlorophyll-*a*, and they found F_WQI values higher than 76 at all sites of the PR basin, indicating a very good water quality during 2018–2019. This could be due to the fact that PR only receives occasional contributions of wastewater from the overflow of a near pumping station, and does not have a mixed sewage system. Therefore, pluvial and sewage effluents are separated. On the other hand, they



CCME WQI		
EXCELLENT	95-100	The water quality is not under any threat and it is not degraded and close to natural levels.
GOOD	80-94	The water quality is not under a little threat and it is rarely seen under desired levels.
FAIR	65-79	The overall water quality is protected;however, it is under threat in some cases and sometimes not in the desired conditions
MARGINAL	45-64	The water quality is frequently under threat and degradation and often not in the desired conditions.
POOR	0-44	Water quality departs from its desirable level.

Fig. 6 CCME water quality index results for Grande River (GR, S1–S9) and Ushuaia (USH) watersheds: Buena Esperanza Stream upstream (BES1) and downstream (BES2); Grande Stream upstream (GS1) and downstream (GS2), Olivia River upstream (OR1) and downstream (OR2), and Pipo River upstream (PR1) and downstream (PR2). Classification table of CCME WQI values (CCME 2001) are also presented

found that at BES and GS the F_WQI showed broader variation between upstream and downstream sites, in agreement with the present study.

4.4 The Integrated Water Resources Management (IWRM) in Tierra del Fuego Basins: Threats and Affected Functions and Services

The hydrographic basins are the territories where the hydrological cycle occurs, being a natural and ideal unit of development planning. Watershed ecosystems provide goods and services to human populations, including protecting water sources, mitigating the effects of natural disasters by regulating runoff, protecting other resources such as fishing, protecting urbanized areas, among others. The quality and quantity of these services are affected by both, natural phenomena and human activity. The actors involved within the basin must adopt behavior in order to promote the conservation and management of ecosystems, improving life quality and their sustainability, trying to have a positive attitude towards the environment, and without harming the activities they carry out in the basin. This balance is a goal that must be achieved, although obstacles and difficulties are always present. The protection and good management of the middle and upper basins will benefit the entire ecosystem (Noir 2019). Several threats on the different ecosystems of the basins and the effects generated on their functions and services were identified by Noir (2019), and are listed in Table 4.

In the analyzed watersheds, there is a great diversity of actors that operate in a divided and uncoordinated way, primarily regarding the use of the different ecosystems. Since most of the actors are linked to the political and institutional sphere, the system is weakened, showing an evident lack of management policies for the administration of provincial water resources.

The lower sectors of the basins are the most disturbed and present the greatest environmental problems, where the most densely populated areas are concentrated and several activities are carried out. These bad practices threaten the natural conditions of the ecosystems. It is necessary to work on water and land use planning to reduce risks, avoid conflicts, and promote activities within a social, economic and environmental sustainability framework.

The hydro-environmental management must be based on the strategic guidelines of each basin within the framework of IWRM with an EA. It must define urgent actions aimed at generating information, education and dissemination, land use planning, water risks management, inter-institutional coordination, and applicable regulations.

Ecosystem management requires the coordination of the actors and depends on the availability of scientific information generated for decision-making. It is essential to promote the strengthening of the technical structures of the local authorities and academic institutions to create knowledge and to improve inter-institutional coordination for the execution of public policies.

Table 4 Threats and affected functions and/or services of the different ecosystems of Tierra del Fuego (TDF)

Ecosystem	Threats	Affected functions and/or services
Watercourses	– Exploitation of wetlands – Peat extraction	– The aesthetics of the landscape and the services related to recreation and ecotourism – Cultural function related to artistic and spiritual inspiration, raising the cultural heritage and identity in the region – Drinking water supply for the population of Ushuaia and Río Grande cities, and for the touristic infrastructure – Economic condition through job increase in tourism companies and water treatment plants – Water provision in appropriate amounts for hydroelectric use – Biodiversity
	– Quarry mining activity and aggregate washing – Sanitary landfill and hazardous waste operating companies – Container's transport and storage companies – Fuel and lubricant dispensing companies – Concrete production plant – Sewage treatment plant	– Sports and recreational activities linked to the use of hydrobiological resources – Ecological services such as habitat maintenance for local species – Generation of gases and toxic leachates – Adequate water provision to the aquaculture station in OR: eggs incubation destined to watercourse repopulation for sport fishing – Water provision for companies that produce beverages such as bottled water, juices and beer production – Adequate provision of water for irrigation and cattle beverage
	– Changes in land use (urbanization of Ushuaia and Río Grande cities) – Irregular clearing	– Sports and recreational activities linked to the use of hydrobiological resources – Ecological services such as habitat maintenance for local species – Adequate provision of water for aquaculture
	– Bad practices in touristic and recreational activities – Activity of invasive species: *Castor canadensis* and *Didymosphenia geminata*	– Sports and recreational activities linked to the use of hydrobiological resources – Ecological services such as habitat maintenance for local species – Adequate provision of water for irrigation, aquaculture – Provision of drinking water for the population

(continued)

Table 4 (continued)

Ecosystem	Threats	Affected functions and/or services
	– Non-point contamination from livestock activity	– Sports and recreational activities linked to the use of hydrobiological resources – Water provision for companies that produce beverages such as bottled water, juices and beer production – Adequate provision of water for irrigation, aquaculture – Provision of drinking water for the population and touristic infrastructure
	– Climate change	– Provision of water for hydroelectric power generation projects – Water provision for the production of drinking water – Adequate provision of water irrigation, aquaculture
Wetlands: peatlands, lagoons, floodplains and estuary	– Peat exploitation – Wetland drainage for the construction of roads or trails – Urbanizations of wetlands – Expansion of the urban area in Ushuaia and Río Grande cities – Effluent discharges on peat bogs and the estuary – Non-compatible recreational activities (trips in trucks, motorcycles, ATVs, etc.)	– Hydrological regulation capacity, slowing water flow in times of water excesses – Freshwater reservoir for different uses – Soil stabilization and erosion reduction in the basin – Sediment retention and improvement of water quality – Reduction of water risks in extreme water events – Biogeochemical regulation in nutrient cycling – Climate change mitigation – Climate regulation by organic matter accumulation and control of atmospheric emissions – Transformation and degradation of pollutants – Recreation and ecotourism – Cultural heritage and identity; artistic and spiritual inspiration – Organic carbon storage in peatlands – Socio-economic function through job increases in tourism companies – Habitat provision and refuge to avifauna – Conservation of biodiversity for flora and fauna species – Scientific and historical function about the evolution of the climate, vegetation, volcanic eruptions, and other environmental aspects

(continued)

Table 4 (continued)

Ecosystem	Threats	Affected functions and/or services
Glaciers and Andean tundra	– Climate change	– Feeding the river systems of the basin – Water storage and regulation of the hydrological cycle of the basin – Water availability in the basin for different uses – Climate evolution for scientific research – Recreational and touristic activities – Relevance of the landscape in a pristine area – Socio-economic function through job increases in tourism companies
Forests	– Irregular occupations and illegal clearings – Changes in land use for unplanned urban and tourist developments – Deterioration of the forest due to the presence of cattle – Clearing for quarrying activity – Clearing to generate areas for container storage – Expansion of the urban area of Ushuaia city – Activity of the invasive species C*astor canadensis* – Forest fires	– Hydrological regulation in water collection and storage – Availability of water for different uses – Protection that reduces erosive power, improving water quality – Reduction of risks facing extreme rain events – Cultural function; enjoyment of the landscape through recreation and tourism – Socio-economic function through job increase in tourism companies – Development of recreational spaces

5 Conclusions

The systematic and continuous study of the water quality of five watersheds of Tierra del Fuego showed that unplanned urbanization and the lack of specific regulations (or failure to comply) are the main problems that Rio Grande and Ushuaia cities are facing today. The implementation of the CCME WQI is an applicable and simple tool to transmit the information to the different actors in order to improve the environmental problems we are subjected to. Severe alterations of the studied watersheds were also determined, which responded to changes in land use and to the development of authorized and unauthorized anthropogenic activities. These activities, carried out without urban planning and ignoring water management guidelines are of environmental importance for the conservation of the ecosystems of Tierra del Fuego. In this sense, it is necessary to implement short and medium-term measures to solve these problems to preserve the health of this relevant environment and the associated population.

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