Co-production of just nature-based solutions to mitigate the impact of domestic effluents on stream water quality in an informal urbanization in Latin America: Diagnosis and a pilot study

Co-production of just nature-based solutions

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Abstract

Nature-based solutions (NbS) are increasingly assessed in sustainable urban projects to improve human welfare and biodiversity. Particularly, the design, implementation and assessment of NbS are in most cases spatial and context-dependent, and just NbS must also be included in the agenda. To this end, alternative paradigms such as transdisciplinary and action research can play a fundamental role in favoring local experiences where transformative changes become a reality. The aim of this work is to evaluate the results of a co-production process with a local social movement analyzing and implementing just NbS to mitigate the impact of domestic discharges on the water quality of an urban stream (Buenos Aires, Argentina). We evidenced the relative impact of domestic effluents on stream water quality, with non-negligible input flows (3-16% across seasons) and high mass loads of Chemical Oxygen Demand (COD), Total Suspended Solids, Biochemical Oxygen Demand, Oil and Greases, nutrients and pathogens, which in some cases double the content of the stream water through a one-kilometer reach. Two Biofilter prototypes were designed, implemented and assessed for the mitigation of domestic pollutants, and a participative monitoring approach was implemented. A significant percentage of the installed devices (50%) withstood heavy rainfall and remained operative for 5 consecutive months, and 25% of these remained operative for 2 years without any maintenance time. Moreover, the first prototype showed excellent efficiency in the removal of N, P and COD (>90%), with moderate efficiency in the removal of Dissolved Organic Carbon (40-67%). In contrast, the second design was easier to construct but showed low performance, with only one device displaying a moderate efficiency (20-40% according to the pollutant). We highlight and discuss the fundamental role of the participation of the local community in the whole co-production process, and key lessons to further optimize the Biofilter design.

Introduction

Urbanization is one of the most important kinds of land use and land cover because it has significant effects on the pattern, dynamics, and functionality of ecosystems, particularly aquatic ecosystems [1,2]. Latin America has undergone a significant process of urbanization, with more than 80% of its population living in urban areas [3]. This rapid population growth was not accompanied, in many cases, by basic sanitary infrastructure. The deficit of basic services not only has an impact on the health and quality of life of the people who suffer from it, but also negatively impacts the quality of the watercourses that receive industrial and domestic effluents with lack of, or deficient, treatment [4,5]. In Latin America, the consequences of urban growth at the periphery are part of the emergence of social movements. Despite the rise in the precariat and unemployment, Latin American social movements have a great potential for prefigurative alternative ways of organizing societies, including social cooperatives, genres, and environmental care, etc. [6]. As a result of applying just nature-based solutions using blue/green infrastructure and water-sensitive designs [7,8], and by involving local actors of Latin American social movements in an action-research approach, we can create an urban space for social-ecological experimentation that addresses some of the most relevant environmental deficits in urban areas [9].

The Latin American region accounts for 33% of global water resources, but has serious problems with water availability, access to water, sanitation, etc.[10]. There is heterogeneity in water availability between countries. Argentine water resources are unevenly distributed across its territory, with the highest concentrations in Pampean and Mesopotamia [4]. This region includes the Buenos Aires Metropolitan Area (AMBA), the third most populous urban agglomeration in Latin America (Fig 1). INDEC [11] reports that 66% of Argentina's population resides in this urban area, which also has some of the most degraded local and regional watersheds [12–14]. The river systems of the AMBA have been highly modified by means of canalizations, rectifications, detours and partial or total pipelines, which has resulted in a strong ecological simplification of the main habitats [9,15]. The simplification of natural channeling, along with unplanned population growth over the floodplain of water bodies, has led to the formation of informal settlements that suffer frequent flooding [16,17] and lack access to basic services such as drinking water and sewage.

Fig 1. Most populated metropolitan areas in Latin America. The most populated urban agglomerates in Latin America. The size of the circle is proportional to its population. The Buenos Aires Metropolitan Area is the third most populated metropolis in the region. Source: [18]

Informal settlements are a complex socio-ecological phenomenon where the social production of habitat is the result of social exclusion. In this sense, the deficit of sanitary infrastructure is strongly linked to patterns of social vulnerability, which leads to associations between poverty, pollution and social exclusion [19,20]. Informal settlements often occur in the most environmentally vulnerable areas, and their lack of adequate sanitation and waste management systems is a major source of environmental pollution and the spread of infectious diseases [21]. It is estimated that in the AMBA the wastewater of more than five million people is discharged into rivers and streams without any treatment [4,22]. As a result, urban streams in the AMBA basins have poor water quality, with high organic matter content, nutrients, and microbiological contamination [23–25]. At the same time, current management of Argentina's urban streams focuses on a hydraulic approach, with a predominance of gray infrastructure and pruning of vegetation associated with watercourses that accentuates socio-environmental impacts, compromises ecological rehabilitation and promote reinforcing loops that give rise to social-ecologicals traps [9].

The above factors combine to create the "urban stream syndrome," systems with low biodiversity, high nutrient concentrations, and loss of nutrient removal efficiency [26,27].

Countering the urban stream syndrome may require the abandonment of the ideal of a "restored" stream in favor of a designed ecosystem [28]. In this sense, Nature-based Solutions (NbS) applied in blue/green infrastructure or water sensitive design can respond to habitat loss and stream degradation by maintaining integrity and connectivity while providing a wide range of ecosystem services beyond stormwater management [29,30]. These include pest control, seed dispersal, pollination, shelter and food for biodiversity [31,32]. Biofilters, or vertical constructed wetlands, are a type of NbS commonly used in surface water management in urban basins [33,34]. They typically consist of a vegetation cover on top of a sandy layer, and have proven to be effective in removing different contaminants that diffusely enter water bodies through a combination of physical, chemical, and biological processes [33,35,36]. Different kinds of biofilters have been designed for both rainwater and gray wastewater management, or even combined [33,34]. Despite being widely evaluated devices under laboratory conditions, one of the main challenges that arise is their feasibility of implementation in a vulnerable urban context and informal settlements, including their feasibility in terms of their durability and *in-situ* efficiency [35].

Coupled to the NbS approach but deepening their social content, alternative paradigms such as transdisciplinary and action research can play a fundamental role in favoring local experiences where transformative changes become a reality, generating bottom-up pressures fostering large-scale social-ecological transformations. A transdisciplinary framework provides an alternative paradigm of generating knowledge that involves both the scientific community and other sectors of civil society [37,38]. The transdisciplinary approach can be complemented with the action research paradigm, which seeks a dialectic synthesis between knowledge production and intervention in the territory, with a focus on the diagnosis, resolution and attempts to promote greater socio-environmental justice through the incorporation of locally relevant questions and the active participation of the civil society [39]. It should be noted that action research in Latin America is particularly fruitful and has made numerous contributions in areas of social research and popular education [40], having the potential to be highly disruptive by empowering marginalized actors [35]. As Cousins first identified [7], NbS rarely dealt with issues of social and environmental justice. We consider that the coupling of an action-research scheme with NbS in a context of social vulnerability can be a transforming approach to deal with it.

Here, we propose to quantify the impact of wastewater from an informal neighborhood without drinking water coverage and sewers that discharge their domestic effluents through the storm drainage infrastructure, and to seek appropriate forms of mitigation using sustainable technology based on it modularity capacity, replicability in a wide geographical space, and capable of being carried out by local actors of the urban community. Results showed that untreated domestic sewage has a relevant impact on stream water flows and organic pollutants loads, which can be partially mitigated by the use of Biofilters co-produced with a local social cooperative. Our pilot study demonstrated their survival capacity against floods or other social factors, a great retention efficiency of suspended solids, and a moderate reduction of dissolved components.

Material and methods

Area of study

The San Francisco stream belongs to the Sarandí-Santo Domingo basin located south of the city of Buenos Aires, is categorized as a first-order lowland stream with a total length of 15 kilometers that flows to the Río de la Plata Estuary after its confluence with Las Piedras stream [9] (Fig 2). It is piped at its origins at the peri-urban area of the Almirante Brown District, emerging to surface at the locality of Claypole (Lat: 34°49′14″S; Long: 58°21′45″W)

(Fig 2 pink), with an estimated flow of 20–30 L sec^{-1} and a mean wetted width of 2–5 m [41]. This body of water exhibits eco-hydrological alterations [42] and clear evidence of pollution along its course with high levels of organic and microbiological contamination [43]. The city of Claypole presents some socio-demographic characteristics of concern given the lack of sewerage coverage (Fig 2 black) and drinking water supply (Fig 2 red) [9]. Given the lack of infrastructure, domestic effluents are discharged through the pluvial drainage network, which consists of open ditches that run through the entire neighborhood and discharge into the stream every 100 meters. The domestic effluents released through this network are mainly gray water (from bathtubs, showers, hand basins, laundry machines and kitchen sinks), although clandestine black water connections are not ruled out. The work was carried out in a section of the San Francisco stream from where it flows up to 1 km downstream (Fig 2 orange).

Fig 2. Area of study. Map showing the Buenos Aires metropolitan area including its administrative subdivisions (in gray). The district of Almirante Brown (in black) with the urban streams that cross it (in light blue) and the city of Claypole (in pink). In red, the area with public water supply, in black the area with sanitary sewage and yellow the study area

Co-production scheme

The general outline of the research-action process is detailed in Fig 3. It is highlighted that since the first works in the territory in 2015, a virtuous circle of research-action has been generated between researchers and workers of a cooperative belonging to an urban social movement, with a strong presence in the territory, called Frente de Organizaciones en Lucha (FOL). [9]. In this sense, four stages can be distinguished that accompanied the co-production process. The first consists of this previous stage of background and evaluation (2015-2019), where the links between social and academic actors were strengthened, as well as the identification of environmental problems, such as the pluvial drainage network, from which the entry of domestic wastewater was suspected due to the lack of sanitary infrastructure in the neighborhood. This led to the second stage of the diagnosis, where a seasonal physicochemical and microbiological characterization of the effluents entering the stream through this network was carried out. The results obtained were discussed and presented in 3 different cases with the workers of the cooperative as well as with the decision-makers of the community of Almirante Brown. The third stage consisted of the co-production of NbS for the reduction of wastewater entering the storm drain network through the implementation of biofilters. For this purpose, 3 days of design, 1 day of construction, and 4 days of installation were carried out. Finally, a phase of socialization and evaluation of what was learned through 3 days with the community and environmental organizations sharing the design, operation, and basis of the biofilters.

Fig 3. Schematic diagram of the action-research process. Four stages are highlighted: background and evaluation (green), diagnosis (purple), co-production (red) and evaluation and socialization of what has been learned (yellow).

Sampling and characterization of domestic effluents

Three seasonal samplings were conducted in winter (7/10/2019 and 07/18/2019), spring (10/21/2019 and 11/05/2019) and summer (02/11/2020 and 02/13/2020) between 11 am and 2 pm. The samplings included midday hours to know the time of maximum demand in the homes. Precipitation recorded at weather station 875760 SAEZ (Lat: 38° 48' 36"S, Long: 58° 31' 48"W) located 35 km from the study area were: 138.4 mm, 282.2 mm and 443.6 mm in winter, spring and summer, respectively. In each sampling date, a sample of five discharges spatially distributed at the study section was collected. It was taken into account that it had not rained at least 48 hrs. before. Water flow rate was measured at each intake measuring the water volume that discharge and the time duration [44,45]. A total of 10 discharges were sampled per season. Composite samples were taken from each discharge in triplicate. One stream sample was also collected per season by triplicate. Streamflow was calculated from hydraulic parameters (width, deep, velocity), measuring flow velocity by the float method [44,46]. For each sample, the following parameters were determined *in situ*: pH, temperature (T) and Electrical Conductivity (EC) using portable equipment (SensION 156 Hach), dissolved oxygen (DO) with an optical sensor (YSI PRO DO) and turbidity with a portable turbidity meter (2100P Hach).

Samples were collected in polypropylene containers of 20 L. Once in the laboratory it was fractionated and preserved (depending on the parameter in question), in amber glass bottles (organic determinants) or plastic bottles (inorganic determinants). The characterization of the samples taken from domestic-pluvial discharges and San Francisco stream included: Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Organic Carbon (DOC), Chlorides, Anionic Surfactants, Oil and Greases (determined as Soluble Substances in Ethyl Ether -SSEE-), nutrients (Total Phosphorus -TP-, Soluble Reactive Phosphorus -SRP-, Ammonium, Total Kjeldahl Nitrogen -TKN-, and nitrates) and bacteriological (*Escherichia coli*, Total Coliforms).

Total suspended solids (TSS) were determined on the shaken sample by filtration onto a pre-weighed glass fiber filter paper (Whatman GF/C 1.2 μm pore) and determined gravimetrically after washing and drying at 105 ± 5 °C [47]. Limits of quantification (LOQ) were 1 mg L^{-1}. BOD was determined within 48 hours of sample collection by the 5-Day BOD Test method [47] where sample dilutions were incubated for 5 days at 20 ± 3 °C. Dissolved oxygen is measured initially and after incubation, and the BOD is computed from the difference between initial and final DO (LOQ = 5 mg L^{-1}). COD was determined by closed reflux, colorimetric method [47] (LOQ = 10 mg L^{-1}). DOC was filtered by 0.5 μm pore glass fiber (Microclar) and preserved with sulfuric acid (Merck). The determination was made by the high-temperature combustion method using a Shimadzu 5000A carbon analyzer [47] (LOQ 0.1 mg

L^{-1}). Chlorides and nutrients (except TKN and TP) were analyzed within 48 hs of sample collection after filtration by 0.5 µm glass fiber (Microclar). Chlorides and nutrients (except TKN and TP) were analyzed within 48 hours of sample collection after filtration by 0.5 µm glass fiber (Microclar). Chlorides were determined by argentometric method [47] (LOQ = 4 mg L^{-1}), nitrates and nitrites by cadmium reduction method (LOQ = 0.3 mg L^{-1}) [48], ammonium by distillation [47,49] (LOQ = 0.1 mg L^{-1}), by ascorbic acid method [47] (LOQ = 0.01 mg L^{-1}). TP was determined by the ascorbic acid method after acid digestion with nitric acid and sulfuric acid (Merck) [47] (LOQ = 0.01 mg L^{-1}). TKN was determined by distillation and colorimetry after Kjeldahl digestion [47,49] (LOQ = 0.1 mg L^{-1}). The "Kjeldahl nitrogen" is the sum of organic nitrogen and ammonia nitrogen, to calculate the Nitrogen organic (Norg) the difference between TKN and ammonium was made. Anionic surfactants were determined by the method of methylene blue active substances (MBAS, from now on referred to as this parameter) [47] (LOQ = 0.02 mg L^{-1}). SSEE were determined by gravimetry after extraction with sulfuric acid (Sintorgan) [47] (LOQ = 1.4 mgL^{-1}). Measurements were realized by colorimetric analysis with a spectrophotometer Shimadzu UV 2450.

For bacteriological analyses, the samples were taken in sterile polypropylene containers of 1 L. Bacteriological analyses were carried out between 24 and 48 hours after the sample was taken. Total Coliforms and *E. coli* abundance was determined on each sample by plate counting using Chromocult® Coliform Agar selective medium (MilliporeSigma). Serial dilutions in sterile ultrapure water were performed to each sample in triplicate and plates were cultured for 24 h at 37°C in the dark [50,51]. Colonies were counted at the best dilution and an average was made per sample. The limits of quantification were 1 CFU ml^{-1} for both determinations.

Biofilter design, implementation and assessment

Two prototypes were designed, one whose structure consisted of three stacked tires and the other whose structure consisted of a 400 µm geotextile weave pot. The composition of the layers consisted of (from top to bottom): sand, fine gravel, LECA (Light Clay Expand Aggregate), pometine, and coarse gravel. Another feature that differentiated the two prototypes was the aeration system, where the first design (Fig. 4 a-b) consisted of 53 mm diameter PVC pipes, while the second design (Fig. 4 c-d) used 10 mm diameter corrugated pipes (widely used in the electrical industry for electrical wiring through the wall). The macrophyte used in both designs was *Typha latifolia*, an emergent aquatic plant commonly used in constructed wetlands. [52–54] and widely distributed in the Province of Buenos Aires.

Fig 4. Design of biofilters. a) scheme of the first design evaluated. Its structure was made up of three filled stacked tires whose layers are composed of (from top to bottom): sand, fine gravel, LECA (Light Clay Expand Aggregate), pometine and coarse gravel. The aerators were 53 mm diameter PVC pipes. b) Image of the biofilter installed in September 2019. c) Schematic of the second design evaluated. Its structure consisted of a pot of geotextile fabric of 400µm pore size and 150 L volume. The layers were composed of (from top to bottom): sand, fine gravel, LECA (Light Clay Expand Aggregate), pometine and coarse gravel. The aerators were 10 mm diameter corrugated pipe tubes. d) Image of a biofilter installed in December 2019.

For the first design, a prototype was installed on 09/06/2019, while for the second design, 8 biofilters were installed in three working days (12/16/2019, 12/17/2019, and 12/19/2019). In both cases, their condition was monitored to evaluate the necessary maintenance measures, resistance to substrate washing due to the effect of the incoming flow, and their survival. This was done in a participatory manner through weekly visits by the cooperative's workers using a WhatsApp group as a means of communication in which they informed if any maintenance had been carried out (removal of garbage), condition after a flood, vandalism, etc. The first prototype was monitored for 3 consecutive weeks until its breakage due to vandalism, while the installed biofilters of the second prototype were monitored from the time of installation until May 2020, where mobility restrictions conditioned their followup. During the period May 2020 and December 2021 their survival was eventually evaluated. Daily rainfall during this period was considered since floods are a determining factor in the persistence of the biofilter.

The installed biofilters were sampled on different occasions to evaluate their pollutant removal efficiency. The first biofilter was sampled for 3 consecutive weeks, while the second biofilters were sampled twice (01/03/2020 and 02/11/2020). In both cases, 1 L samples were taken from both the inlet and outlet effluent of each biofilter, and the following compounds were analyzed following the methodology described above: pH, EC, DO, TKN, TP, COD, and DOC. For each of them, the percentage removal efficiency was determined as the ratio between the concentration of the outflow effluent with respect to the inflow effluent.

Data analysis

First, to compare the levels of pollutants present in domestic discharges with the national regulations, we compared the discharge concentration allowed in the Argentine regulations (Res. ACUMAR 283/19). Subsequently, we performed a linear discriminant analysis (LDA) in order to analyze the variables that allow us to discriminate the effluents according to the season. For the pair of variables that had a Pearson's correlation coefficient (Pearson's ρ) > 0.90, one of the two was selected to avoid collinearity problems (S1 Fig.). The significance of correlation coefficients (Pearson's ρ) was adjusted by multiple comparisons (Benjamini- Hochberg method) [55,56]. Of all the variables analyzed, the following were used (previously standardized) for LDA analysis: Norg, DOC, *E. coli*, Total Coliforms, Chlorides, TP, MBAS, and COD.

From the flow measured in the samples of each season of the year, a flow model was made with the objective of obtaining an estimated flow distribution for a stretch of one-kilometer of stream, and thus be able to estimate the relevance of the effluent discharge on the stream under study. The flow distribution model associated with domestic effluents on the San Francisco stream was estimated using a Bayesian model (warmup = 1000, chains=3, iter =5000, thin=3) for each season. To determine the a priori distribution, the empirical flow data were fitted to three possible distributions: lognormal, normal, and gamma, with the lognormal distribution being the best fit and therefore the one used. The model was used to obtain the domestic discharge flow probability distribution curve. Forty random values were taken randomly from the probability distribution of theoretical flow of rainfall discharges and summed. In this way, the theoretical flow entering through rainfall discharges after 1 km was estimated (4 active domestic discharges every 100 m were considered). Finally, theoretical mass loads were estimated after 1 km by multiplying the mean concentration obtained for each pollutant by the estimated flow for each season. These loads were relativized to the mass loads present in the stream for each season to calculate their percentage contribution to those of the stream. Statistical procedures were implemented with the packages MASS [57], ggmcmc [58,59], fitdistrplus [60] and brms [58] in R (version 4.2.2) [61].

Results

Microbiological and physico-chemical characterization of effluents from domestic discharges

In order to evaluate the organic, nutrient, and bacterial load entering the stream through the storm drainage network and their impacts on the receiving body, 10 composite samples were collected from the discharges of this network along 1 km of the San Francisco stream, together with one sample of the stream water located upstream of the analyzed discharges (Fig 5). Spatial and seasonal variability was observed in the flow rate of the different discharges

(Fig 5 and Table 1) and in the different physico-chemical and bacteriological parameters evaluated (Table 1).

Figure 5. Map with the area of study. The blue star indicates the stream sampling site. The black circles indicate the analyzed domestic discharges where the size of the circle is proportional to the measured flow (red= winter, yellow= summer, orange= spring). The arrow indicates the direction in which the stream water flows.

Table 1. Descriptive statistics of the microbiological and physicochemical characterization of the effluents domestic. The mean, standard deviation, maximum and minimum for each parameter evaluated per station (n=10) are reported.

Season	Parameter	Unit	Mean	Standard deviation	Max	Min
Winter	Flow	ml seg^{-1}	97.2	174	581	5
	E.coli	CFU ml^{-1}	9,2E+03	6,3E+03	2,2E+04	4,0E+03
	Total coliforms	CFU ml^{-1}	1,5E+05	8,5E+04	3,9E+05	8,9E+04
	Turbidity	NTU	116	47.6	195	38
	Norg	$mgNL^{-1}$	6.37	2.85	11.0	1.99
	DIN	$mgNL^{-1}$	19.9	13.0	50.0	11.3
	SRP	mg $P\text{-}PO_4^{3-}$ L^{-1}	1.16	0.648	2.35	0.39
	TP	mg $P\text{-}PO_4^{3-}$ L^{-1}	2.11	0.958	3.85	1,00
	TSS	mgL^{-1}	76.5	61.8	201	29
	MBAS	mgL^{-1}	6.07	1.97	8.98	1.67
	SSEE	mgL^{-1}	42.2	52.7	186.	10.1
	BOD	mgL^{-1}	167	155	594	64
	COD	mgL^{-1}	434.	333	1340	211
	DOC	mgL^{-1}	56.8	17.0	73.6	16.4

	Chlorides	mgL^{-1}	127	11.9	149	106
	pH	units pH	7.96	0.269	8.51	7.42
	T	º C	14.3	1.51	17.2	12.2
	EC	μScm^{-1}	1595	180	1849	1198
	DO	mgL^{-1}	3.95	1.18	5.62	1.85
Spring	Flow	ml seg^{-1}	138	224	715	10
	E.coli	CFU ml^{-1}	6,1E+03	5,5E+03	1,6E+04	1,3E+02
	Total Coliforms	CFU ml^{-1}	2,6E+05	2,7E+05	9,6E+05	2,5E+04
	Turbidity	NTU	64	44	168	16
	Norg	$mgNL^{-1}$	14.7	21.7	76.2	3.61
	DIN	$mgNL^{-1}$	32.8	45.7	137	5.25
	SRP	mg P-PO_4^{3-} L^{-1}	2.86	5.07	15.8	0.04
	TP	mg P-PO_4^{3-} L^{-1}	3.86	5.80	19.1	0.61
	TSS	mgL^{-1}	60	49	146	18
	MBAS	mgL^{-1}	5.74	2.29	9.02	2.47
	SSEE	mgL^{-1}	34.5	17.3	66.3	14.1
	BOD	mgL^{-1}	102	120	412	28
	COD	mgL^{-1}	282	217	845	143
	DOC	mgL^{-1}	54.3	20.1	97.7	39.5
	Chlorides	mgL^{-1}	140	42	255	113
	pH	units pH	7.96	0.145	8.12	7.59
	T	º C	26.5	3.03	31.9	20.7
	EC	μScm^{-1}	1690	404	2810	1434
	DO	mgL^{-1}	2.28	2.48	7.72	0.34

	Flow	ml seg^{-1}	50	78	241	2
	E.coli	CFU ml^{-1}	6,1E+03	4,4E+03	1,6E+04	1,5E+03
	Total Coliforms	CFU ml^{-1}	1,5E+05	1,7E+05	5,8E+05	8,9E+03
	Turbidity	NTU	51	30	107	18
	Norg	$mgNL^{-1}$	5.40	3.29	11.8	0.59
	DIN	$mgNL^{-1}$	13.6	6.50	24.4	5.23
	SRP	mg $P\text{-}PO_4^{3-}$ L^{-1}	1.30	1.05	3.38	0.1
	TP	mg $P\text{-}PO_4^{3-}$ L^{-1}	1.70	1.10	4.33	0.34
	TSS	mgL^{-1}	41.1	31.2	98.4	7.14
Summer	MBAS	mgL^{-1}	3.42	2.04	8.49	1.12
	SSEE	mgL^{-1}	19.5	18.3	61.1	1.4
	BOD	mgL^{-1}	43	31	102	12
	COD	mgL^{-1}	192	96.1	397	82
	DOC	mgL^{-1}	95.4	27.8	161	58.7
	Chlorides	mgL^{-1}	141	40.0	240	89
	pH	units pH	8.30	0.123	8.49	8.16
	T	° C	28.1	1.59	30.7	25.6
	EC	μScm^{-1}	1618	301	2225	1026
	DO	mgL^{-1}	4.01	1.88	6.3	0.52

The discharge of domestic effluents through the pluvial drains exceed the permitted discharge values established by Argentinian regulations [62] (Fig 6a). Several parameters mostly related with suspended organic material exceed the regulations at all sampling times

(Fecal coliforms/*E. coli*, BOD, COD, MBAS, and TSS), while others only at spring (total nitrogen and dissolved ammonium).

To explore the discrimination of effluent composition across seasons, a Linear Discriminant Analysis was performed. The season established three well-defined groups of samples, mostly discriminated by the first component of the LDA (82%): Winter samples were better discriminated according to their increased levels of COD and MBAS, and lower levels of dissolved organic nitrogen and carbon, while summer samples behaved in opposition. Spring samples instead showed a better discrimination with the second axis (LDA 2, 18%), associated with increased levels of dissolved organic nitrogen and MBAS, but lower levels of COD and *E. coli*. (Fig 6b).

Fig 6. Characterization of domestic effluents. a) Values of discharge allowed to a pluvial network with respect to Argentine regulations [62]. The size of the circle represents how much the parameter is exceeded and the color whether it complies (green) or not (red) with the regulation. b) Linear Discriminant Analysis (LDA) according to the composition of the effluent with respect to season.

Modeling of domestic discharges

Applying a Bayesian model, we obtained an estimated distribution of flow's discharges around a one-kilometer stream reach of the San Francisco stream assuming the occurrence of four active discharges per 100 m of stream (Fig 7a). This has relevance to evaluate the percentage contribution of discharges in terms of flow through the pluvial network with respect to stream flow. The highest inflows were estimated for the spring and winter seasons with a percentage ratio with respect to stream flow of 16% and 9%, respectively, while for the summer it was only 3% (Fig 7b). In turn, by crossing the modeled data with the empirical data obtained in each of the samples, it was possible to estimate the percentage of increase, measured in mass load, of the different pollutants with respect to those transported by the stream (Fig 7c). It was observed that the most severe conditions occurred in the winter season, with a percentage increase in mass load after 1 km of about 60% for BOD and MBAS; *E. coli*, total coliforms, DOC, and chlorides between 20 and 50%; nutrients between 10 and 25%; while for TSS and SSEE the load transported upstream will double. In the spring this effect is reduced with increases in mass load between 10% and 20% and in the summer between 5% and 10%. These results showed the relevant contribution of domestic effluents to the water quality of the stream, and open the possibility of designing nature-based solutions to mitigate their impact on the stream.

Fig 7. Modeling of domestic discharges flow and estimation of the mass loads transported by the storm drainage network. a) Distribution of flow probabilities for each station obtained from the Bayesian model. b) Estimated contribution of domestic discharges in terms of flow after 1 km by the storm drainage network (green) with respect to the flow of the stream (yellow). c) Percentage contribution evaluated, as mass load, of the different pollutants after 1 km with respect to what is transported by the stream at each station.

Biofilter implementations and monitoring efforts

The first biofilter prototype that was installed remained operative for 3 weeks since in week 4 it was vandalized by removing the aerators and consequently mixing all the layers. During the time it was in operation, it showed a high removal efficiency of nutrients, evaluated as TKN (94%) and TP (86-96%); of organic matter, evaluated as COD (95-97%) and a moderate removal efficiency of the soluble organic fraction, evaluated as DOC (41-67%) (Table 2).

Table 2. Removal efficiency of installed biofilters (n=9). Only those in which it was possible to collect a sample, or which were operational at the time of sampling are listed.

Date of installation	Sampling date	Biofilter ID	COD	TKN	DOC	TP	IN/ OUT	pH	EC	DO
								upH	μScm^{-1}	mgL^{-1}
9/6/2019	9/17/2019	prototype	97%	94%	41%	96%	IN	7,48	1709	0,27

							OUT	8,49	1632	5,86
	9/27/2019	prototype	95%	---	67%	86%	IN	8,47	1639	3,89
							OUT	8,58	1616	4,56
	10/7/2019	prototype[a]	-10%	27%	2%	2%	IN	8,00	1638	2,40
							OUT	7,90	1589	1,20
12/19/2019	1/3/2020	B2	3%	1%	15%	1%	IN	7,93	1619	4,02
							OUT	8,10	1625	9,34
12/16/2019	2/11/2020	B4	-10%	2%	22%	1%	IN	8,39	1751	4,52
							OUT	8,22	1726	4,66
12/17/2019	1/3/2020	B5	40%	26%	25%	21%	IN	8,18	1653	1,74
							OUT	8,23	1660	9,43
12/17/2019	1/3/2020	B6	-3%	5%	2%	0%	IN	8,16	1605	10,73
							OUT	8,24	1611	11,04
12/17/2019	1/3/2020	B7	-23%	-54%	34%	2%	IN	8,12	1483	9,16
							OUT	8,08	1494	1,21
12/17/2019	1/3/2020	B8	7%	2%	6%	1%	IN	8,40	1708	10,73
							OUT	8,24	1713	7,49

[a] Vandalized (removal of aerators).

The second prototype, which was designed to facilitate the construction and survival of the devices, was tested installing eight biofilters in different discharges along a 1 km stretch (Fig 8a) in December 2019. This design, being more discreet, did not suffer vandalism in any of the 8 biofilters installed along the period of evaluation (December 2019 - December 2021). Of the 8 biofilters installed, 50% remained operational for 1 year and 25% for 2 years (Fig 8b). Flooding and progressive deterioration were the main causes of loss of the biofilters. It should be noted that several door-to-door visits were also made to inform neighbors about the installation of the biofilters, in addition to community workshops, which helped to intensify the care of the devices (Fig 8c). Biofilter's surface washing was moderate, requiring weekly cleaning of residues and refilling of the top layer to reduce the impact (Fig 8d). In both cases, monitoring was carried out by local community stakeholders, interacting with them through a dedicated WhatsApp group (Fig 8e).

Regarding Biofilter efficiency, generally speaking, after one or two months of installed they did not evidence good efficiency (Table 2), with low or null removals with the exception of biofilter B5, where oxygenation was favored in the first weeks of operation (from 1.74 mg O2/L inlet to 9.43 mg O2/L outlet), which resulted in better COD (40%), TKN (26%), DOC (25%) and TP (21%) removals (Table 2).

Figure 8. Installation and participative monitoring of the biofilters. a) Location of the biofilters installed (n=8) during the days of December 2019. b) Graph of daily rainfall from December 2019 to December 2020. It is detailed when the loss of any of the biofilters was reported. c) Workshops together with the neighborhood community where the installation tasks of the biofilters were communicated and their operation was exemplified using infographics and a model. d) Cooperative worker performing maintenance tasks in the biofilters. e) Cooperative worker transferring a sample of the biofilters to be transported and processed in the laboratory and WhatsApp group where the cooperative workers communicated the news related to the biofilters.

Discussion

We presented the results of a co-production process that starts with the need to evaluate the impact of the domestic discharges entering by the pluvial drainage system on the water quality of the San Francisco stream. Based on this context, we evidenced the relative impact of these effluents on stream water quality, with non-negligible input flows and high mass loads of organic matter, nutrients and pathogens, which in some cases double the contribution of stream water through a one-kilometer reach. Following this, two biofilter prototypes were designed, implemented and assessed for the mitigation of domestic pollutants. First, it should be noted that a significant percentage of the installed devices (50%) withstood heavy rainfall and remained operative for 5 consecutive months and 25% of these remained operative for 2 years without any maintenance time. Moreover, the first prototype showed excellent efficiency in the removal of N, P and total organic matter, with moderate efficiency in the removal of dissolved organic matter. On the other hand, the second design was easier to construct but showed low performance, only one Biofilter evidenced a moderate efficiency between 20-40% according to the pollutant. Finally, we highlight the fundamental role of the participation of the local community in the whole co-production process. Their participation allowed us to evaluate the feasibility of construction, installation and local maintenance. Future work on biofilter's optimization can be secured and re-appropiated through the co-production of socially robust knowledge.

Diagnosis of the physicochemical and microbiological characterization of the effluents of the pluvial network

Although the physicochemical composition of domestic effluents is very varied, the domestic discharges analyzed showed patterns similar in composition and quantity to graywater (kitchen, bathroom, laundry) reported by Eriksson et al. [63]. A marked variability was observed in the concentrations between each discharge for the same parameter, even at the same season station. This confirmed our hypothesis that graywater from households is discharged clandestinely through the rainwater network due to the lack of sanitary infrastructure. They presented a higher NT load (min-max: 6 - 214 $mgNL^{-1}$) than that reported by other authors [63,64] given that the main source of nitrogen in domestic wastewater, urine, should not be present in gray wastewater [63,65]. As for TP, expected values (0.34-19.1 $mgP\text{-}PO_4^{3-}L^{-1}$) were found in areas where detergents containing P are used. The COD: BOD ratio was 2.6, in the winter; 2.8 in the spring, and 4.5 in the summer, indicating a higher proportion of non-biodegradable organic matter with respect to wastewater [65,66]. The high bacterial load found (Total coliforms: 8.9 10^3- 9.6 10^5 CFU/100ml; *E. coli*: 1.3 - 2.2 10^2 CFU/100ml) can be attributed to the quality of drinking water accessed by households. *E. coli* is commonly used as an indicator of fecal contamination [63]; in this regard, it should be noted that the residents of the neighborhood, since they do not have drinking water service through the network, are forced to meet their needs through water abstractions [67], where in many cases the wells do not reach the adequate depth to access the aquifers with good quality water since the first aquifers are contaminated due to failures in the cesspools of the houses [68,69].

On the other hand, a Bayesian model was applied to obtain a theoretical distribution for the flow at each season from the empirical flow data. This allowed us to relate the concentration data measured in terms of mass load and to evaluate the inflow at the reach level. It should be noted that in terms of flow, what enters through discharges after 1 km with respect to the flow of the stream represents between 3 and 16% depending on the season. In the winter, the highest mass loads are observed, with a significant increase in SSEE and TSS. More precisely, the impact on the stream will be associated with the incoming mass loads, but it can also be greater or lesser depending on the stream flow at that time. In our study, this situation was exacerbated during the winter season, when rainfall was lower and stream flow was also lower than in other seasons. Low stream flows, as evidenced during winter, imply less dilution power, compromising the self-purification processes. In contrast, during summer a synergistic situation arose that caused the impact to be lower: lower flows entering through discharges added to a higher stream flow due to rainfall. This combination of factors resulted in a lower impact on water quality in terms of mass load. We attribute the lower flows in discharges to the evapo-transpiration process that could be associated with the characteristics of the pluvial drainage network (open-air, vegetated). This opens the possibility of implementing NbS directly in the ditches by increasing its vegetation to favor evapotranspiration processes and the assimilation of N and P. On the other hand, despite the variability in quantity and composition between discharges in the same season, it was possible to discriminate seasonally, showing an effect of environmental factors on the composition of the effluents during their transport in the drainage system.

Implementation and assessment of biofilters in the context of an informal urbanization

In our work, two biofilter designs were evaluated and subjected to the hostilities of the territory: vandalization, flow variability, mass load variability, and flooding. The first one showed excellent efficiency in the removal of N, P, and total organic matter and moderate efficiency in the removal of dissolved organic matter. It was operative for only 3 weeks since it had a sufficiently striking aeration system that resulted in their subtraction. The second design was easier to construct since the material used was geotextile fabric and it contemplated a less conspicuous aeration system with a section 5 times smaller. We believe that this decrease in the section could have had a negative impact on efficiency since these were low except in one sampling (01/03/2020) of the biofilter, B5, where an increase in DO and a moderate removal of TKN, COD, TP, and DOC were observed. Another factor that we believe may have influenced this difference is the hydraulic retention time (HRT). Although this parameter was not determined, a higher HRT was visually observed in the first design with respect to the second. For this reason, we began to test this hypothesis in a laboratory-scale experiment where we compared this design against a new system of aeration and reformulation of the layers to increase the HRT.

Water governance of urban streams, just nature-based solutions, and the co-production of socially robust knowledge

Chronic pollution from domestic effluents entering the stream is a threat to aquatic life in particular and to the health of the community in general but also an opportunity for the application of NbS, generating a revegetated stormwater/domestic network with native species that mitigate the pollutant load as well as provide shelter and food for a variety of insects and birds. While the holistic principles underlying NbS can create opportunities for social inclusion in a context of informality, their success requires an understanding of neighborhood dynamics, where socio-spatial exclusion is intertwined with environmental degradation [70]. In this sense, the management of urban streams in Argentina presents centralized and strongly hierarchical 'top-down' governance styles, promoting a rigid scheme of intervention and an "engineering" conception of the system, without being able to address the complexities that any socio-ecological system entails [71]. This style of governance coupled with social inequity intensifies the negative perception by the community towards streams and associated vegetation given the direct link to the risk they represent (flooding, health, delinquency, pollution) [70]. This negative perception operates as a limiting factor in the implementation of NbS and reinforces the need to generate new ways of interaction between governance systems, society, and scientific research to achieve effective changes in our reality, incorporating alternative ways of co-production of knowledge from the participation of other actors of civil society [72,73]. We can analyze this work as a case-study related to the execution of bottom-up transformative spaces at the local scale in which collective action and collaborative learning take place to generate new pathways toward sustainability [74].

In this sense, we highlight the fundamental role of the participation of the social movement members in the whole co-production process. Their involvement was essential to understand neighborhood dynamics of the drainage system, the assembly of an important number of biofilters, as well as the installation and preparation of the land. The workers of the cooperative were able to learn about the construction of small-scale treatment systems. Also, they participated in the weekly monitoring, as their insertion in the territory allowed them to monitor the devices more closely and report any issue. The WhatsApp group turned out to be a very important and dynamic tool for monitoring these biofilters. The social movement also organized a day of dissemination of the project's results among neighbors where the protection of the stream's ecosystem was highlighted as well as some proposals for mitigation. This experience gave rise to an endless number of iterations that enriched all those who participated in the process.

The proposal was also discussed with decision-makers, in this case from the local municipality. One of the direct consequences of the lack of sewers in the neighborhood was presented, as well as a proposal for a palliative measure. This led to the signing of a collective work agreement between the civil association, the university, a governmental science and technology institution, and the municipality to continue strengthening cooperation and action links. This is in line with what has been pointed out about the formation and consolidation of experimentation niches in urban contexts, which considers the need to take into account specific institutional settings and the importance of social movements as "knowledge brokers" between the community and academia [75]. Thus, the positive experience shown in this work can be seen as a satisfactory example of niche consolidation.

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Supporting information

S1 Fig. Pearson correlation matrix. Relationship between the variables determined.Levels of significance of Pearson's correlation among parameters are expressed as '***', $p<0.001$; '**', $p<0.01$; '*' , $p<0.05$ and '.' $p<0.1$.

S1 File. Supplementary Information

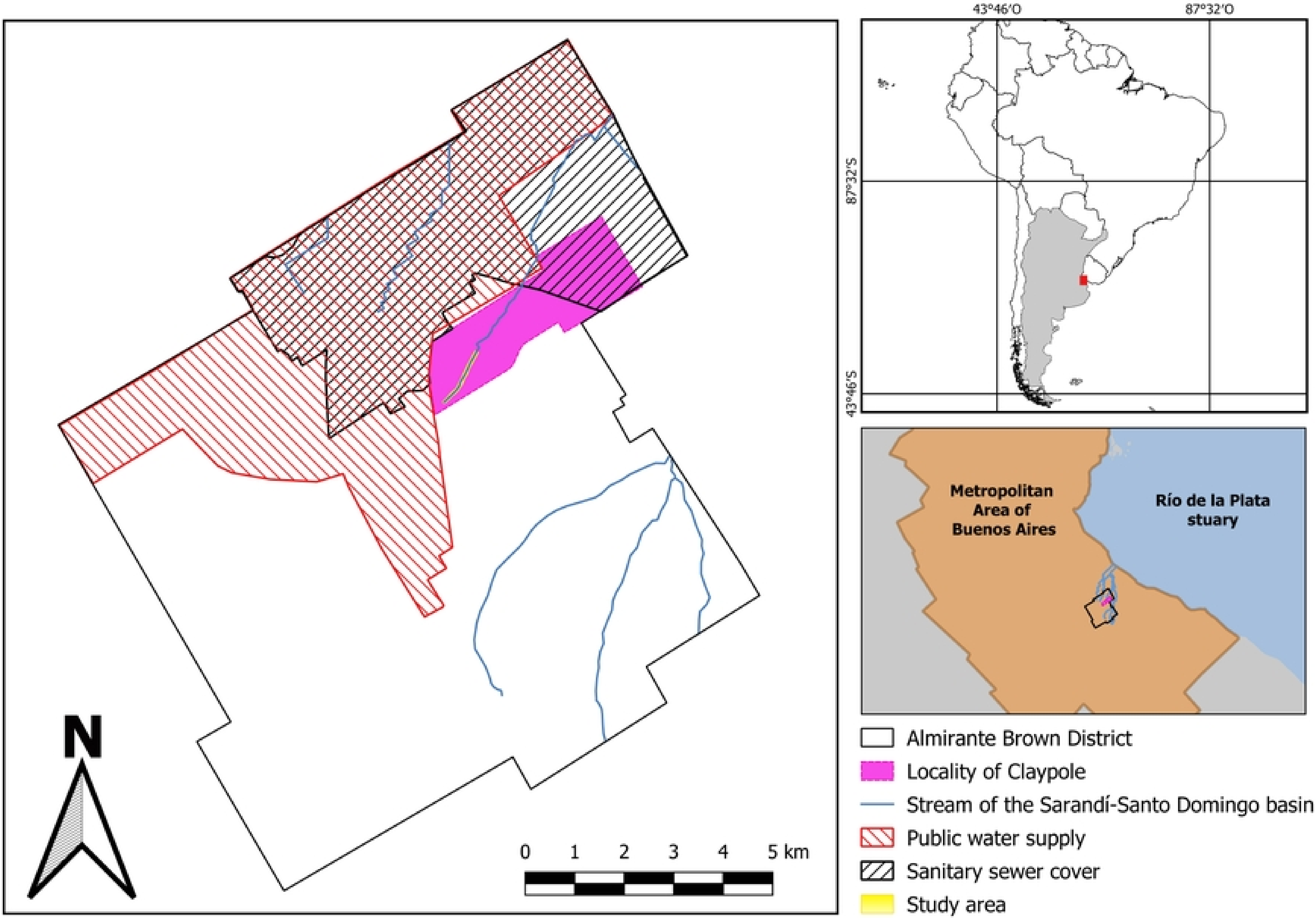

43°46'O
87°32'O
87°32'S
43°46'S
Metropolitan Area of Buenos Aires
Río de la Plata stuary
Almirante Brown District
Locality of Claypole
Stream of the Sarandí-Santo Domingo basin
Public water supply
Sanitary sewer cover
Study area
N
0 1 2 3 4 5 km

Figure 2

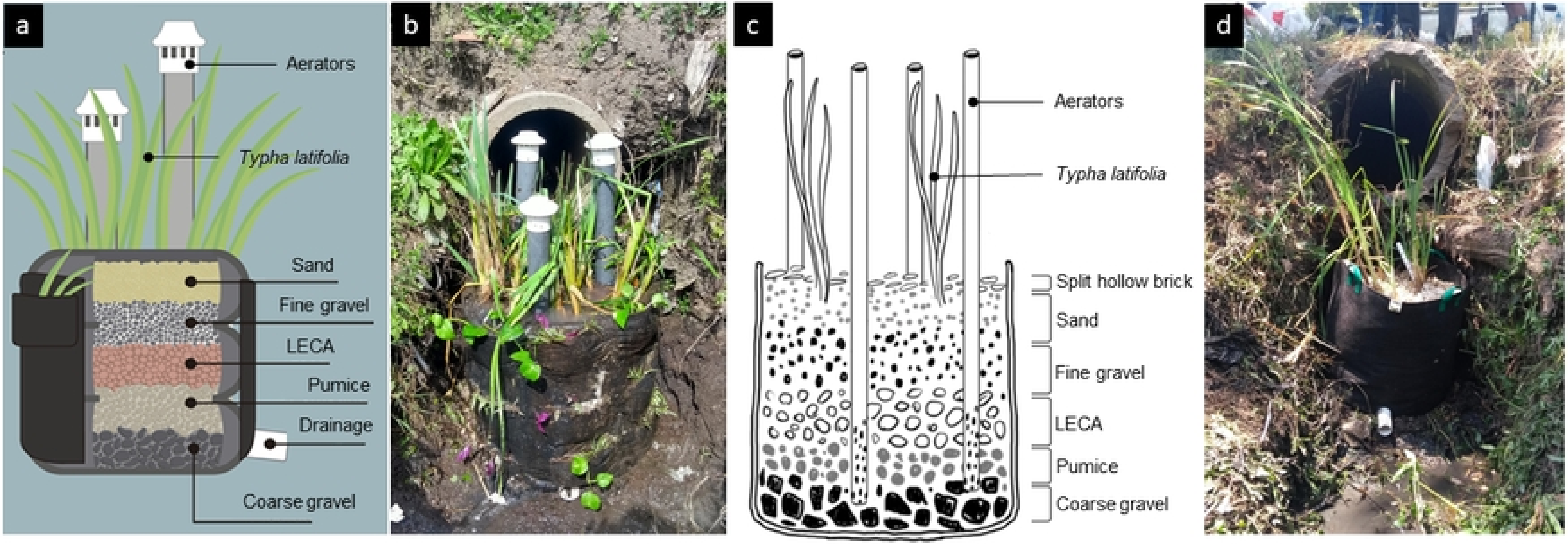

a
Aerators
Typha latifolia
Sand
Fine gravel
LECA
Pumice
Drainage
Coarse gravel
b
c
Aerators
Typha latifolia
Split hollow brick
Sand
Fine gravel
LECA
Pumice
Coarse gravel
d

Figure 4

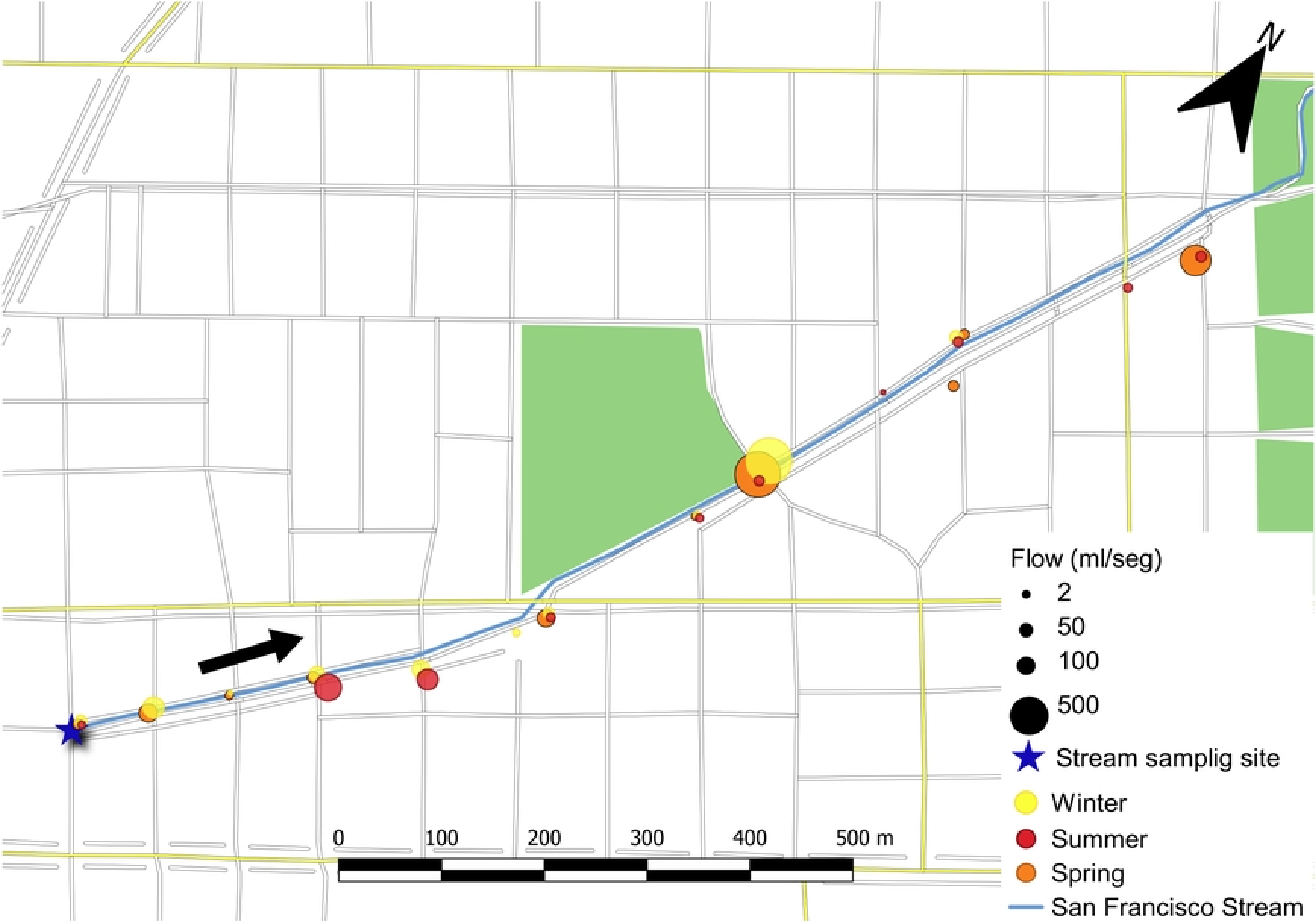

N
Flow (ml/seg)
2
50
100
500
Stream samplig site
Winter
Summer
Spring
San Francisco Stream
0
100
200
300
400
500 m

Figure 5

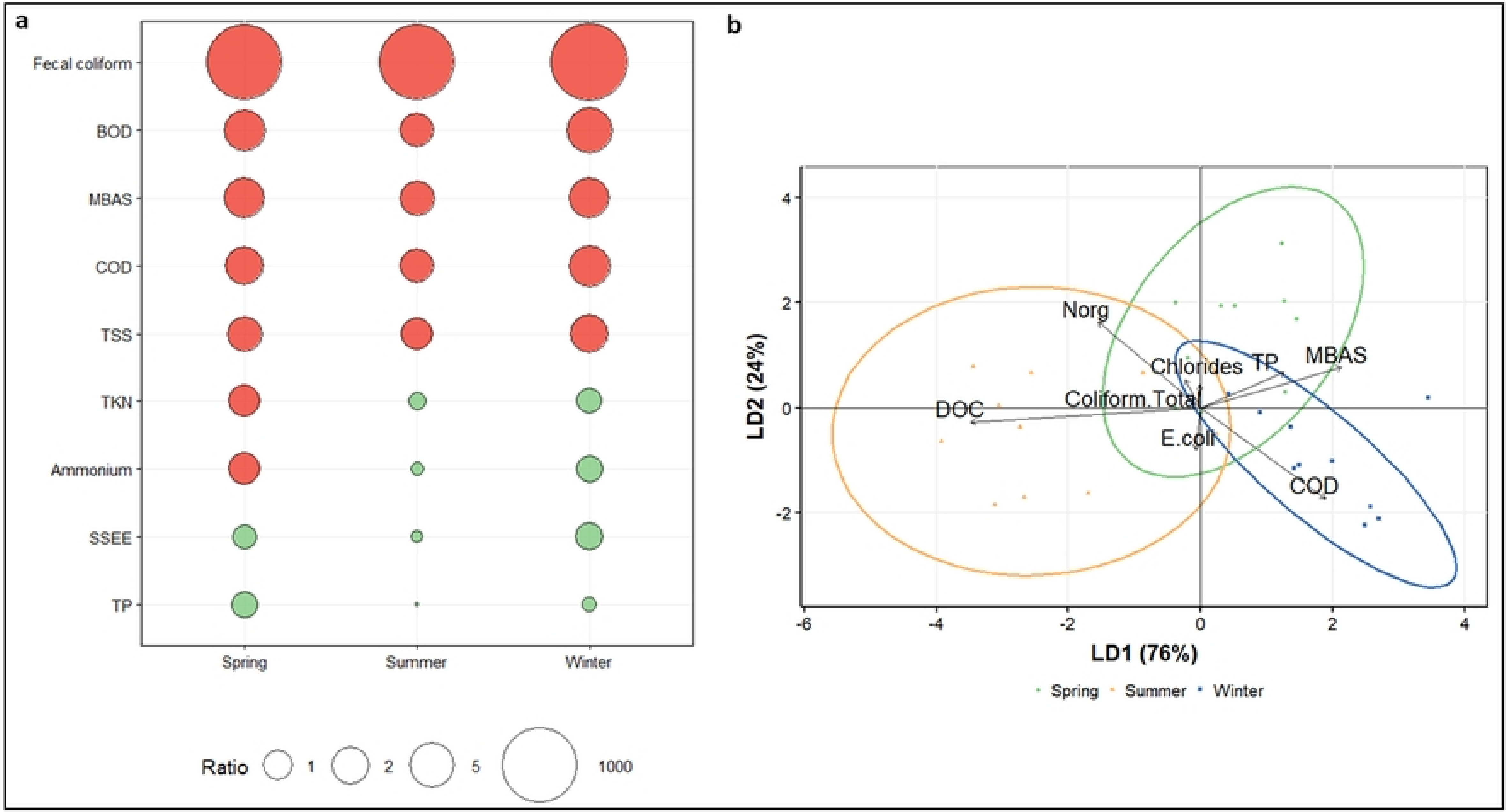
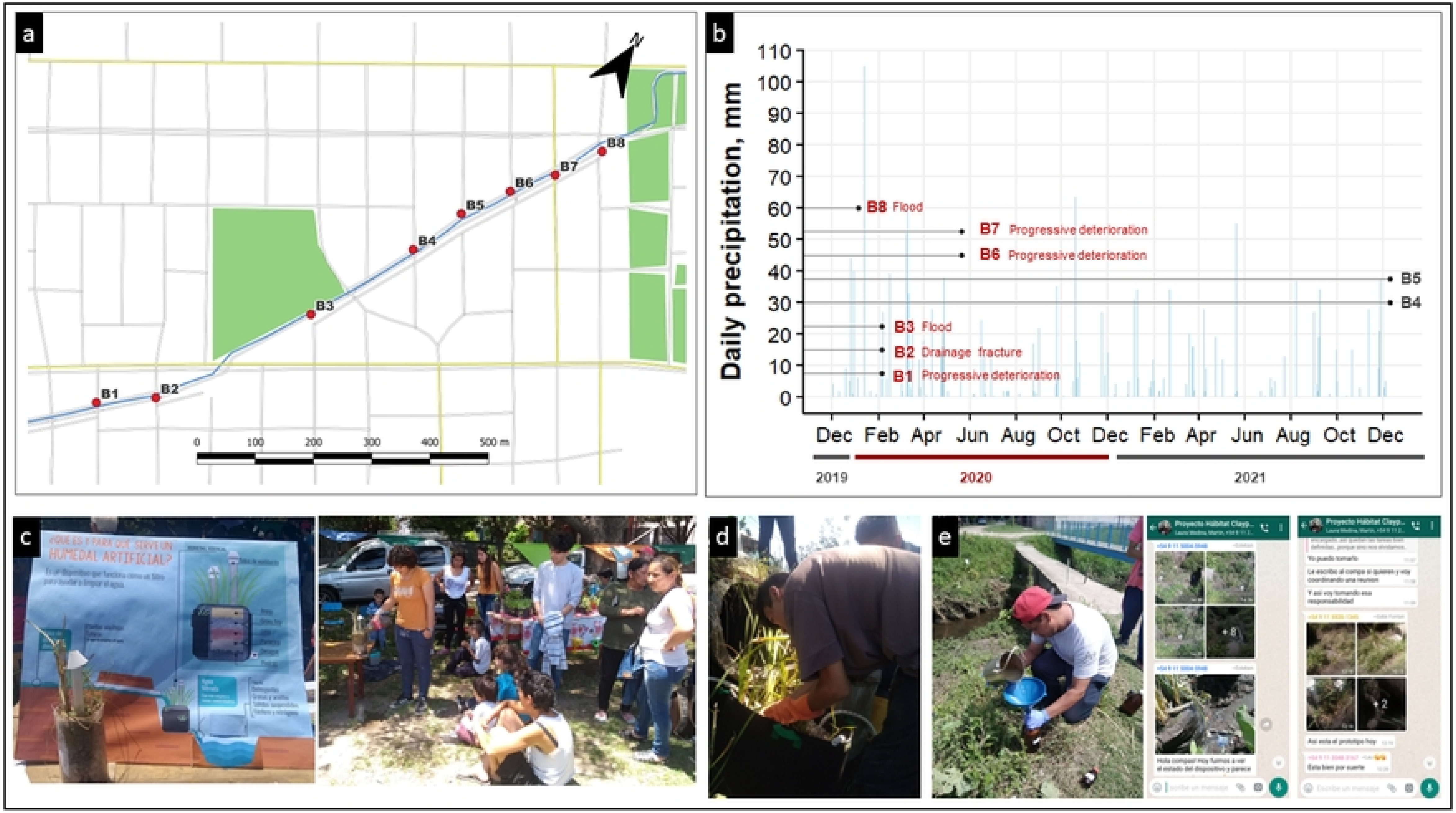

a
Fecal coliform
BOD
MBAS
COD
TSS
TKN
Ammonium
SSEE
TP
Spring
Summer
Winter
Ratio
1
2
5
1000
b
LD2 (24%)
LD1 (76%)
Norg
Chlorides
TP
MBAS
DOC
Coliform.Total
E.coli
COD
Spring
Summer
Winter

Figure 6



a
B1
B2
B3
B4
B5
B6
B7
B8
N
0
100
200
300
400
500 m
b
Daily precipitation, mm
110
100
90
80
70
60
50
40
30
20
10
0
B8 Flood
B7 Progressive deterioration
B6 Progressive deterioration
B5
B4
B3 Flood
B2 Drainage fracture
B1 Progressive deterioration
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
Jun
Aug
Oct
Dec
2019
2020
2021
c
¿QUE ES Y PARA QUE SIRVE UN HUMEDAL ARTIFICIAL?
d
e

Figure 8

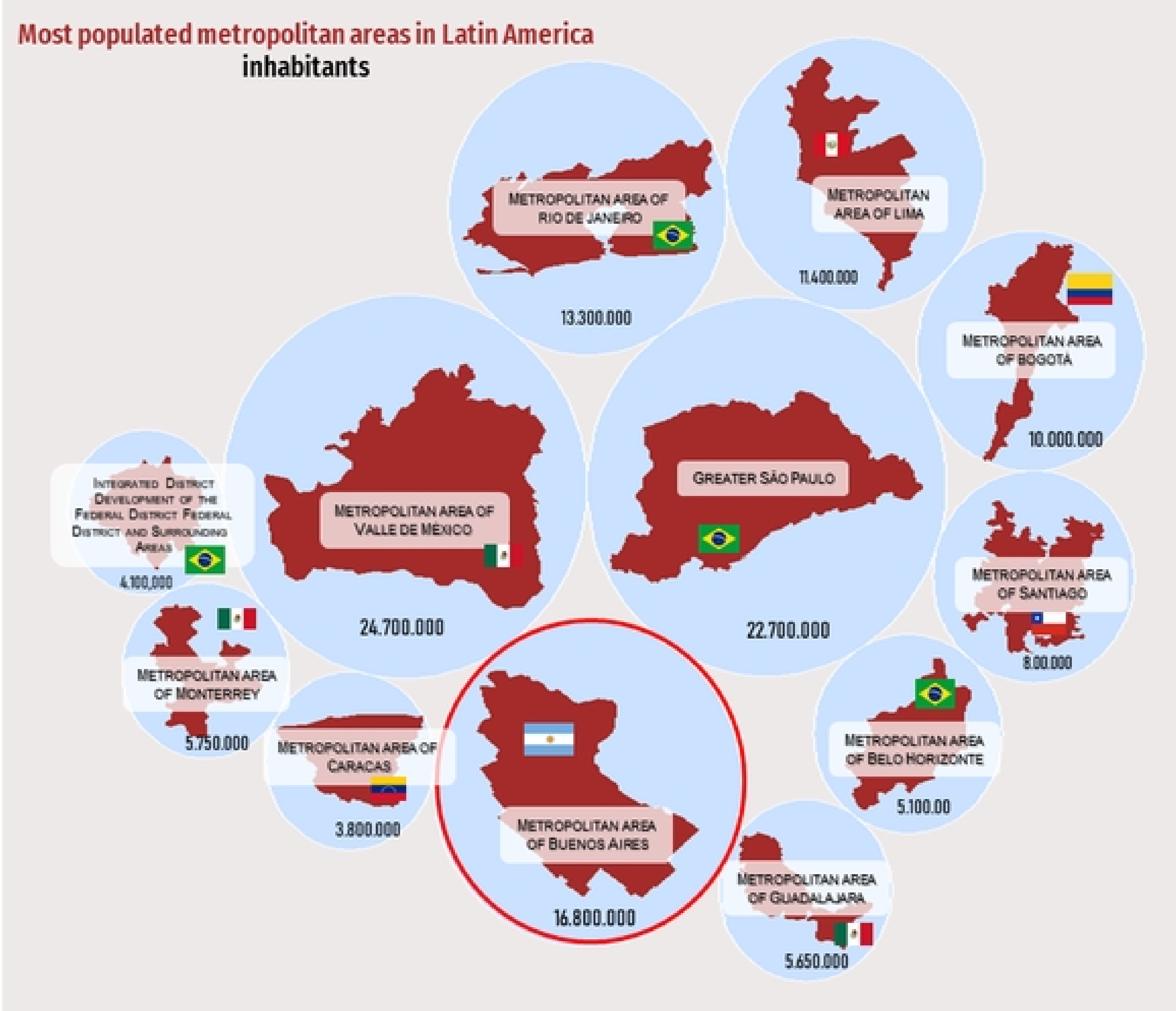

Most populated metropolitan areas in Latin America
inhabitants
Metropolitan area of Rio de Janeiro
13.300.000
Metropolitan area of Lima
11.400.000
Metropolitan area of Bogota
10.000.000
Integrated District Development of the Federal District Federal District and Surrounding Areas
4.100.000
Metropolitan area of Valle de México
24.700.000
Greater São Paulo
22.700.000
Metropolitan area of Santiago
8.00.000
Metropolitan area of Monterrey
5.750.000
Metropolitan area of Caracas
3.800.000
Metropolitan area of Buenos Aires
16.800.000
Metropolitan area of Belo Horizonte
5.100.00
Metropolitan area of Guadalajara
5.650.000

Figure 1


2015-2019
2019-2020
2019-2020
2020
BACKGROUND AND EVALUATION
DIAGNOSTIC
Characterization of domestic-pluvial drains
CO-PRODUCTION
Work meetings, construction and participatory monitoring of the biofilters
EVALUATION AND SOCIALIZATION OF LEARNING

Figure 3

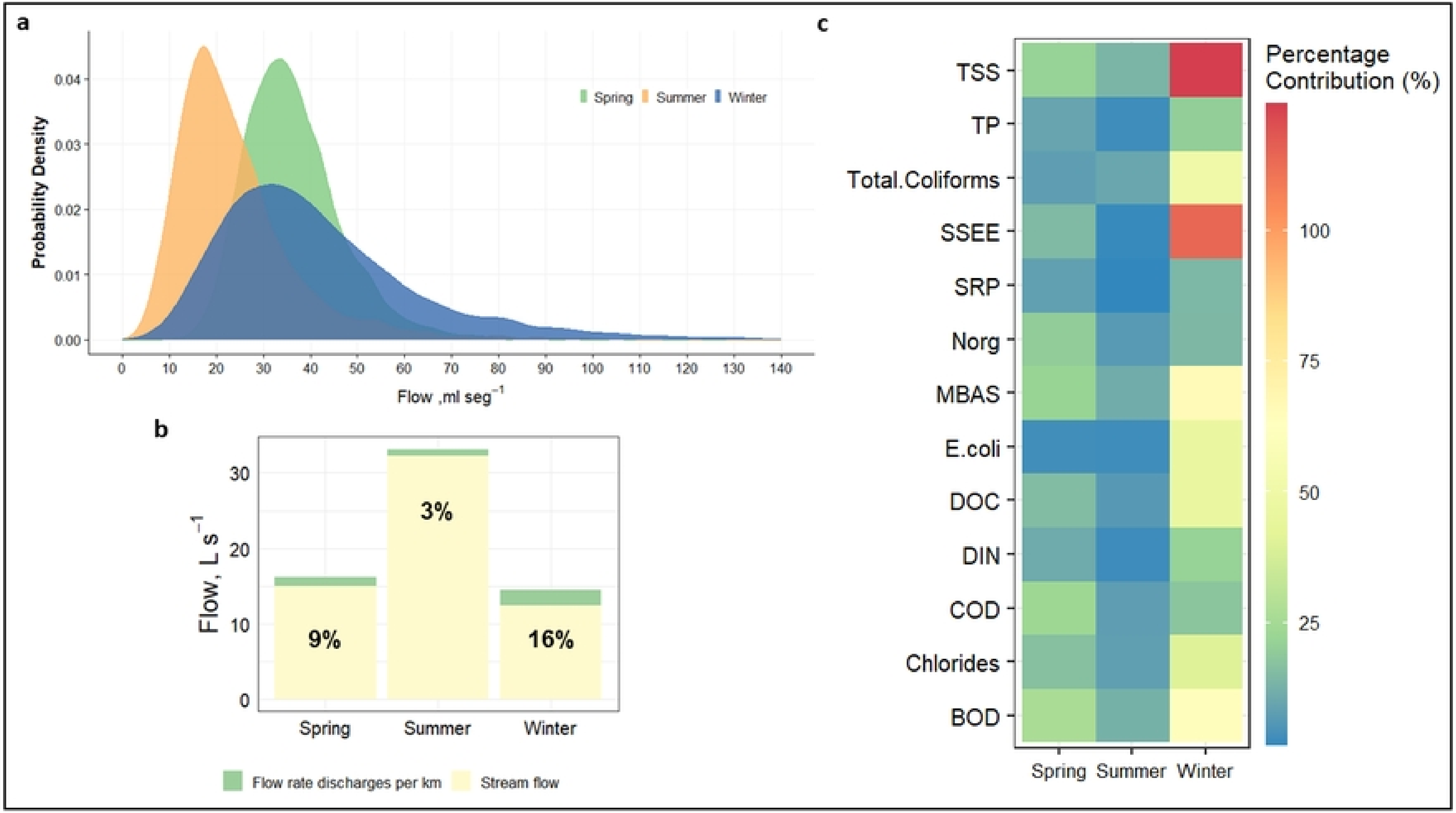

a
Probability Density
0.04
0.03
0.02
0.01
0.00
Spring
Summer
Winter
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Flow ,ml seg-1
b
Flow, L s-1
30
20
10
0
9%
3%
16%
Spring
Summer
Winter
Flow rate discharges per km
Stream flow
c
TSS
TP
Total.Coliforms
SSEE
SRP
Norg
MBAS
E.coli
DOC
DIN
COD
Chlorides
BOD
Spring Summer Winter
Percentage Contribution (%)
100
75
50
25

Figure 7