



# “The springs are untouchable”: amid community management and government neglect, the last springs in peri-urban areas of Mexico City

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## Abstract

In Latin America, conservation is a subject that cannot be understood outside of the social processes that determine the different conceptions, uses and customs related to nature and water. Mexico is an example of ecosystem diversity, where rural populations see their homes and ecosystems threatened by the uncontrolled advance of urban sprawl. In addition, the lack of governance in water matters leaves both the ecosystem and people in a situation of vulnerability. The aim of this research was to determine the ecological and social indicators of the state of conservation and management of the springs within Mexico City’s Conservation Soils, through: ecological quality, biological diversity and the perceptions of rural-urban communities of water management resources. The springs were found to still conserve elements of good ecological quality and unique traits, making these sites hotspots of local diversity. However, ongoing activities endanger its integrity, such as *in situ* water extraction, the lack of local organization for water management resources and the poor presence of government institutions to support it. The establishment of a citizen and government participation system for water management is recommended, considering local economic development, socio-cultural complexity, ecosystem richness and fragility, and the socio-ecological context in which these water distribution mechanisms are established. Such actions should include a census of water bodies and the economic activities that depend on them, the ecological evaluation of actively used springs, and water distribution agreements at the local level that consider the previous points.

**Keywords** Peri-urban springs · Water governance · Rural water management · Socio-ecological vulnerability

## Introduction

In Latin America, the history of conservation is necessarily linked to social history and, in many cases, a fight for territorial rights. In Mexico, the process of conserving natural areas began with the establishment of national parks (non-state), differing from other parts of the world. This idea was based on the establishment of “national pride.” Under this view, conservation areas should be located close to cities in order to promote the creation of rural businesses through tourism, under the slogan “living nature museums” (Quezada-Grant 2013). In such a way,

Mexico contained the largest number of national parks in the world by 1940 (Velázquez 2013). Conservation areas were established that marginalized peasants and indigenous populations who were inhabitants and owners of the land. Expropriations due to the establishment of national parks gave rise to claims to preserve land rights. Part of these claims were transformed into social demands made during the Mexican Revolution with a language of environmental justice (Quezada-Grant 2013). In the case of Mexico City (CDMX), exponential demographic growth has put very serious pressure on the relicts of natural areas that supply ecosystem services to the city. To prevent the deterioration of these areas, the local government created an administrative status called Conservation Soils (CS), which limits human activities around the management of natural resources and economic activities. Currently, the CS governmental agency oversees rural and indigenous communities that own the last natural resources available to the city, including water. Naturally, water consumed

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within the city originates from springs that flow down the mountain. Along their paths, they are subject to recurrent human uses such as irrigation, fish farming, and the local supply of drinking water.

### Springs as ecological and human resources

Springs are runoffs distinguished by a relatively constant contribution of water, scarce variation in chemical composition, constant temperature, and low organic matter concentrations (Hynes 1970). In ecological terms, springs provide habitat for particular biological communities and are therefore considered hotspots of regional diversity, making them great indicators of human disturbance (Reiss and Chiffard 2017). In social terms, springs are an essential source of drinking water in adjacent population centers. For example, it is estimated that approximately 50% of rural communities depend exclusively on groundwater as their main source of water supply (PAHO (Pan American Health Organization) 1998). Despite their biological importance and how vulnerable springs are to human interventions, they are rarely protected under legislation (Cantonati et al. 2012). In this context, public policies have been developed in Mexico that are implemented through a vertical vision (top-down), in which the government makes decisions about the management of natural resources with little or no participation from local communities whose livelihoods mainly depend on local natural resources (Santana-Medina et al. 2013). Such is the case for drinking water, a resource that is increasingly precious due to its scarcity and the evident lack of equitable distribution. The history of spring management in Mexico, and more generally in the rest of Latin America, is marked by a lack of governance over natural resources, vertical action decision-making by governments, and conflicts associated with the social ownership of land (Tinoco et al. 2022; Hommes et al. 2020). In many cases, these factors define the fate of water bodies, either from pollution due to human activities, the depletion of springs due to excessive extraction, or a combination of both (Tinoco et al. 2022).

Finally, this lack of management and action to protect springs shows the disconnect between the ecohydrological aspects of these natural resources and the social traits related to local use and management (Nel et al. 2017). In addition to the above, and independent of the particular agreements on land property rights, community interaction with natural resources is usually framed by actions of individual use, which limits the effect of collective action that favor group well-being (Hommes et al. 2020; Muradian and Cárdenas 2015). Therefore, within communities, communication and teamwork are key elements to achieve sustainable resource management regardless of government intervention, which is complementary and desirable.

### Social organization in the Magdalena River conservation soil

Management of natural resources based on the collective actions among community members has been cataloged as a vital component to achieve success in ecosystem conservation and consequently social welfare (Muradian and Cárdenas 2015; Auer et al. 2020). These improvements are reflected in the development of social skills such as better organization, building bonds of trust and respect, inclusion and participation of different social actors, and more constructive links with government institutions (Pretty 2003; Muradian and Cárdenas 2015; Auer et al. 2020). The indigenous and agrarian community "*La Magdalena Atlitic*" has a history that dates back 700 years and has been consolidated through intergenerational inheritance of land property. Recently, the community has been faced with rapid urban growth from the neighboring CDMX, causing them to defend their territory and the water (Olmos 2011). This community currently owns the largest extension of land within the Magdalena River sub-basin (approximately 70%), which is part of the larger Mexico Basin. The first record of water management and use dates to the year 1635 and was focused on distribution for the following activities: textile factories, fruit tree crops, farm maintenance, and domestic activities of the local population (Caro-Borrero et al. 2017). From the late 1800s to the mid-1900s, the sub-basin served as the engine of industrial development in terms of hydroelectric power generation and forest management. Canals were built over the river, while dams and four motors were installed to generate electricity (dynamos). This management functioned through water concessions granted by the government and administered by a local water board established in 1944 (Caro-Borrero et al. 2017). With the closure of the factories in the mid-1990s and the growing urbanization of the area, water use went from being industrial to domestic. Starting in 1979, the government began to carry out actions regarding the sanitation of the Magdalena River. Despite this plan, intense flooding occurred throughout the following decade as a result of the large amount of accumulated garbage in the riverbed. In 1997, the river's ecological status was placed on the political agenda after residents and community members promoted government attention to rescue the river despite skepticism and mistrust in the authorities (Olmos 2011; Caro-Borrero et al. 2021). In 2006, the CDMX Environment Secretariat launched the "Rescue Plan of Magdalena River," which was presented as an executive project by the National Autonomous University of Mexico (UNAM). This document outlined the main drivers of change and possible mitigation and/or restoration measures for the ecosystem.

Despite these efforts, the scarcity of drinking water was a key element in the area that compromised different social and economic interests, causing the rescue plan and the establishment water governance to fail (Zamora 2013; Caro-Borrero et al. 2021). Currently, community members distrust the local and federal government as a mediator for the management of natural resources. In addition, different internal interests regarding water use and management have led to a division in agrarian community members, further hindering decision-making regarding community life and natural resource management (Caro-Borrero et al. 2021).

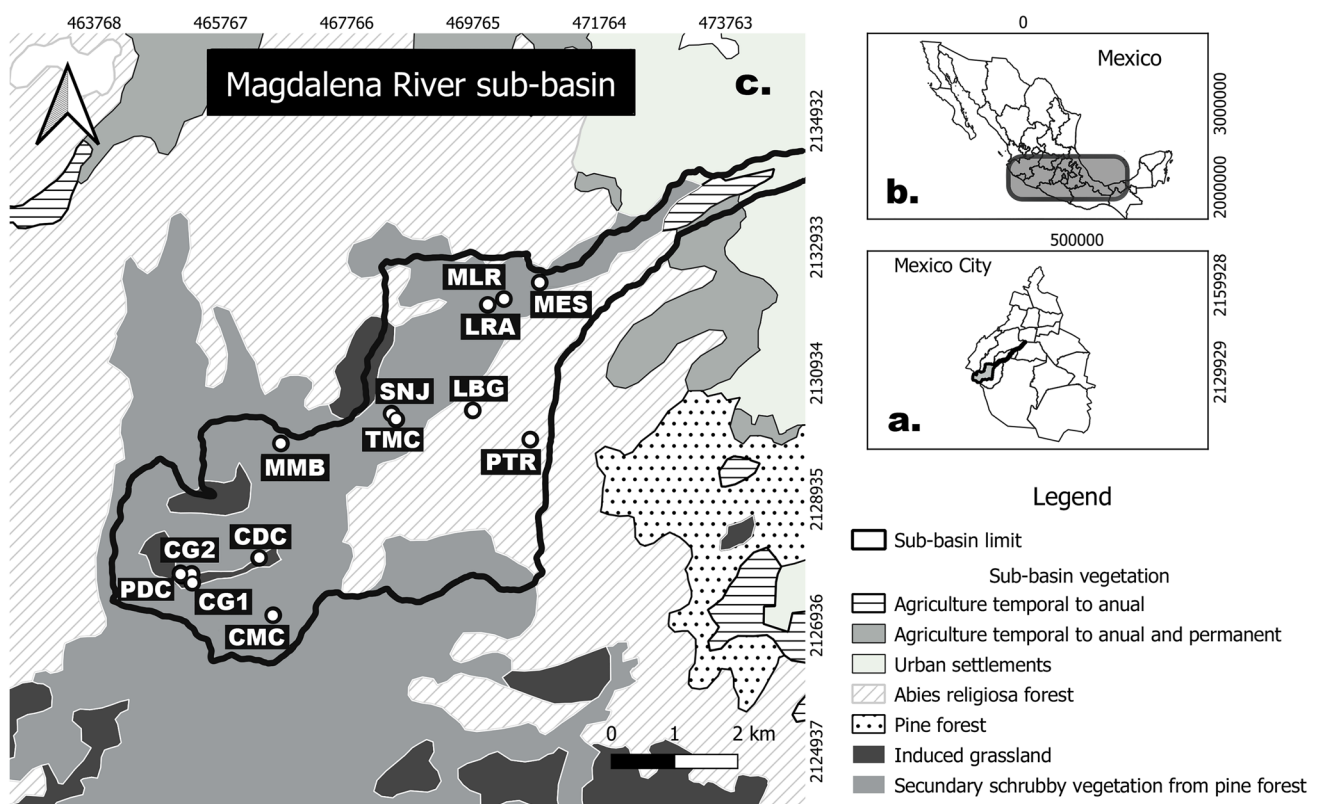
In the megalopolis of CDMX, numerous springs and mountain streams run off from mountainous areas that are currently legally protected under the administrative designation of Conservation Soils (CS), before reaching and disappearing into the urban area (Mazari-Hiriart et al. 2014). The region's high altitude (over 2,400 m asl) and latitude (subtropical) generate temperate conditions that differentiate this geographical area from the rest of the country. This makes the CS unique in terms of its diversity and the fact that it contains the water and forest reservoirs that sustain the development of the megalopolis. Being the only source of local surface water for CDMX, the region's state

of conservation is related to both ecological and socio-economic aspects. The aim of this research was to determine the ecological and social indicators of the state of conservation and management of springs within the Conservation Soil of Mexico City, specifically in the Magdalena River sub-basin, through the characterization of: (i) ecological quality (the physical, chemical, and hydromorphological quality of the water), (ii) biological diversity (macroinvertebrates and macroscopic algae), and (iii) the rural-urban community perceptions of water management resources.

## Material and methods

### Study area

The Magdalena River sub-basin is part of the larger Mexico basin and is located between 19°13'–19°18' LN and 99°14'–99°20' LW (Fig. 1). It forms part of the Trans-Mexican Volcanic Belt morphotectonic province, whose geology is characterized by rocky bodies of andesitic and basaltic lavas that are highly permeable and susceptible to erosion (Ferrusquía-Villafranca 1998). The remnants of conserved forested areas within CDMX have been legally protected



**Fig. 1** Geographic location of Mexico City (a), central Mexico (b) and the sampled springs/streams in the Magdalena River sub-basin (c). Sites code according to Table 1

with the designation of Conservation Soil (CS) (Caro-Borrero et al. 2017), with the objective of conserving the forests and mountain rivers. Although these areas are legally protected, they continue to face strong anthropogenic pressures. CS have become highly valued, not only for their ecological role, but also due to the increased need for housing within the growing CDMX metropolis (Caro-Borrero et al. 2021).

Due to the altitudinal gradient, two climate types are recognized within the sub-basin: sub-humid climate in the urban part and up to 3,050 m asl, and semi-cold climate in the higher parts between 3,100 and 3,650 m asl (García 1988). Both climates experience abundant rains from June to October and a dry season from November to May (García 2004). The average annual temperature ranges from 10 and 14 °C, with the warmest months being April, May, and June. The predominant vegetation is *Pinus hartwegii* Lindl forests in the upper section, *Abies religiosa* (Kunth) Schltldl forests in the middle section, and *Quercus* spp mixed forests in the lower section (Ávila-Akerberg 2010). In the upper and middle sections of the sub-basin, numerous springs feed into the main channel of the river, resulting in a perennial flow. Spring selection for the study was determined by: location within the Conservation Soil; the presence of cartographic references within the hydrographic records; and references by Magdalena Atlitic community members regarding well-conserved springs that are reliable for local water consumption.

### Physical, chemical and hydromorphological quality assessment

Samples were collected from 13 small springs and streams (first and second order, not exceeding one meter wide on average), all distributed throughout the designated Conservation Soil, located above 2800 m asl, within areas of mountain vegetation, of shallow depth (on average 8 cm), with a slow current speed regime, and very low flow values (Fig. 1, Table 1). We conducted three sampling collections at the same points of each spring/stream in: June 2019 (the end of the dry season in spring just before the onset of the rains, when the greatest abundance of macroinvertebrates is observed); September 2019 (the rainy season), and January 2020 (the cold, dry seasons, when the greatest abundance of algae is observed). The following physical and chemical parameters were recorded *in situ* with a Hanna Multiparameter probe 991300 (Dallas USA): water temperature, specific conductivity and pH. Oxygen saturation (YSI-85 meter, YSI, Ohio, USA) and current velocity (Global Water FP111, Texas, USA) were also recorded. Stream discharge was calculated according to Gore (1996). At each sampling station, 500 ml samples of water were filtered *in situ* and analyzed in the laboratory according to criteria established in the Mexican official guidelines and international

standards (NOM-127-SSA1-1994 in DOF (Diario Oficial de la Federación) 2000; APHA 2005). Nitrite nitrogen, nitrate nitrogen, ammonium nitrogen, dissolved inorganic nitrogen (DIN), and soluble reactive phosphorus (SRP, in theory mostly in the form of orthophosphate, PO<sub>4</sub>-P) were analyzed with a DR 3900 laboratory Spectrophotometer (Hach, Loveland, CO; Hach 2003). We compared nutrient concentrations in the springs with the maximum permissible limits (MPL) established in two official Mexican standards: the standard for the Protection of aquatic life-NOM 001 SEMARNAT 1996 (DOF 2003a) and the standard of water for human use and consumption-NOM 127 SSA1 1994 (DOF 2000).

Hydromorphological quality (HQ) and anthropogenic activities were evaluated per “Hydrogeomorphological Quality Index for Springs (HYQIS) of the Magdalena River Sub-basin” (Temís-García 2021). This index evaluates three major aspects (with distinct parameters in parenthesis): 1) quality of the riparian habitat or the area surrounding the spring (native vegetation cover, livestock and agricultural development, substrate disturbance, and bank stability); 2) hydrology (alteration of the channel, presence of dams and/or artisanal pipes); and 3) amount of anthropogenic disturbances (direct effluents to the spring from domestic use, urban development, human development, presence of organic/inorganic waste, and presence of protection around the spring). Each parameter is valued at 10 points, for a maximum possible total score of 120 points, which would indicate practically pristine conditions (see supplementary material). The hydromorphological quality scores are divided into the following categories: optimal (120–100), good (99–83), medium (84–47), low (46–13) and poor (<12).

### Biological indicators

Ecological quality refers to the naturalness of the structure and function of the ecosystem in the absence of significant human disturbance (Stoddard et al. 2006). In this sense, biological proxies can be used to assess the state of conservation of ecosystems, in which a healthy ecosystem is viewed as preserving biotic and abiotic diversity and their interactions (Poikane et al. 2016). In particular, conspicuous macroscopic algae growth plays a preponderant ecological role in mountain rivers, mainly serving to cycle nutrients and provide food and refuge for freshwater fauna (Carmona-Jiménez et al. 2022). Similarly, macroinvertebrates are abundant and oblique along riparian systems, being fundamental to the maintenance of the food chain within the concept of the river continuum concept (Vannote et al. 1980). Due to the evolutionary diversity of the different macroinvertebrate taxa, this group’s assemblage can be ensured to show a response to pressures or changes stemming from anthropogenic origins (De Pauw et al. 2006; Dunbar et al. 2010).

**Table 1** Geographic location, as well as physicochemical and hydromorphological characteristics of sampled springs in the Magdalena River sub-basin

Site and ubication (Latitude North/ Longitude Western)	Altitude (a m.s.l.)	Width [m]	CV [m/s]	Depth [m]	Q [m <sup>3</sup> /s]	T [°C]	K25 [µS/cm]	pH	DO [mg/L]	SRP [mg/L]	NO <sup>2-</sup> [mg/L]	NO <sup>3-</sup> [mg/L]	NH <sup>4+</sup> [mg/L]	HQ*	Algae (percent coverage) <sup>a</sup>	MIBs <sup>b</sup>
<b>1. Mananial Ermita</b> <i>San José (MES)</i> 19°17'05.18'' 99°16'39.62'' First order	2882	0.37 (0.20- 0.50)	0.1 (0.1)	0.018 (0.013- 0.025)	0.0007 (0.0003- 0.001)	11.9 (10.8- 12.8)	117.5 (116-119)	6.9 (6.7-7.1)	7.1	0.28 (0.26-0.3)	0.01 (0.01- 0.01)	0.02 (0.02- 0.03)	0.03 (0.03- 0.04)	92	ND	Du,Hi, O,Li, Hy,Le, He,Xi, Ba,Hp, Ve,El, Si,Ch, Ti,Is, St
<b>2. Arroyo La Rosita</b> <i>Alto (LRA)</i> 19°16'53.98'' 99°17'07.55'' First order	2947	1.8 (1.4-2.2)	0.249 (0.17- 0.31)	0.073 (0.051- 0.11)	0.02 (0.004)	11.3 (10.1- 12.1)	128.5 (103-154)	6.3 (5.5-6.8)	7.5	0.36 (0.23- 0.59)	0.00 (0.00- 0.01)	0.03 (0.02- 0.05)	0.31 (0.07- 0.55)	110	ND	ND
<b>3. Mananial La Rosita (MLR)</b> 19°16'56.83'' 99°16'59.03'' Second order	2916	0.48 (0.3-0.6)	0.223 (0.15- 0.32)	0.032 (0.025- 0.04)	0.0031 (0.002- 0.004)	11.6 (10.4- 12.3)	112.5 (112-113)	6.9 (6.5-7.1)	7.1	0.20 (0.14- 0.27)	0.00 (0.00- 0.01)	0.03 (0.02- 0.04)	0.04 (0.03- 0.06)	90	ND	Du,O, Li,He, Lp,Gi, Li,Po, Hy,Le,Ba,Hp,Ne,Ch
<b>4. Mananial La Bodega (LBB)</b> 19°15'59.54'' 99°17'15.20'' First order	3072	0.42 (0.35-0.5)	0.163 (0.1-0.2)	0.021 (0.013- 0.034)	0.0012 (0.001- 0.0014)	12.2 (12-12.3)	68.5 (30-107)	6.0 (5.3-6.5)	7.6	0.37 (0.3-0.47)	0.00 (0.00- 0.00)	0.05 (0.01- 0.13)	0.02 (0.0-0.03)	72	Me,Di (100)	Du,O,Hi,Hy,Le,Li, Xi,Ba,Hp,Ne,Pe,Ca, Ve,As,El,Dr, Ch
<b>5. Mananial Poivro (PTR)</b> 19°15'45.82'' 99°16'45.51'' First order	3138	0.62 (0.16-1.1)	0.99 (0.23- 1.77)	0.041 (0.025- 0.065)	0.014 (0.008- 0.018)	10.6 (10.4- 10.8)	78.5 (103-154)	6.2 (5.7-6.5)	7.1	0.31 (0.14- 0.49)	0.00 (0.00- 0.01)	0.04 (0.03- 0.06)	0.01 (0.01- 0.02)	78	No (100)	Du,O, Li,Li, He,Gi,Xi,Ba,Ne,Em, Ep,Ch,As
<b>6. Mananial San José (SNJ)</b> 19°15'56.64'' 99°17'59.36'' First order	3221	0.77 (0.6-1.0)	0.33 (0.15-0.6)	0.067 (0.063- 0.073)	0.02 (0.007- 0.04)	10.9 (10.9-11)	97.5 (97-98)	6.5 (5.7-7)	6.5	0.18 (0.12- 0.26)	0.00 (0.00- 0.00)	0.06 (0.02- 0.12)	0.04 (0.03- 0.06)	92	No,Hi, Fe,Co (26)	Du,Hr,O, Li, Le, Ba, Pe, Ti, Di, Ve
<b>7. Mananial Temascalco (TMC)</b> 19°15'57.68'' 99°17'59.94'' First order	3236	0.82 (0.45-1.2)	0.305 (0.224- 0.37)	0.061 (0.023- 0.09)	0.016 (0.004- 0.03)	11 (10.9- 11.2)	95.5 (94-97)	6.4 (6-7.3)	6.8	0.22 (0.14-0.3)	0.00 (0.00- 0.00)	0.06 (0.03- 0.08)	0.14 (0.03- 0.25)	93	No(1)	Du,O, Li, Le, Li, Ph, He, Xi, Hp, Ba, Ne, Sa, Ch
<b>8. Arroyo Cañada de Cuervos (CDC)</b> 19°14'43.5'' 99°19'12'' First order	3446	0.8 (0.5-1.4)	0.232 (0.16- 0.31)	0.067 (0.05- 0.096)	0.014 (0.004- 0.03)	12.3 (11-13.7)	72.5 (69-76)	6.5 (6.0-7.1)	6.6	0.24 (0.17- 0.38)	0.00 (0.00- 0.00)	0.01 (0.01- 0.02)	0.07 (0.05-0.1)	91	Me, No, Oe, Rh, Sp, Ul, Va (40)	Hi, O, Li, He, Li, Po, Ba, Hp, Fe, Ch, Ti
<b>9. Mananial Magdalena Barbechos (MMB)</b> 19°15'44.7'' 99°15'44.7'' First order	3471	1.10 (1.0-1.2)	0.345 (0.28- 0.44)	0.041 (0.03- 0.05)	0.015 (0.01- 0.02)	9.4 (9-10)	58.9 (57-60)	6.7 (6.3-7.4)	7.5	0.17 (0.12- 0.23)	0.00 (0.00- 0.01)	0.01 (0.0-0.02)	0.04 (0.02- 0.06)	102	Cy, Di (10)	Du, O, Li, Hr, Hy, Le, Ba, Ti

Table 1 (continued)

Site and ubication (Latitude North/ Longitude Western)	Altitude (a m.s.l.)	Width [m]	CV [m/s]	Depth [m]	Q [m <sup>3</sup> /s]	T [°C]	K25 [μS/cm]	pH	DO [mg/L]	SRP [mg/L]	NO <sup>2-</sup> [mg/L]	NO <sup>3-</sup> [mg/L]	NH <sup>4+</sup> [mg/L]	HQ*	Algae (percent coverage) <sup>a</sup>	MIBs <sup>b</sup>
<i>I0.Mananital Cie- neguillas 2(CG2)</i> 19° 14' 32.6'' 99° 19' 48.2'' First order	3524 (0.3-0.7)	0.5 (0.012- 0.04)	0.24 (0.163- 0.37)	0.024 (0.012- 0.063)	0.003 (0.001- 0.0075)	10 (10)	72 (70-74)	6.4 (5.9-7.1)	6.5	0.46 (0.37- 0.58)	0.01 (0.00- 0.01)	0.01 (0.01- 0.02)	0.04 (0.04- 0.05)	102	No (40)	Du,Hi,Li,Ba,Pe,Ne, Ei,Ch,St,Is
<i>I1.Mananital Cie- neguillas 1(CG1)</i> 19° 14' 35.1'' 99° 19' 48.1'' First order	3528 (0.5-1.0)	0.7 (0.02- 0.063)	0.15 (0.11- 0.17)	0.036 (0.02- 0.063)	0.0033 (0.002- 0.005)	9.9 (9.9-10)	69.5 (68-71)	6.8 (6.2-7.7)	5.5	0.56 (0.33- 0.95)	0.01 (0.0-0.01)	0.02 (0.01- 0.02)	0.04 (0.02- 0.05)	100	No (10)	Du,Hi,He,Li,Ba,Pe, Di,St
<i>I2.Arroyo Presa Cie- neguillas (PDC)</i> 19° 14' 35'' 99° 19' 54.4'' Second order	3530 (0.1-1.2)	0.73 (0.01-0.4)	0.19 (0.1-0.4)	0.08 (0.01-0.2)	0.026 (0.001- 0.06)	10.9 (9.9-12.9)	68 (58-78)	6.5 (5.8-7.5)	6.7	0.08 (0.06- 0.12)	0.00 (0.00- 0.01)	0.01 (0.01- 0.02)	0.06 (0.03- 0.08)	97	Fc,Sp,Oe (93)	Li,OI,Po,Xi,Ba,Ch, Ep,Me
<i>I3.Mananital Cañada de Cuervos(CMC)</i> 19° 14' 13.5'' 99° 19' 3.8'' First order	3602 (0.4-0.9)	0.47 (0.01- 0.03)	0.12 (0.1-0.2)	0.013 (0.01- 0.03)	0.002 (0.001- 0.005)	11.7 (9.7-15.6)	65 (65)	5.7 (5.4-6.0)	5.3	0.14 (0.07- 0.18)	0.00 (0.00- 0.01)	0.01 (0.0-0.01)	0.03 (0.03- 0.04)	79	ND	Du,OI,Hy,Li,Ba,Ne, Em,Ch,Si,Ep,Ge,Dy, Is

(CV) Current velocity, (Q) Discharge, (T) Temperature, (K25) Specific conductivity, (DO) Dissolved Oxygen, (SRP) Soluble Reactive Phosphorous, (NO<sub>2</sub>-) Nitrite, (NO<sub>3</sub>-) Nitrate, (NH<sub>4</sub><sup>+</sup>) Ammonium, (HQ) Hydromorphological quality

ND Not detected

\*Hydromorphological quality values: optimal (120-100), good (99-83); medium (84-47), low (46-13) and poor (<12)

<sup>a</sup>Algal species: *Coleodesmium wrangelii* (Co), *Diatoma mesodon* (Di), *Fase Chantransia* (Fc), *Hildenbrandia rivularis* (Hi), *Nostoc* sp (No), *Oedogonium* sp (Oe), *Cyanoplaconoma regulare* (Cy), *Rhizoclonium* sp. (Rh), *Spirogyra* sp (Sp), *Ulothrix* sp (Ul), *Vaucheria bursata* (Va)

<sup>b</sup>Benthic macroinvertebrates families (MIBs): Asellidae (As), Baetidae (Ba), Canacidae (Ca), Chironomidae (Ch), Dixidae (Di), Dugesidae (Du), Dytiscidae (Dy), Dryopidae (Dr), Elmidae (El), Empididae (Em), Ephydriidae (Ep), Gerridae (Ge), Glossosomatidae (Gl), Helicopsychidae (He), Heptageniidae (Hp), Hirundinidae (Hi), Hydrobiosidae (Hy), Hydrinidae (Hr), Isotomidae (Is), Lepidostomatidae (Le), Leptoceridae (Lp), Limnephilidae (Li), Mesostigma (Me), Nemouridae (Ne), Oligochaeta (Ol), Perlodidae (Pe), Philopotamidae (Ph), Polycentropodidae (Po), Sialidae (Sa), Simuliidae (Si), Stenaelidae (St), Tipulidae (Tu), Veliidae (Ve) Xiphocentronidae (Xi)

### Benthic macroinvertebrate sampling

Specimen collection was carried out following a multi-habitat criterion and using a Surber-type D-net 30 cm wide with 250 µm mesh. Sediment was removed by kicking during a five-minutes period, and organisms were moved to a tray for extraction. Organisms were also caught by manual examination and extraction from submerged rock faces, pieces of dead wood, and leaves. The sampling was random, and no organism was excluded given the objective of analyzing the diversity and representativeness of the different taxa in the assemblage. For a representative sample, at least 100 individuals were collected from each site and preserved in 70% alcohol. Individuals were separated out under an Olympus SZX7 stereoscopic microscope (Olympus Corporation, Tokyo, Japan) and identified to family level following Bueno-Soria (2010) and Merritt et al. (2008). This level of taxonomic resolution was considered sufficient given a previous study in the same area that evaluated the indicator value of macroinvertebrates (Reyes-Celis 2023; Caro-Borrero et al. 2016). Subsequent data analyses were carried out after recording the taxonomic diversity and abundance of the organisms present in the samples.

### Macroscopic algae sampling

We collected all growths of macroscopic algae that were visible to the naked eye to characterize diversity in the springs. Abundance of macroscopic algae (percent coverage) was evaluated with a circular sampling unit of 10 cm radius (area 314 cm<sup>2</sup>) (Necchi Jr et al. 1995; Bojorge et al. 2010). Algae were identified to genus or species level by referencing relevant taxonomic keys and bibliographic resources (Komárek 2013; Anagnostidis and Komárek 2005; Wher and Sheath 2003). For taxonomic analyses, an Olympus BX51 microscope with an SC35 microphotography system was used. The analysis of the ecological quality based on the species found was carried out following the proposal by Carmona-Jiménez et al. (2022) for the basin of Mexico.

### Statistical analyses

To assess benthic macroinvertebrate abundance and taxa richness, we ran a SIMPER statistical test (similitude percentages) (Clarke and Gorley 2006) that determines the representative taxa of the different ecological quality states evaluated. Average abundances of the three collections were used. Data were transformed with the square root algorithm, and similarities were evaluated at 90%.

### Management strategies and social diagnosis of the Magdalena Atlitic community

In order to recognize the use, distribution, and management strategies of springwater, nineteen in-depth interviews were conducted with community members and key stakeholders. Sixteen of these were with men and three were with women. The inequality in gender distribution is reflective of the predominance of men as landowners in the community. The occupations of the interviewed men were diverse and include: two people who have served previously as community authorities, two people who at the time of the interviews were currently serving as a community authority, three people who owned trout fish farms and restaurants, one person from the water management committee, three people who participate in the forest surveillance committee, a participant in the water monitoring committee, two people dedicated to ecotourism, and one dedicated to raising sheep. As for the women interviewees, two belonged to the forest surveillance committee and one owned a restaurant on the stream bank. The initial contact with the community was carried out by presenting the research group to the local authorities and obtaining permission to carry out the study within their territory.

The interviews were guided by the following thematic axes that include both community and governmental water management: 1) time of residence and what the river and springs mean to them; 2) current uses of water bodies, management rules within the community, and existence of organized groups; 3) factors that can affect or benefit the quality and quantity of water; 4) regulations surrounding the use of water bodies by local and federal authorities and institutional participation in creating such regulation; 5) rules for the use, extraction, and distribution of water for different economic activities; 6) perception, compliance, and follow-ups of government management rules; 7) government programs or non-governmental institutions that support the conservation of water bodies; and 8) conflicts in the community over the management and distribution of water.

All interviews were recorded with prior consent of the interviewees and transcribed in Word format. Transcripts were analyzed with the specialized software Atlas.ti version 8.4.4 (Friese 2017). The analysis was carried out through four codes that determined the use and management of water, as well as the local and governmental organization to carry out water uses. This software allowed us to manually highlight quotations within the texts that correspond to the different categories or analysis codes that can be subsequently extracted from the interviews. In this sense, the software allows us to analyze the speeches in a qualitative and semi-quantitative way.

## Results

### Physical, chemical and hydromorphological quality

During the three collections, the thirteen assessed bodies of water registered a constant surface water flow. In terms of physical and chemical parameters, all sites were similar. Water temperature was warm (11 to 12 °C), with minimal mineralization (circumneutral pH; low specific conductivity, 60 to 110  $\mu\text{S}/\text{cm}$ ) and well-oxygenated (saturation greater than 90%). In general, the concentration of nutrients presented low values, reflecting the suitable use of the springs for human consumption and support of aquatic life in accordance with Mexican standards (DOF 2000, 2003b). Soluble reactive phosphorous (SRP) was less than 0.04 mg/L, dissolved DIN was less than 0.02 mg/L, and sulfates were less than 11.5 mg/L. However, some springs were found to be in conditions close to the maximum permissible limits for nitrites (Cieneguillas 1 (CG1) and Ermita San José (MES)), nitrates (Temascalco (TMC) and Cañada de Cuervos (CDC)), and ammonium (Temascalco (TMC) and La Bodega (LBG)). Despite this, none of the bodies of water exceed the MPL based on Mexican regulations.

Hydromorphological qualities of the springs spanned three of the five possible quality categories. Three springs registered optimal conditions (CG1, CG2 and LRA), with the Arroyo La Rosita Alto obtaining the highest rating (110 pts) in the grassland and pine forest zone. Most of the springs (six) were classified as being in good conditions, with scores varying very little between 90 and 97 (MES, MLR, SNJ, TMC, CDC, PDC). Finally, four springs registered medium scores (LBG spring with the lowest score of 72 pts) within the mixed forest zone. None of the water bodies were categorized as being of low or poor quality. The three sections evaluated based on the hydromorphological quality protocol all presented affectations at different scales. The greatest affectations were registered in the hydrology section (24 pts average) due to water diversions for local uses, the presence of small gabion dams (built with stones and sandbags), and in some cases the presence of organic waste in and around the body of water. On the other hand, the basin section was the best preserved (33 pts average), containing a riparian zone that included high-quality vegetation, low levels of erosion, and only slightly affected land usage (supplementary material).

### Aquatic bioindicators

#### Benthic macroinvertebrates

A total of 1279 individuals were collected and identified, including larvae, pupae, and adults. These were classified

into two subclasses (Oligochaeta and Hydracarina) and 12 orders with 35 families: Trichoptera (9 families), Diptera (7 families), Plecoptera (3 families), Hemiptera (3 families), Coleoptera (3 families), Ephemeroptera (2 families), Isopoda (2 families), and Collembola (1 family). The site that presented the least diversity of families was MMB (7), while LBG and MES registered the highest number of families (both 17). The families with the greatest number of registered individuals were: Dugesidae (246), Baetidae (220), and Heptageniidae (100). The families with the lowest abundance records were Perlidae (1), Dytiscidae (1), and Isotomidae (1). The two orders with the highest number of individuals and frequencies of appearance were Trichoptera (Limnephilidae, Helicopsychidae, and Lepidostomatidae families) and Ephemeroptera (Baetidae and Heptageniidae families) (Figs. 2 and 3).

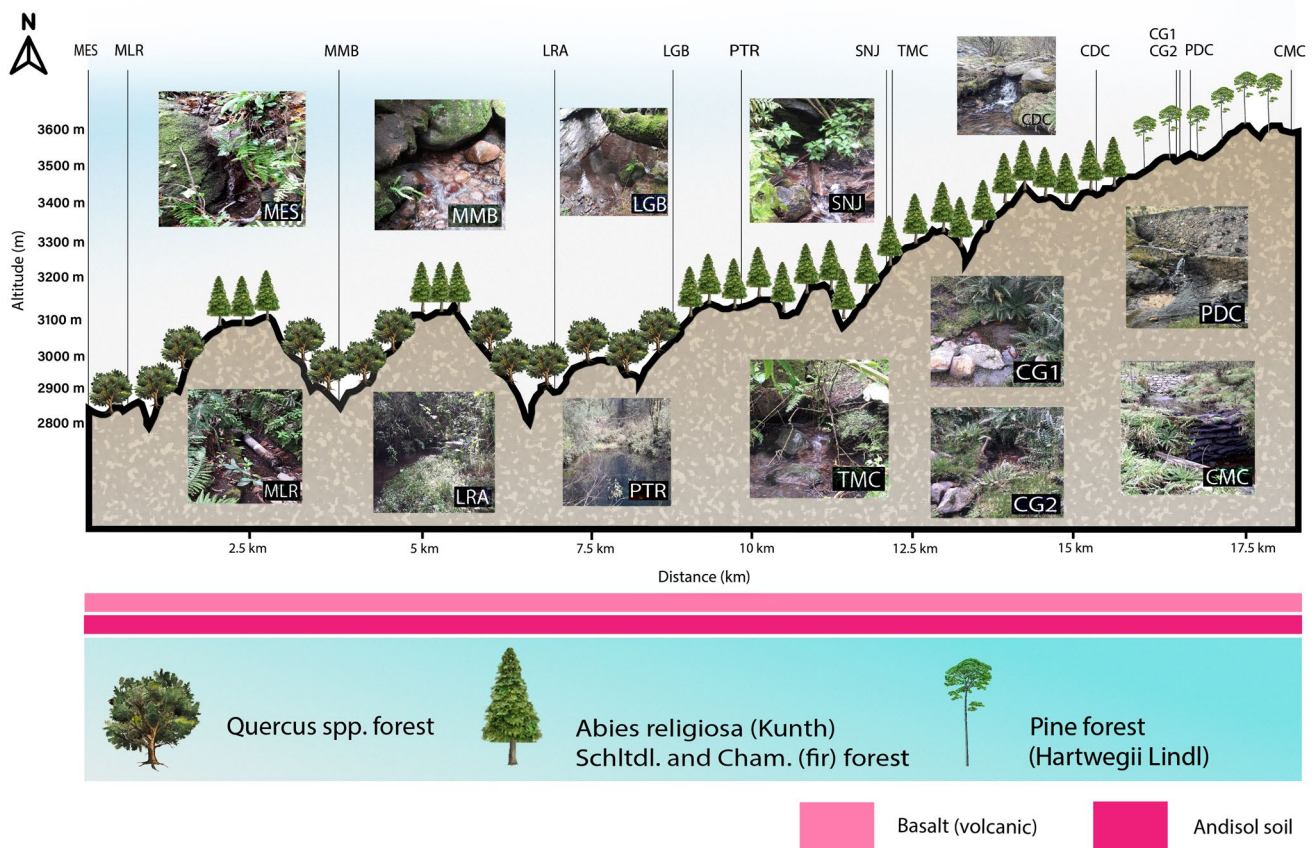
The SIMPER procedure (Fig. 4) found that three macroinvertebrate taxa were present across the three groups of identified ecological quality (optimal, good, and moderate); however, no clear indication signal was found for these taxa (i.e., no progressive decrease or increase in certain taxa was observed with the loss of water quality). The three taxa found in all water qualities were Limnephilidae, Hirudinae and Dugesidae. Helicopsychidae and Perlodidae were exclusively found in optimal conditions, while Empididae, Asellidae and Nemouridae were exclusive to moderate conditions. The Chironomidae family was representative of good and moderate conditions, but absent in optimal conditions.

#### Macroscopic algae

Twenty-two species of algae with visible growths were recognized, of which five belong to the Cyanoprokariota, six to the Chlorophyta, two to the Rhodophyta, and one to the Heterokontophyta. The most abundant and frequent species were *Nostoc* aff. *parmelioides* and *Cyanoplacoma* aff. *regulare*, with *Nostoc* being the most frequent. The Chlorophyta *Ulothrix* sp, *Oedogonium* sp and *Spirogyra* sp were diverse in the springs, and the presence of *Hildenbrandia rivularis* stood out in the SNJ spring (Fig. 3). Macroscopic algal growths were not recorded in three springs: Ermita San José, La Rosita, and Cañada de Cuervos. The greatest diversity of taxa was recorded in the LBG spring with 9 species, while a single species was recorded in the springs PTR, TMC, CG1, and CG2.

The site that registered the greatest combined diversity (total number of taxa) of macroinvertebrates and macroscopic algae was the LBG spring. On the other hand, sites with lower macroinvertebrate diversity did not necessarily show similar patterns with algae, highlighting the need to





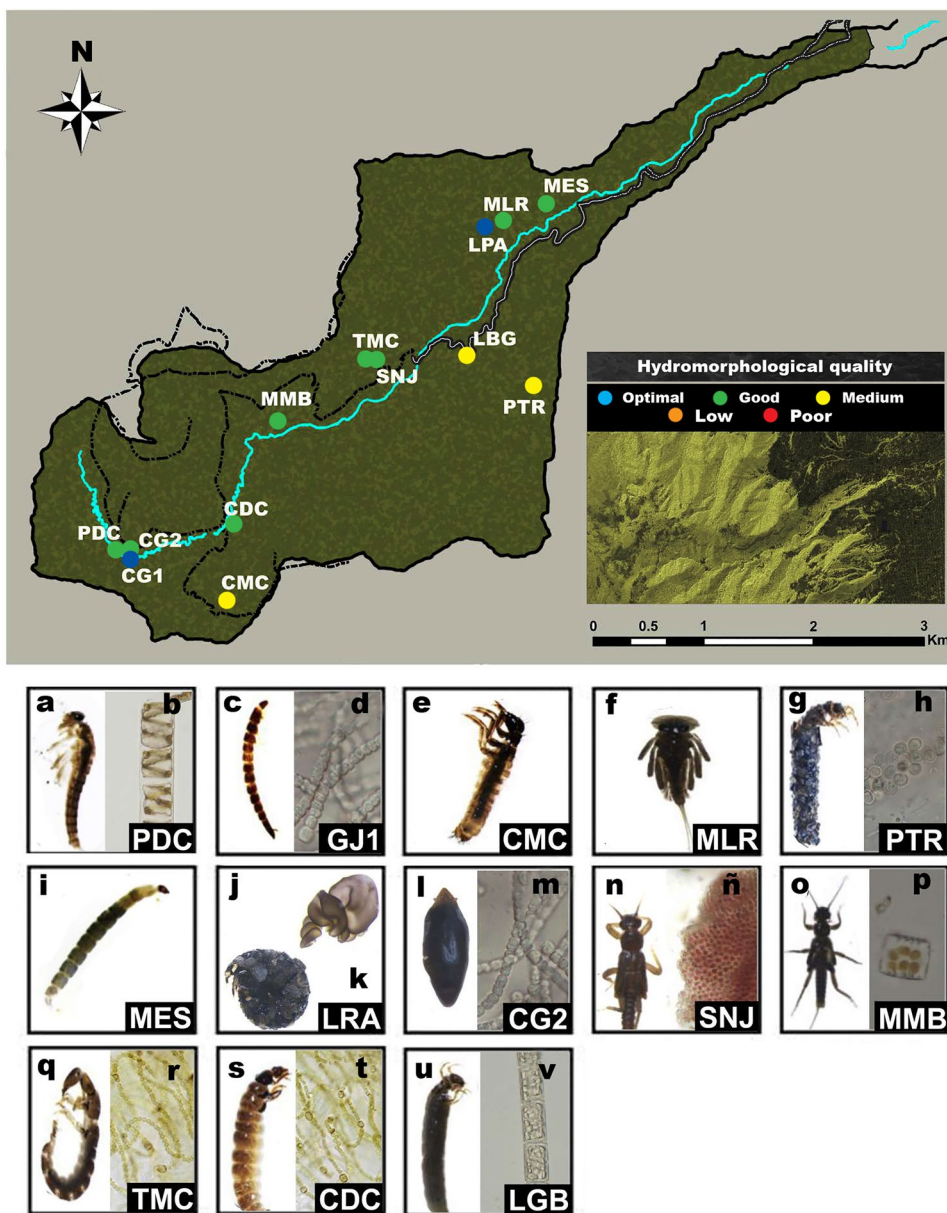
**Fig. 2** Altitudinal profile of springs and streams in Mexico City’s Conservation Soils. Distance is a reference parameter measured from the first sampled spring to the last, in descending altitudinal order

combine autotrophic and heterotrophic biological indicators to obtain integrated information on the different aspects of ecosystem functioning. No conclusive relationship was observed between the presence of organisms and hydromorphological quality, as springs with medium hydromorphological quality (the lowest observed quality) did not show diversity to be affected in a negative manner. In general, no major effects related to the change in land use were observed, but we did find effects related to infrastructure for water extraction. The organisms evaluated in this work do not respond in the same way to structural changes. The algae have characteristics that allow them to survive through periods of decreased water, as nutrients can even be taken from atmospheric fractions such as nitrogen. Macroinvertebrates respond to a greater extent to changes in the diversity of substrates in the channel bed and decreases in riparian vegetation. This led to reductions in diversity in sites like the MMB spring. All the springs were well oxygenated with low nutrient concentrations, which corresponds to the types of organisms found, which in turn are indicators of mostly clean waters.

**Social characterization**

All the people interviewed were born in the study area and actively participate within the community either as part of local authorities, vigilance committees, or local businesses related to tourism. The age range of the interviewees was between 29 and 79 years. For all those interviewed, the river forms part of their daily lives and represents a source of income associated with the sale of products and/or tourism. In addition, 65% of those interviewed mentioned that the river is part of their cultural heritage and patrimonial identity as collective owners of the natural area. Half (50%) of those interviewed acknowledged that they depend on the area’s water resources for their domestic and livelihood activities. Only 20% of those interviewed acknowledged having some contact with the local authorities in charge of water, corresponding in all cases to people who have held or currently hold a local authority position. Finally, every interviewee who recognized themselves as part of the vigilance committee acknowledged having continuous problems due to the presence of disorderly tourism and garbage in the

**Fig. 3** Biological communities most representative at each sampling site in the Magdalena River sub-basin. **a** Baetidae, **b** *Spirogyra*, **c** Elmidae, **d** *Nostoc* sp., **e** Limnephilidae, **f** Heptageniidae, **g** Limnephilidae, **h** *Nostoc* sp., **i** Chironomidae, **j** Helicopsychidae, **k** *Cyanoplasma* aff. *Regulare*, **l** Dugesiidae, **m** *Nostoc* sp., **n** Perlodidae, **ñ** *Hildenbrandia rivularis*, **o** Nemouridae, **p** *Diatoma mesodon*, **q** Philopotamidae, **r** *Nostoc* sp., **s** Glossosomatidae, **t** *Nostoc* sp., **u** Lepidostomatidae, **v** *Melosira varians*



area, as well as a lack of support from the government for managing problems related to water and city visitors.

**Characterization of spring uses and water management strategies**

**Water uses and distribution strategies**

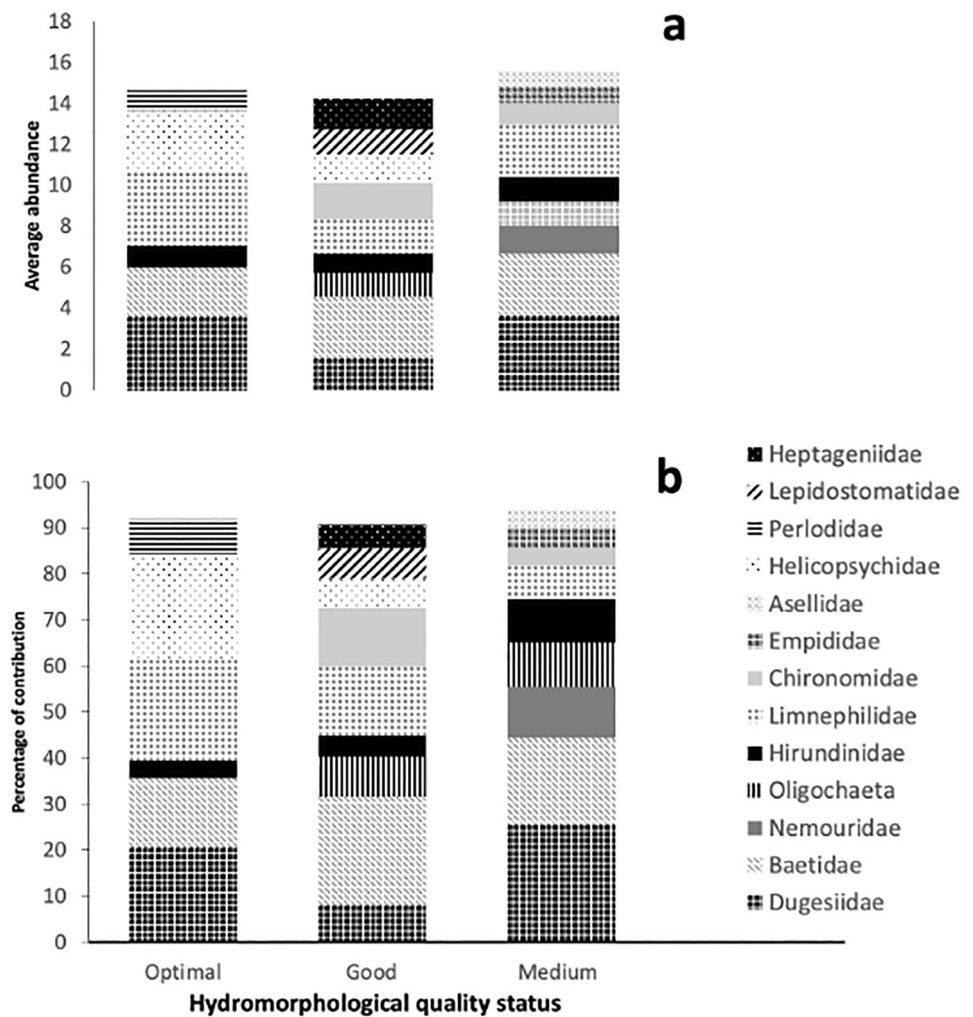
Every person interviewed agreed that the use of spring water is mainly local. The uses that were mentioned recurrently were: domestic use for irregular settlements within conservation land, supply for houses in the urban area carried out by the water system of Mexico City (SACMEX), breeding

of animals and trout farms, water supply for restaurants, and as tourist attractions.

Each of these uses has a water distribution system in response to specific supply problems that are solved individually or in small groups. For example, water distribution to the restaurant area (middle sub-basin area) works through a system of direct extraction from two springs. This system consists of local networks of hoses of different thicknesses that take advantage of the force of gravity given the slope of the landscape. Many of the restaurateurs are also owners of fish farms that use the springs to supply water to the ponds.

All the interviewees mentioned that no organizational system exists for the distribution of water, such as records

**Fig. 4** Simper analysis. Average abundance of benthic macroinvertebrates taxa per hydromorphological quality (a) and percentage of contribution of taxa per hydromorphological category (b)



of quantity, name of the user, or usage. Additionally, there is no agreement with the local water entity for concessions for lucrative and non-profit use.

*We don't have (organization) right now because we haven't thought about how to organize the water... Fortunately, no one sells it. Whoever wants it takes his carafe, his bottle of water, up to four, five 20-liter jugs."*

A tacit form of community consensus has focused on the right of antiquity. Two people interviewed who are associated with trout farming argued that their right to the springs corresponds to antiquity, a valid right that to date is maintained and respected within the community:

*"Yes, there are several ways (of assigning water intakes). Some are by seniority — some people who are many years old continue to drink water."*

Other trout farmers are even certified by the authority as local producers. This generates heterogeneity between both

government and local regulations to water access rights, neither of which are necessary within the area to make use of the springs. Finally, all the interviews showed that no regulations exist for the various uses of water. There are no written agreements, and most of the rules are guided by the uses and customs that govern the social system of the community.

#### Regulation and conflicts over distribution and access to water

Two types of conflicts were documented: 1) those that occur within the community, and 2) those that occur between the community and government authorities. The first of these is less conflictive, since the community recognizes that all members have rights to use the water, although on certain occasions it may not be equitable. However, these problems also include corrupt arrangements between communal authorities and people outside of the community for the distribution of water:

*“There are commissioners (communal authorities) that negotiate with other neighboring communities and pass them the water[...].”*

Problems related with the government authorities mainly concern water extraction by SACMEX for areas with greater socio-economic value within the city, ignoring the community, local agreements, and Mexican legislation on water:

*[...] The problem is the governments [...]. They sold the water, they sold the water, to the hospital [...]. They piped it and sold it to the Hospital [...].*

According to interviews, there are no regulations to access the water from the springs or the river. The community solves water demands trusting in the personal judgment of the local users, but they recognize that the growth of the local population is pushing another system of organization. In addition, they recognize the lack of communication with the local authority as a problem since they recognize that the amount of water has decreased over the years:

*“I firmly believe that there is no contradiction regarding the sustainable use of water. There is no conflict. It is not opposed to productivity. What is needed are the experts, but the real experts, not the experts who no longer emit trials and this and that. No, experts are needed.”*

**Factors Affecting Water Quantity and Quality.** Most of the interviewees (85%) agreed that excessive extraction of water has caused a decrease in the amount of available water, including significant losses during the dry season in some springs:

*Before, there was a lot of water. But they exploit it, that is, everything is super exploited. Even for example from here on this side, a lot of water came down, but right now there are a lot of diversions [...].*

Problems regarding the amount of water are seen as something that diminishes the well-being of residents. Interviewees (72%) think that the amount of water coming from springs and the river would be enough to supply all the neighborhoods within the Municipality of Magdalena Contreras; however, they agree that the sale of water to remote and luxurious neighborhoods is a detrimental practice that limits the availability of local water:

*[...] It's embarrassing to have so much water and also suffer from water at the same time, right? Magdalena Contreras has water to supply all its neighborhoods, without any problem. But the problem that I have seen here for many years is that our water is sold.*

The interviewees who participate in the forest surveillance and water monitoring committees (32%) related the

lack of water to illegal logging and the piping of rivers and springs to the construction of highways that cross through preserved ecosystems:

*The problem is deforestation [...]. There are people who, when they go to cut down wood, lower about 12 loads (one load being equal to one full dump truck)[...]*

*[...] There are so many damn highways, the government is interested in having highways. What for? If they cut the springs to have roads [...]*

Regarding the quality of water, all interviewees (100%) agreed that water from the springs is of good quality and can be used for human consumption:

*[...] Well, that water is clean, that is, it is very good to drink [...]*

*[...] I drink water from the spring, I go for it directly at the spring [...]*

However, a small group of interviewees (25%) related with cattle farming mentioned that there are problems related to cattle rearing, since feces are a constant source of contamination. The presence of restaurants, bathrooms, and tourism in general was seen as an element that negatively affects water quality (65%). Faced with these pollution problems, the community does not have the capacity or the legal support to prevent the waste discharges:

*“It's clean, it's clean, but when they (restauranters) wash the dishes, all the detergents, everything goes into the river [...].”*

*“Tourism is very dirty. There is a lot of garbage in the river — beer cans that are already very rusty, chips, the food that people leave there. In fact, I don't know why the community or the mayor's office doesn't do something to help.”*

The interviewees belonging to the forest surveillance group suggested the use of informative signs communicating the message of keeping the forest and water bodies clean as a helpful way of avoiding contamination. They also pointed out that the fact that local garbage collection services do not have a route in the wooded area prevents them from placing garbage containers.

### **Inequity of water access and distribution**

The main characteristic that regulates access to water is the proximity to bodies of water. In addition, proximity determines the extraction mechanism and the level of difficulty to bring the water to the houses, restaurants, or trout farms. As such, inhabitants of remote homes must make internal

arrangements within the community to extend hose networks from the water bodies to their homes:

*[...] I have a piece of water, and I have an inch and we are ten people. Well, I have to irrigate this piece of land to have a harvest, and I cannot give it to you, because, well ... if it cost me and I organized myself well, I have my water, but that's how I've suffered, right? [...]*

In this sense, access to water from the springs and river is free, but not equitable. Different internal agreements, informal, manage the access to the springs and therefore to the water. These practices lead to small monopolies over the resource and favor the existence of elite capture systems that marginalize equitable access to water. A final factor mentioned was money invested by small groups of people to arrange the infrastructure for transporting and storing water:

*“We received the water from here, from Los Dinamos. We piped it. We did that work ourselves when the community was formed.”*

## Discussion

According to the evaluated characteristics, springs and streams within the protected area of the Magdalena River sub-basin in Mexico City are classified as first or second order springs. The springs are small, with low and permanent water discharge. These characteristics make them vulnerable to extraction activities, which in some cases are intense. The proximity of the springs to anthropogenic activities were found to be a driver for changes that deteriorates ecological quality. This was reflected in the mixed results, where only three of the studied sites had optimal quality conditions, six were classified as good, and four as medium quality conditions. None of the water bodies were classified as having low or poor hydromorphological quality. One of the biggest factors affecting the structure and ecological functioning is the lack of institutional organization, both local and municipal, over the access and extraction of water. At the local level, this concerns the presence of the community with the water committee, which in the interviews was shown to exist. At the municipal level, the Mexico City Water System (SACMEX) is in charge of managing the concessions and uses of water in CDMX. In regard to the nutrient concentrations, the water was suitable for human use and consumption (DOF 2000). However, five springs presented concentrations close to the maximum allowable limits. Following the criteria used by the United State Environmental Protection Agency-USEPA (Barbour 1999) and Directive Water Framework (DWF 2003) for determining water quality, the assessed springs would be classified as

being in a state of contamination, although not severe. This highlights the need to update official Mexican standards to incorporate environmental indicators and physicochemical values that regulate ecological quality. The increased levels of nutrients is a clear sign of human activities related to agriculture, grazing, water retention dams, extraction pipes, and organic and inorganic waste. Of the four sites most affected (Magdalena Barbechos (MMB), Ermita San José Spring (MES), La Rosita Spring (MLR) and Potrero (PTR)) the MES spring is most at risk since, in addition to hydromorphological effects, nutrient concentrations were recorded as being close to the maximum permissible levels. It is important to mention that the PTR spring exports its water to a neighboring community (Jujnovsky 2003), leading to an additional risk factor.

Overall, biological indicators were good proxies of ecological quality. In the case of benthic macroinvertebrates, most of the families presented a low number in terms of absolute abundance. The presence of families in the orders Trichoptera (Limnephilidae and Helicopsychidae) are indicators of good oxygenation, low turbidity, and oligotrophic waters in general, revealing ideal conditions for the development of native fauna (Springer, et al. 2010). The second representative order was Ephemeroptera (Baetidae and Heptageniidae), which also develop in cold and well-oxygenated waters (Gullan and Cranston 2010). Likewise, larvae recorded in this study of the order Plecoptera (families Nemouridae and Perlodidae) are sensitive to habitat degradation and organic pollution (Merritt et al. 2008; Gullan and Cranston 2010). These orders and families have already been recognized as good indicators of ecological quality both in the sub-basin (Reyes-Celis 2023; Caro-Borrero et al. 2016) and at the regional level within the Basin of Mexico (Carmona-Jiménez and Caro-Borrero 2017). Most of these findings were corroborated by the SIMPER procedure; however, the Limnephilidae family was an indicator of both ‘good’ and ‘moderate’ qualities, and as such require a higher taxonomic resolution for their utility as bioindicators. In the same way, the classes Hirudinea and Dugesidae require a more specific taxonomic approach since they were present in sites of differing quality states.

The orders Ephemeroptera, Plecoptera, and Trichoptera (EPT) are characteristic of oligotrophic waters and environments with good ecological quality (Merritt et al. 2008). Biological metrics such as abundance and richness can help determine the state of conservation of the springs, as their reduction/disappearance is often attributed to an alteration in habitat and/or physical and chemical characteristics (Tierno de Figueroa and López 2015; Caro-Borrero et al. 2016). However, according to the SIMPER procedure, families such as Baetidae and Polycentropodidae are tolerant of conditions ranging from medium to optimal quality. These families have been previously recognized as being capable

of living in moderately disturbed environments (Reyes-Celis 2023; Caro-Borrero et al. 2016). Within the Heptageniidae family, most of the genera (*Epeorus*, *Stenacron*, *Rhithrogena*) decrease in abundance and even disappear as the deterioration of ecological quality increases (Reyes-Celis 2023). According to Carmona-Jiménez and Caro-Borrero (2017) and Caro-Borrero et al. (2016), 37 families of benthic macroinvertebrates are reported in the Magdalena River, of which 65% were found in this study. The remaining 35% are families exclusive to the springs, such as: Isotomidae, Asellidae, and Stenasellidae, all common inhabitants of the hyporheic zone. More than half of the species described for these families are obligate groundwater inhabitants (Thorp and Covich 2010; Pérez and Edmond 2001), so their presence in spring beds could indicate some type of disturbance at the level of benthos. For example, the family Asellidae was representative of conditions of moderate ecological quality, possibly due to disturbances in the bedrock of the springs.

Thirteen species of macroalgae were reported in the springs. This represents approximately one third (38%) of the diversity described in the main channel of the Magdalena River (Rodríguez-Flores and Carmona-Jiménez 2018), indicating the presence of particular species of this environment. The dominance of cyanobacteria in the springs is related to their ability to inhabit nitrogen-free sites, a condition that has been similarly observed in little-disturbed mountain streams within the Mexico basin (Carmona-Jiménez et al. 2016). The presence of the red alga *Hildenbrandia rivularis* stands out due to its exclusive distribution within rivers in the temperate regions of North America and Europe (Carmona et al. 2002; Wher and Sheath 2003), suggesting a biogeographical affinity and the determination of temperate springs from tropical regions. This represents an important record for Mexico, since the rivers and springs of this area serve as potential habitat for this alga, but the species had not been previously registered here. Other species of algae have similarly been reported from well-preserved tributaries and rivers of the basin of Mexico and southern United States (Rodríguez-Flores and Carmona-Jiménez 2018). On the other hand, abundant and cosmopolitan species of diatoms such as *Melosira varians* were recorded in the spring with the highest concentration of nutrients (LB). These species have been found in oligo-mesotrophic rivers from other regions of the world (Seghetto et al. 2016; Spaulding 2020). Munn et al. (2002) documented a shift from forested streams dominated by cyanobacteria to diatom-dominated urban streams. Changes in diatom composition from oligotrophic to eutrophic species have been commonly reported (Chessman et al. 1999; Winter and Duthie 2000; Newall and Walsh 2005).

According to the interviews, the springs' state of conservation is socially perceived as being good and reliable. However, it was also apparent that negative human alteration

is beginning to affect the ecosystem, mainly in relation to a need for water for human use and consumption (e.g., dams, diversion, and hoses for water extraction). In general, the conditions described by the physicochemical, hydromorphological, and biological indicators coincided with the descriptions from the people interviewed, specifically of processes of gradual deterioration of peri-urban basins such as the Magdalena River sub-basin within Mexico City (Walsh et al. 2005; Varis et al. 2006). These conditions have not been reversed due to the limited legal actions taken towards the conservation and management of water bodies within the basin of Mexico. The perception of local inhabitants regarding aquatic resources, together with the cultural adaptation of water management to local conditions, should be the starting point for establishing a legitimate system of water governance. For this, it is important to establish a cultural and social learning process that facilitates the management of aquatic resources without detriment to local uses and customs (Pahl-Wostl et al. 2008; Pearson et al. 2010).

A set of factors contribute to the fact that the springs, and more generally the bodies of water surrounding Mexico City, are in danger of disappearing. First, the community interviews reflected a sense of institutional invisibility, represented by the absence of a water management organization. The national water law in Mexico establishes that government institutions must oversee the evaluation of water usages and establish concessions based on the type of water body, its quality, and the usage to which it is going to be assigned (DOF 2003b). Between the local and federal administrations, a shared responsibility for water governance translates into a kind of administrative and operational abandonment (Caro-Borrero et al. 2021). Second, the lack of knowledge of local collective action is a serious problem within the community that manages the natural resources of the sub-basin. Collective action was a documented process for the benefit of small sectors or groups, but not for the common good. This lack of organization/action translates into a detriment to both the ecological conditions of the ecosystems and the well-being of the inhabitants who depend on the quantity and quality of water for their livelihoods (Muradian and Cárdenas 2015; Varis et al. 2006). In the case of the Magdalena River sub-basin, the establishment of a single collective action system that functions well would be complex and complicated due to the different existing social groups within the community that at times may have opposing interests. The community interviews conveyed an apparent interest in conserving and regulating the use of water. However, it was also evident that some groups are only interested in economic activities that are profitable in the short term, while ignoring their dependence on local water. Some people even think that conserving water from the forested area only favors select elite social groups within the city, as has been documented in other case studies (Hommes et al. 2020). Under these circumstances

of complex social organization, the consolidation of water management through a single regulation that prioritizes the welfare of the socio-ecosystem is recommended. However, implementing this regulation is dependent upon the formation of groups organized around shared interests, while also generating awareness around the different activities' social dependence on water resources. This strategy could achieve a change in social attitudes, favoring collective learning through cooperation and the solution of common problems, while building small governance systems that contribute to water management at the basin scale (Pahl-Wostl et al. 2008).

With this panorama, it is necessary to adopt a management strategy that considers local development above the urban development of the megacity. The case of Mexico City is complex, not only in ecological terms given the limited number of surface water bodies that are rapidly decreasing due to urban expansion (Caro-Borrero et al. 2021; Varis et al. 2006), but also in social terms since the effective and equitable governance of natural resources seems to be an unattainable goal in conditions of poverty and socio-economic inequality (Hommes et al. 2020; Pahl-Wostl et al. 2008; Varis et al. 2006).

We propose that a regulation system be established for the use and distribution of water that considers the ecological monitoring of spring quality, the fragility of the ecosystem, local operations, and the cultural uses of water in the area, while also including the knowledge and capacity for social learning as a tool to establish local governance systems (Lebel et al. 2010; Pahl-Wostl et al. 2008). An intervention plan should include the following actions in a participatory manner between the community and both local and federal authorities: (i) Censuses and assessments of current spring locations in the sub-basin. Many local people refuse to reveal spring locations for fear of overexploitation and even alienation by the government. (ii) Ecological evaluations of actively used springs. Since they are viewed only as water reservoirs and for ecosystem services, their provisions beyond water are ignored. Additionally, ecological flow studies must be included to assess the maximum permissible extraction amount. (iii) Censuses of the local economic and domestic activities that depend on the springs. (iv) Finally, local water distribution agreements. This practice has been exercised in the sub-basin since the 19th century when water users established local agreements for the equitable distribution of water.

The results of this research demonstrate a known problem across many peri-urban areas of the world, in which domestic and urban water usages compete with local and rural usages in the midst of city development. Therefore, small conservation areas such as the Magdalena River sub-basin seem to be trapped in a development inertia in both ecological and cultural terms that is not comparable with the local

dynamics. This set of conditions warrants social learning processes that allow for conservation planning and resource use that are equitable and do not favor one social group over another, generating consensus and certainty throughout the socio-ecosystem and therefore establishing resiliency in socio-ecological terms (Folke et al. 2003; Lebel et al. 2010).

## Conclusion

The ecological quality evaluation of the selected springs shows mixed results, with conditions ranging from optimal to medium. In general, the springs evaluated in this study conserve physical, chemical, hydromorphological and biological features that classify them as bodies of water in optimal (three of thirteen) and good (six of thirteen) ecological conditions. However, some streams were found to show signs of change due to human activities related to local water extraction, the establishment of tourism and livestock activities, and above all, a lack of governance that facilitates the assignment of attributions regarding rights and co-responsibilities. In ecological terms, macroinvertebrate and algal species typical of clean waters characteristic to springs were found, making these sites hotspots of local diversity that translate into a particular structure and function. These ecological characteristics are at latent risk considering the expansion of human activities that cause a decrease in flow, the removal of sediment in the riverbed, and the incorporation of organic matter that modifies the original conditions of the springs. From the socio-ecosystem perspective, a lack of governance was apparent. In lieu of this, local agreements were found that involve landowners, business owners, and local governments for a distribution of water characterized as unequal by the interviewees. The establishment of a citizen and government participation system for water management in peri-urban basins is recommended. This system must jointly consider local development, socio-cultural complexity, richness, ecosystem fragility, and the socio-ecological context in which these water distribution mechanisms are established. Finally, an action plan is proposed that includes the following elements: censuses of water bodies within the Conservation Soil; ecological evaluations of actively used springs (as well as unused springs as a reference element); censuses of local economic and domestic activities that depend on the springs; and water distribution agreements at the local level that take into account the previous points.

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## Declarations

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