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The use of macroinvertebrates and algae as indicators of riparian ecosystem services in the Mexican Basin: a morpho-functional approach

Angela Caro-Borrero[1] · **Javier Carmona-Jiménez**[1]

Abstract

Peri-urban rivers have been subjected to poor environmental management, especially in developing countries, due to urban expansion and channel transformation in the context of a lack of public conservation policies. As an example, Mexico City, the second largest city in the world, has a socioenvironmental mosaic that allows the evaluation of ecosystem services (ES) associated with aquatic ecosystems amid urbanistic pressures. The main objective of this research was to identify sites with the greatest ES potential supplied by conserved areas that are in a rural-urban transition using the ecological traits of riparian bioindicators, including eco-physiological metrics of communities and assemblages and hydromorphological quality. The aquatic ES most influenced by the peri-urban context was nutrient cycling through the incorporation of organic matter from the riparian ecosystem into the river. Water quantity was also influenced, due to local extraction and structures such as gabion dams. The support and provision ES were sensitive to changes in the geomorphology configuration. In conclusion our results showed that the biological morpho-functional indicators of blue ES were an objective tool to assess the state of river functioning and translate these functions into the language of decision makers. Finally, we determined that the ES provision into the Mexico Basin mainly responds to three major factors: physical characteristics, hydromorphological functioning and the functional ecology of organisms.

Keywords Aquatic functions · Peri-urban rivers · Biological ecosystem indicators

Introduction

Rivers are ecosystems that most people know something about, but in an ecological and functional sense, few truly understand them. This statement could be supported by a reductionist view of their usefulness and recognition of rivers as a source of water to maintain human wellbeing (Yao et al. 2016). Additionally, basins and rivers have been subjected to poor environmental management due to a set of factors, such as ineffective public policies regarding conservation, economic pressures on forested areas, expansion of the agricultural frontier and the establishment of irregular human settlements into basin areas, especially in developing countries (Vollmer et al. 2016; López-Morales and Mesa-Jurado 2017). In this sense, the maintenance of ecosystem services (ES) in cities depend mainly on the sustainability of public policies and the implementation of strategies to raise awareness among citizens and users of the benefits provided by the rivers in urban landscapes to avoid their unsatisfactory management and use (e.g., irreversible impacts associated with land use changes, BenDor et al. 2017; Vollmer et al. 2016).

A strategy to generate awareness about ecosystem functions on human wellbeing was to explain these functions with simple and practical language, how humanity obtains and benefits from ecosystems in natural conditions with little or no human alterations, or at least close to it (MEA, 2005). The ecosystem services approach could explain the relationship between anthropogenic activities and their effects on environmental degradation (Brauman et al. 2007; Vidal-Abarca et al. 2014; BenDor et al. 2017). However, in many cases, this conceptual framework has served to make explicit the most obvious benefits, such as quantity and quality of the water supply, but not those "hidden" or less obvious processes that are translated into important functions that keep ecosystem well-being in good health or in equilibrium (Affek and Kowalska 2017).

✉ Javier Carmona-Jiménez
jcj@ciencias.unam.mx

[1] Facultad de Ciencias, Departamento de Ecología y Recursos Naturales, Laboratorio Ecosistemas de Ribera, Universidad Nacional Autónoma de México, Circuito exterior s/n, Ciudad Universitaria, Coyoacán, Ciudad de México 04510, Mexico

These processes are maintained by two fundamental characteristics: the first refers to the amount of water flowing through a natural stream course, which is needed to sustain ecological functions, and the second characteristic refers to local diversity and the biotic and abiotic framework arrangements that shape the landscape and therefore its structure and function (Gopal 2016). Therefore, the flow regime, the organisms present and their diversity are the key components to sustaining the ES provision (Maron et al. 2017; Sirakaya et al. 2018). Considering this ecological base, in this manuscript, we apply the conceptual definition proposed by Jeffers et al. (2015), who define ES as "*Benefits that humans received from the natural functioning of healthy ecosystems*". Ecosystems need good or acceptable ecological integrity to be able to carry out their functions, and those qualities are colloquially understood as ES. According to the Water Framework Directive of the European Union (2000), ecological integrity is an expression of the structure and functioning of ecosystems, evaluated through biological indicators, which are capable of reflecting the physical, chemical and hydromorphological conditions in the ecosystem in which they are located (Sánchez-Montayo et al. 2009). In turn, these environmental and microhabitat conditions are related to the natural characteristics of the hydrological basin and with the level of human activities in it (Mendoza-Cariño et al. 2014).

In natural conditions, the rivers and their drainage basins are composed of a complex and dynamic mosaic of zones with different hydrological, geomorphological and ecological characteristics (Frissell et al. 1986). Changes in time and space of the river configuration are driven by perturbations in water flow and transport of sediments acting along climatic, hydrological and biogeochemical gradients (Ward et al. 2002). In this context, human activities have direct and indirect negative impacts on rivers. The direct impacts are generated by overexploitation, diversion, damming, exhaustion and pollution caused by water discharge from houses and industries, which modifies the volume and quality of water (Nilsson et al. 2005; Vidal-Abarca et al. 2014; López-Morales and Mesa-Jurado 2017). The indirect impacts are characterized by poor management of the basins and involvement processes, such as deforestation and fragmentation of ecosystems due to land use changes and urban growth, among others (Rosenberg et al. 2000; Vollmer et al. 2016; Brill et al. 2017).

Despite these changes and alterations, hybrid rural-urban systems can be important sources of ES for maintaining city requirements in ecological terms (Sirakaya et al. 2018). For example, Mexico City, the second largest city in the world due to its inhabitant density and spatial extension, has a wide socioenvironmental mosaic within the city that includes forestry conservation areas with some rivers that still surface runoff and are a source of ES for the city and its inhabitants (Carmona-Jiménez and Caro-Borrero 2017). If these areas are in an acceptable to good status of ecological integrity, they allow the evaluation of aquatic ES associated with rivers despite the complicated scenario present due to historical urbanistic pressures (López-Morales and Mesa-Jurado 2017; Oswald 2011).

However, developing countries face several challenges in assessing ES at the basin level, among them, the lack of data sets consistent in time and space and the absence of adequate indicators and environmental metrics that allow linking the ES state with the hydromorphological and ecological parameters of rivers in an urban context (Brill et al. 2017). Therefore, it is important to generate studies that highlight the ecological and functional aspects of biological communities as well as the methodological strategies that can be used to construct aquatic ES indicators. In this sense the central questions that guides this research are:¿how can the provision of ecosystem services be affected in rural-urban transition environments? and ¿what biological and ecological components of the ecosystem could be good indicators of the different ecosystem services provision in basins? Takin account these questions and as an empirical contribution to the information and methodologies gap, the main objective of this research was to identify sites with the greatest ES potential supply in conserved areas in a rural-urban transition using biological and ecological measures as aquatic bioindicators, including eco-physiological metrics of communities and assemblages as well as riparian ecosystem integrity.

Materials and methods

Study area The Mexico Basin (Table 1, Fig. 1) lies in the morphotectonic region of the Trans-Mexican Volcanic Belt at 19° 00′-19°40’ N and 98°30′-99°30’ W and has a total surface area of 9,600 km^2, of which 5,518 km^2 comprise mountain ranges that rise above 2,400 m a.s.l. (Ferrusquía-Villafranca 1998; Legorreta 2009). The basin has experienced rapid population growth since the 1950s, having an approximate population of 22 million inhabitants, and is currently estimated to be the second largest metropolitan area in the world (after Tokyo) (Oswald 2011). The climate of the region is sub-moist and temperate (annual median temperature is 13.4 °C, annual median precipitation is between 1,200 and 1,500 mm), with abundant rains from June to October and a dry season from November to May (García 2004). Its geological traits consist of rock pockets alternating with andesitic to basaltic lavas (Ferrusquía-Villafranca 1998), above which forests of *Abies religiosa*, *Pinus hartwegii* and *Quercus* spp. grow in the upper area of the watershed, with mixed forest in the middle and lower areas (Ávila-Akerberg 2010).

Thirty sites were selected that represented 10 subbasins with perennial rivers located at altitudes ranging from 2345 to 3596 m and having an average flow from 0.02 to 1.03 m^3/s. In previous studies, these rivers were considered as potential

Table 1 The subbasin where sampled peri-urban streams are located and their land use soil and hydromorphological quality status (from 0 to 120 points) from the Mexico Basin. Status of governmental protection and the name of the protected area: State reserve "Sistema Telotzotzingo" (RE), Ecological park Zempoala "Otomí Mexica" (PETR), Water and forest sanctuary "Manantiales Cascada Diamantes" (SAF), National Park "Desierto de los Leones" (PNDL), National Park "Izta-Popo" (PNIP), Conservation soil (SC), not recognized (NR)

Sub-basin name	Sampling locality, river order and altitude (m asl)	Use of soil and vegetation	Protected area status	HQ
Ameca-Canal Nacional AMEC	1. La Castañeda I (4) 2647	Mixed forest	NR	104
	2. La Castañeda II (4) 2625	¨	NR	104
	3. La Castañeda III (4) 2625	¨	NR	104
	4. La Castañeda IV (4) 2900	*Pinus* forest	NR	120
	5. Las Castañeda (4) 2608	Mixed forest	NR	96
Coatlaco CTCO	6. Rancho nuevo I (1) 2895	¨	NR	100
	7. Rancho nuevo II (2) 2799	Primary activity	NR	82
Coaxcacoaco CXCO	8. Molino de Flores (4) 2345	¨	RE	74
	9. Santa Catarina (3) 2855	Mixed forest	RE	98
Cuautitlán CUATI	10. Los Organillos (1) 3378	Primary activity	PETR	108
	11. Manantial Capoxi (1) 3177	Mixed forest	PETR	114
	12. Manantial San Pedro (1) 3305	Primary activity	PETR	118
	13. Nacimiento Presa Iturbide (1) 3334	¨	PETR	108
	14. Río Capoxi (1) 3183	Mixed forest	PETR	114
La Colmena CLM	15. La Caldera (4) 3124	*Quercus* forest	PETR	116
	16. Xopachi (2) 2867	Mixed forest	PETR	115
Las Regaderas RGS	17. Monte Alegre alto (3) 3596	*Pinus* forest	SC	77
	18. Monte Alegre bajo (3) 3378	Grassland	SC	77
Magdalena- Eslava M-E	19. Chautitle alto (1) 3357	¨	SC	116
	20. Chautitle cañada (2) 3350	*Pinus* forest	NR	120
	21. Confluencia Eslava-Magdalena (4) 2465	Urban zone	SC	54
	22. Nacimiento Eslava (1) 3261	*Pinus* forest	SC	110
	23. Santa Teresa (5) 2492	Urban zone	SC	52
	24. Truchero alto Magdalena (4) 3278	*Pinus* forest	SC	88
San Ildefonso SIFS	25. Las Palomas (1) 3417	Mixed forest	PETR	120
	26. Truchero Don Álvaro (4) 3236	¨	PETR	107
San Rafael-Tlalmanalco SRFL	27. Agua dulce (4) 2802	¨	SAF	100
	28. Canal San Rafael (4) 2865	¨	SAF	94
	29. Cascada Compañía bajo (4) 2676	*Quercus* forest	SAF	66
	30. Cascada Compañía (4)	Mixed forest	SAF	112

Table 1 (continued)

Sub-basin name	Sampling locality, river order and altitude (m asl)	Use of soil and vegetation	Protected area status	HQ
	2847			
	31. Cosamala alto (4) 2803	¨	SAF	92
	32. Cosamala bajo (4) 2757	¨	SAF	104
	33. Estación UAM (5) 2429	Primary activity	NR	72
	34. Inicio Canal San Rafael (4) 2895	Mixed forest	SAF	118
	35. San Rafael (1) 3144	*Pinus* forest	SAF	85
	36. San Rafael Canal (4) 2780	*Quercus* forest	SAF	96
	38. Apatlaco (3) 3582	Mixed forest	PNIP	111
Santo Desierto STDT	39. Arroyo Desierto de los leones (2) 3014	¨	PNDL	120
	40. Convento desierto de los leones (2) 2925	¨	PNDL	65
	41. La Capilla Santa Rosa (1) 2840	Primary activity	PNDL	104
	42. Santa Rosa Alto (2) 3050	Mixed forest	PNDL	110
	43. Santa Rosa Manantial (1) 3410	¨	PNDL	114
	44. Santa Rosa Medio a (2) 3014	¨	PNDL	114
	45. Truchero Valle de Monjas (3) 2700	¨	PNDL	79
	46. Valle de Monjas, Escuela (2) 2777	¨	PNDL	89
Río Frío RFO	47. El Llano alto (4) 2840	¨	PETR	102
	48. El Llano bajo (4) 2845	¨	PETR	104
San Rafael SR	49. La Cabañita (5) 2413	¨	NR	114
	50. La Planta (5) 2358	¨	NR	100

reference sites (Carmona-Jiménez and Caro-Borrero 2017), with minimal human intervention in forested areas and with some legal conservation status, such as having protected areas and/or conservation soil at the headwaters. However, according to a cartographic analysis conducted by government of Mexico City using GIS tool in the conservation soil (scale: 1: 10 000), showed that 70% of land use is dedicated to primary activities such as no intensive agriculture, and 20% is dedicated to human settlements that are mostly classified as irregular (PAOT, 2011). In this sense, the rivers are exposed to different degrees of human intervention, where the headwaters (above 2800 m) suffer minimal intervention and the downstream areas immersed within the city are severely altered (Cai et al. 2017). This local context is given within a general panorama, where 90 million people in Mexico (75% of the total population) face problems due to scarce water at least 1 month per year, and the amount of water, high rates of deforestation and loss of diversity are the most important environmental challenges at the country level (López-Morales and Mesa-Jurado 2017).

Environmental characterization: Physicochemical parameters, ecological quality assessment and water discharge Sampling was carried out between March 2012 and June 2015 during the rainy season (June–November), dry cold season (December–February) and warm dry season (March–May). The following physicochemical parameters were recorded in situ with a Hanna Multiparameter probe 991300 (Dallas, USA): water temperature, specific conductivity and pH. The recorded oxygen saturation (YSI-85 m, 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 water samples were filtered in situ and analyzed in the laboratory according to the

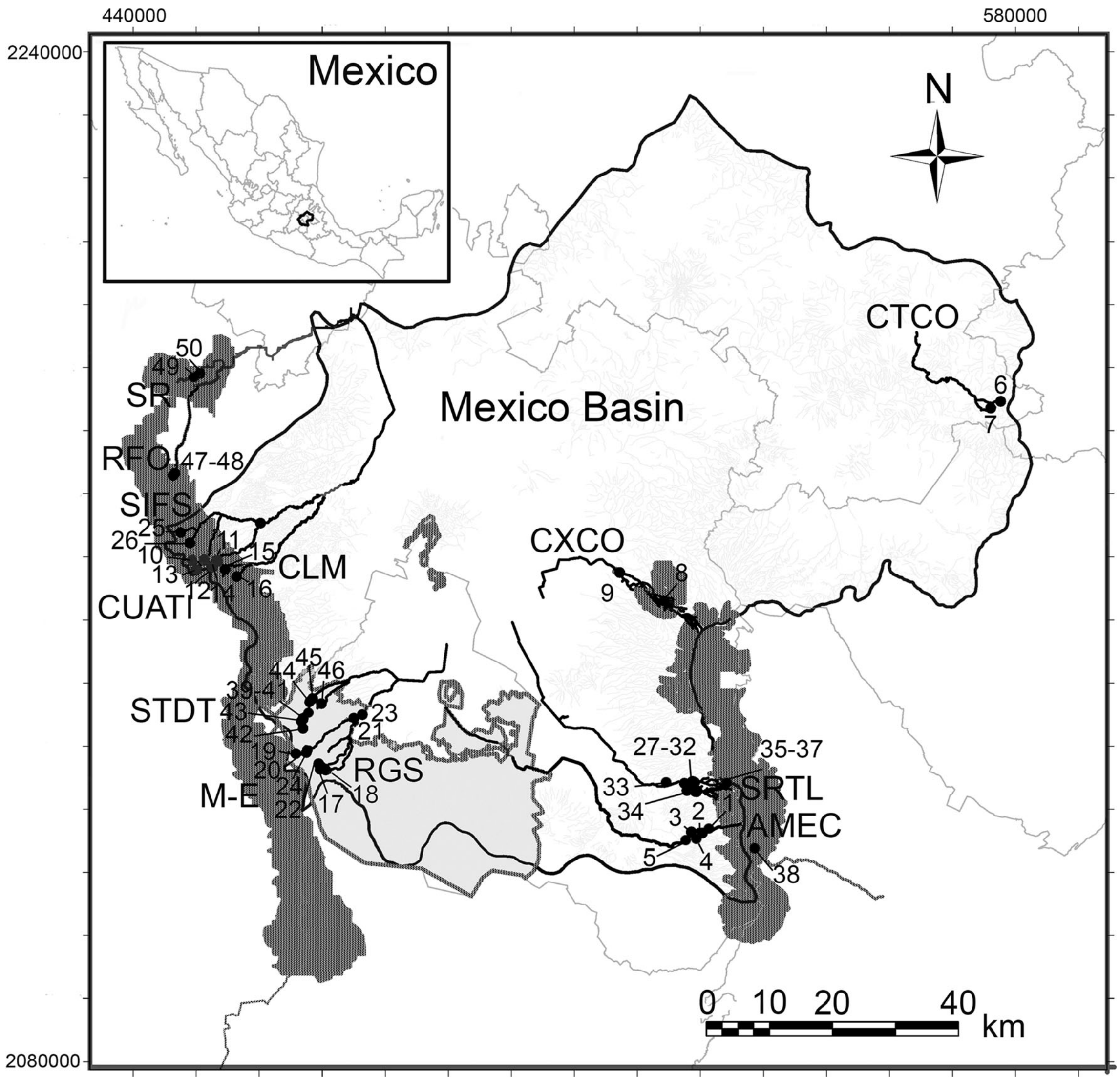

Fig. 1 Location of sampled peri-urban rivers from the Mexico Basin. Acronym of the subbasin name and the number of the river locality of the sampling collection is according to Table 1. Territorial limits of the protected areas are presented as dark gray area and conservation soil in gray area

criteria established in the official Mexican guidelines and international standards (DOF, 2003; APHA, 2005). Nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP, in theory, mostly in the form of orthophosphate, PO_4-P) were analyzed with a DR 3900 laboratory spectrophotometer (Hach 2003). The criteria used to validate water quality and its fitness for human contact were those considered the Mexican norm (DOF, 2003). Hydromorphological quality (HQ) and anthropogenic activities were evaluated using the proposal by Encalada et al. (2011).

Macroinvertebrate sampling Specimen collection points were selected at each sampling location following a multihabitat criterion and using a 30 cm-wide Surber-type D-net with 250 μm mesh. Sampling was performed along a 10 m transect. Sediment was removed by kicking during a 5-minute period in the center of the channel river and banks, and organisms were moved to a tray for manual extraction. Organisms were also caught by manual examination and extraction from the submerged faces of large rocks, pieces of dead wood and leaves to cover all possible habitats. At least 100 individuals were collected from each sampled site as representatives and preserved in 70% alcohol. Individuals were separated under an Olympus SZX7 stereoscopic microscope (Olympus Corporation, Tokyo, Japan) and identified to the family level according to Bueno-Soria (2010) and Merritt et al. (2008). Finally, individuals were assigned to functional feeding groups (FFG) based on (Cummins et al. 2005). The classification of the FFG considers a diversity of convergent evolutionary characters in organisms that inhabit the same environment, which face the same environmental limitations. However, without being from the same evolutionary line, present the same adaptation structures to obtain food and to consume it. Therefore, the assemblages can be characterized in such a way as to allow a morpho-functional evaluation within the ecosystem (Cummins et al. 2005).

Macroscopic algae and riparian vegetation sampling. Algae, macroinvertebrates and riparian vegetation were collected at the same sites. Sampling consisted of five quadrats, each separated by 2 m. Quadrats were positioned within each site on areas with >1% algal cover. Quadrat direction and localization were chosen randomly in intervals between 0° and 180°. This procedure was repeated along the sampling quadrats in an upstream direction. The abundance of macroscopic algae (percent cover) was evaluated with a circular sampling unit with a 10 cm radius (area 314 cm^2) (Bojorge et al., 2010; Necchi Jr. et al. 1995). Algae were identified to the species level by reference to taxonomic keys and bibliographic resources (Anagnostidis and Komárek 2005; Carmona-Jiménez and Necchi Jr. 2002; Carmona-Jiménez and Vilaclara 2007; Ettl and Gartner 1988; Komárek 2013; Rieth 1980; Wher and Sheath 2003). For taxonomic analyses, an Olympus BX51 microscope with an SC35 microphotography system was used. The recognition of naturalness for riparian vegetation (native or exotic species) was evaluate on the diversity in 10 m parallel of the littoral zone and 10 m in a perpendicular alignment of the water mirror towards the forest. The diversity was determinate using Rzedowski and Rzedowski (2005), Espinosa and Sarukhán (1997), Ávila-Akerberg (2010) and Ortíz-Fernández (2016).

Ecosystem services approach We evaluated four groups of ES: 1). the supporting services considered were biodiversity conservation, nutrient cycling, primary production, bank stability and habitat heterogeneity; 2). the provision services we evaluated were water quantity and habitat provision; 3) the only regulating service considered was water quality; and 4) the cultural service selected was scenic beauty (Table 2). These ES were considered because we had data systematically measured from the evaluated rivers, they were consistent data in methodology, and they allowed the use of a biological and functional approach to evaluate aquatic ES.

For this proposal, we selected some ecological features represented by diversity of the benthic algae community, benthic macroinvertebrate (MIB) assembly and the physical evaluation of habitat quality as indicators of aquatic ES at the biotope scale. In this sense, the definition of biotope is the physical, morphological unit that is home to a particular species assemblage rather than to a single species, as implied by the use of the habitat (Demars et al. 2012). River biotopes are visually distinguishable in-channel patches composed of different vegetation, mineral substrate, and organic matter types. In the case of macroinvertebrate assemblages, the functional feeding group (FFG) approach was used as an indicator of ES because FFGs function as proxies for the functional attributes of the ecosystem (Cummins et al. 2005). Using the relationships among FFGs, it is possible to provide useful information about ecosystem stability, energy flow and trophic webs (Merritt et al. 2008). The ratios were calculated with the absolute abundance of the organisms.

Data analysis Data were analyzed as a whole set to evaluate the state of the perennial rivers of the Mexico Basin, and later they were analyzed by subbasin unit to offer a local perspective of ES provision based on external factors such as the legal conservation status of the studied areas. A principal component analysis (PCA) was performed to identify the environmental indicators that were more important in characterizing the sampled sites and influencing the ES potential. The analyses were performed with PRIMER V statistical program 1.4. (Clarke and Gorley 2006).

Ecological quality: Hydromorphological, physical and chemical parameters and biological diversity Diversity of macroinvertebrates, algae and riparian vegetation was assessed by the Shannon-Wiener diversity test (H log_{10}). Other indicators of ES were expressed and constructed as a function of the morpho-functional characteristics of biological communities as described in Table 2.

Results

In general, all studied rivers have some legal conservation status, which in most cases corresponds to conservation soil (CS), a legal local category that prevent land use change from natural use to any other use, which equates to a certain degree of naturalness and good water quality in the rivers (Table 3). The diversity of the two biological groups considered, macroinvertebrates and algae, was low in general and corresponded to what is expected for mountain rivers: oligotrophic with few nutrients supplied from terrestrial inputs. The estimations of SE indicators are presented below.

Supporting services

Biodiversity conservation The richness of the benthic macroinvertebrate taxa was high in all subbasins, indicating a status of good for the substrate heterogeneity on the riverbed as well as several food sources. In the case of algae species, some rivers showed high richness (CUATI, STDT and M-E), which represents good hydromorphological quality conditions for mat establishment. However, the highest values of specific richness for algae did not correspond with the MIB richness values. Likewise, the CTCO subbasin without any conservation status did not register the lowest value of richness as

Table 2 Definition and methodology to assess and construct indicators proposed for aquatic ecosystem services in mountain rivers. The last column offers an interpretation of the results. The functional feeding group ratios and their interpretations from Cummins et al. (2005) are owner proposals

Supporting services	Method and units	Interpretation
Biodiversity conservation (BC)	This service was evaluated thorough the composition (diversity and richness) of the macroinvertebrate assemblages, macroscopic algae and riparian vegetation associated with the different biotopes. BC: Richness and diversity of taxa follows an ecological transect method (50 m) with the multihabitat criteria approach to collecting (Necchi Jr. et al. 1995; Merritt et al. 2008).	Comparing the maximum and minimum values between sampling sites and literature references
Cycling nutrients-MIB (CN-MIB)	The incorporation of coarse (CPOM) and fine (FPOM) particulate organic matter was assessed through the functional feeding groups approach proposed by Cummins et al. (2005). The functioning of the riparian ecosystem was related to the number of shedders to collectors and with the transport and incorporation of coarse and fine organic matter made by them. For collectors, FPOM food would be derived from shedder feeding on CPOM (Merritt et al. 2002). CN-MIB: CPOM/FPOM SHREDDERS to TOTAL COLLECTORS	Normal shredder association linked to functioning riparian system >0.25
Cycling nutrients-CYANOBACTERIA (CN-CY)	The incorporation of atmospheric nitrogen into the system was measured through the presence and relative abundance of nitrogen-fixing cyanobacteria through heterocyst cell presence. CN-CY: Cyanobacteria with heterocyst/total cyanobacteria and algae without heterocyst	Poor: Absence of nitrogen-fixing cyanobacteria Good: > 1 individual by subbasin Excellent: ratio ≥ 1
Primary production (PP)	This ES was measured through primary productivity vs. breathing processes of the functional groups to determine if the river behaves in an autotrophic or heterotrophic way. PP: AUTO/HETERO SCRAPERS to SHREDDERS + TOTAL COLLECTORS	Autotrophic: > 0.75
Bank stability (BS)	This ratio reflects that when there is high channel or bank stability of the river there is a higher density of macroinvertebrates due to a greater availability and heterogeneity of substrates and, as a consequence, higher habitat diversity (e.g., bedrock, boulders, cobbles, large woody debris). BS: SCRAPERS+FILTERING COLLECTORS to SHREDDERS + GATHERING COLLECTORS	Stable substrates plentiful >0.5
Habitat heterogeneity (HH)	The diversity of algae growth formed reflects the heterogeneity of biotopes available for the different morphological adaptations (Sheath and Cole 1992). HH: Number of growing forms by transect and site: free filaments, mats, gelatinous colonies, crust and tissue-like forms	1–2 poor 3–4 high
PROVISIONING SERVICES		
Water (W)	Evaluated through the water discharge in each sampled river. The flow of surface runoff has the potential to be used by locals and maintain biodiversity and nearly basically all river functions. W: Q = W*V*D W: Width of the river V: current velocity D: depth	Amount of water passing through a point on the river per unit time Poor: 0.01 to 0. 49 m^3/s Good: 0.5 to 0.8 m^3/s Excellent: > 0.81 m^3/s
Habitat (H)	This service was evaluated with the algae and benthic macroinvertebrates in each sampled site, the ecological basis being that environmental heterogeneity provides more habitats to colonization and it is results in greater diversity (Maes et al. 2011). H: $H' = -\Sigma^{s}_{i=1}\,(pi)\,(\log_2 pi)$	Higher values of diversity will reflect a greater number of potential habitats to colonize (Caro-Borrero et al. 2015) Poor: H′ < 1 Moderate: H′ 1–2 Good: H′ > 2
REGULATING SERVICES		
Water quality (WQ)	Evaluated through physical-chemical parameters measured in situ. WQ: Mexican Water Official Norm (NOM-127), for use and human consumption	Maximum permissible limits established in the Mexican water NOM (DOF, 2003): total dissolved solids (1000 mg/l), nitrites (0.05 m/l), nitrates (10 m/l), ammonium (0.5 m/l), phosphorous (5 m/l).
CULTURAL SERVICES		
Scenic beauty (SB)	Hydromorphological quality (Encalada et al. 2011) was evaluated under the assumption that a higher level of naturalness (conservation) is proportional to a greater scenic beauty and therefore susceptible to increasing the tourism appreciation. SB: Four components evaluated: basin, hydrology, stretch of the river, and riverbed.	Values: very good >96, good 76–95, intermediate 51–75, bad 26–50 and very bad 25 (Encalada et al. 2011).

expected. The greatest diversity of riparian vegetation and native species was recorded in the upper portions of the basin in conservation zones (M-E) or in protected natural areas (AMEC and SR-FL). Riparian vegetation obtained the lowest values of diversity, which is indicative of possible modifications with anthropogenic aims, for example, monocultures or the introduction of plants useful to man.

Cycling nutrients, primary production, bank stability and habitat heterogeneity Nutrient cycling was evaluated through shredder associations and in all cases showed values less than 0.25, the threshold established to detect normal associations; this shows that in our rivers, there are few shredders, and therefore, the input of exogenous coarse organic matter is not high due to the characteristics of native vegetation and/or because the rivers' floodplains had a coverage of modified riparian vegetation, by the introduction of either crops or exotic species.

In the case of algal species, the recurrent association and greater abundance of cyanobacteria, Chlorophyta and Heterokontophyta was related to the presence of growth forms adapted to water flow (filaments, mucilaginous colonies and sheets) as well as specialized cells and/or cell inclusions (heterocyst, terminal hairs, polyphosphate granules, among others), suggesting that physiological strategies have been used to incorporate limiting nutrients (such as phosphorus, nitrogen and carbon) in subbasins with the best state of hydromorphological quality conservation. Regarding primary production, 67% of the rivers were heterotrophic, predominately breathing rather than photosynthesizing. Eighty-five percent of the rivers maintained a balance in the transport of suspended sediments in the water column to the riverbed and had adequate channel stability to provide more habitat diversity, which was reflected in the high richness of MIB taxa.

Provision services

Water and habitat With respect to water provision, the rivers evaluated have low runoff, and only the CUATI and SR subbasins showed higher values than the other evaluated subbasins (1 m^3/s). These values demonstrate the characteristics of headwaters with few inputs from tributaries. The habitat provision values in most cases were in the range between 1 and 2, and only one site (SR) registered values higher than 2.5, which can be classified as high diversity. These results were expected for a mountain river. No relationship was found between subbasins with less surface runoff and less biological diversity, which suggests an adaptation of the species and taxa to these conditions.

Regulating services

Water quality Most of the evaluated subbasin rivers presented conditions between oligotrophic and mesotrophic, and only the CXCO subbasin had quality conditions between mesotrophic and eutrophic. This may be due to the low intensity of activities such as agriculture, livestock placement and the impacts of human populations living within protected forest areas. The above conditions not only improve water quality but also favor the establishment of biological communities that participate in the generation of aquatic ES, such as the cycling of nutrients.

Cultural services

Scenic beauty This service was evaluated through different hydromorphological quality parameters. We found six subbasins with total scores above 100 points, a result that can be considered good to excellent in quality, and we found five subbasins with scores below 100, results that can be considered regular or poor. These conditions reflect some types of alterations that break with the natural landscape of the subbasins, such as the presence of gabion dams, water extractions in situ, livestock and crop systems, and the proximity of human settlements to the river. These alterations are reflected in the low individual scores of parameters such as river stretch.

Principal components analysis (PCA) was used to determine factors that affect the blue ecosystem services provision. Seventy-seven percent of the variation in the data could be explained by three main factors (Fig. 2). The first (35.7%) was found to be positively related to the greater total lengths of the river channel (0.26), the length of river running within the protected area (0.26), the number of locations collected in the subbasins (0.29), and the number of these locations collected within the protected area (0.26) as well as the greatest richness of algae (0.25) and the water quality status between mesotrophic and eutrophic (0.22). These factors represent physical characteristics and are associated with the CUATI, M-E, SIFS, SRFL and STDT subbasins. The second factor explained 21% of the total variance and is related to hydrological parameters such as the total length of the river channel (0.3) and the highest values of water discharge (0.26); therefore, they are assumed to be large rivers (AMEC, CXCO, SR).

Finally, we looked at the average of the rivers sampled. The third factor (12.8%) represented the parameters or functional river indicators and showed a positive correlation with nutrient cycling through the MIB taxa (0.28) and cyanobacteria species (0.46), autotrophic systems with higher primary productivity (0.47), higher bank stability (0.25), and higher values of algal diversity (0.16) and riparian vegetation (0.11).

Discussion

The Mexico Basin maintains a conservation status that still provides diverse ES derived from aquatic local ecosystems to

Table 3 Hydrological characteristics and ecosystem services indicator values by subbasin unit provided by the mountain rivers in the Mexico Basin. Cumulative values refer to ES by the Mexico Basin as a whole unit. Acronyms of the subbasin are according to Table 1

Ecosystem services indicators /subbasins	AMEC	CXCO	CUATI	CLM	RGS	M-E	SIFS	SRFL	STDT	CTCO	SR	RFO	Cumulative values
HYDROLOGICAL CHARACTERISTICS													
Total length (km)(TL)	51.1	37.5	64.2	27.1	10.6	30.4	8.4	53.4	34.2	25.1	15.9	16	373.9
Protected area length (km)(PAL)	2	16.5	41.8	4.4	10	18.5	6.6	12	7.9	0	3.7	3.8	127.2
Number of locations analyzed (NLA)	5	2	5	2	2	6	2	11	8	2	2	2	50
Number of locations in protected area (NLPA)	0	1	5	2	2	4	2	10	8	0	0	2	36
SUPPORTING SERVICES													
Biodiversity conservation (BC)													
Macroinvertebrates taxa (% respect total) (MT)	20 (43)	8 (17)	28 (61)	20 (43)	17 (37)	16 (35)	26 (57)	23 (50)	20 (43)	11 (24)	13 (28)	12 (26)	**46 (100)**
Algal species (% respect total) (AS)	6 (32)	3 (16)	14 (74)	9 (47)	6 (32)	10 (53)	8 (42)	9 (47)	11 (58)	7 (37)	2 (11)	4 (21)	**19 (100)**
Cycling nutrients-MIB (CN-MIBS)	0.015	0	0.04	0.045	0.07	0.013	0.049	0.06	0.052	0.07	0	0.06	0.146
Cycling nutrients-CYANOBACTERIA (CN-CY)	0	0.25	0.33	0.5	0.17	0.1	0	0.3	0.14	0.06	0	0.17	2.02
Primary production (PP)	0.61	1.33	0.60	1.43	0.89	0.30	0.46	0.44	0.40	0.08	0.09	0.92	0.44
Bank stability (BS)	1.18	1.33	1.13	1.66	0.434	0.45	0.83	0.92	0.77	0.85	1.07	2.53	0.8
Habitat heterogeneity (HH)	2.6	1.5	2.46	2.6	2.25	3.33	3.0	2.85	2.44	2	1.5	1.74	
PROVISIONING SERVICES													
Water discharge (Q $m^3\ s^{-1}$)	0.27	0.24	1.0	0.03	0.006	0.33	0.06	0.24	0.13	0.02	1.03	0.31	3.66
Habitat H′ algal (HA)	1.01	0.5	1.3	1.1	1.04	1.23	1.5	1.13	0.8	0.8	0.14	0.7	
H′ macroinvertebrates (H-MIBS)	2.12	1.3	2	2.3	2.2	1.7	2.7	1.9	1.9	2.1	2.6	2.1	+
H′ riparian vegetation (HV)	0.29	NA*	0.24	0.23	0.20	0.27	0.23	0.26	0.22	NA*	0.24	0.24	+
REGULATING SERVICES													
Water quality (WQ)	O-M	M-E	O-M	O-M	O-M	O-M-E	O-M	O-M-E	O-M-E	O-M	O-M	O-M	+
CULTURAL SERVICES													
Scenic beauty (SB)													
Basin (B)	28	21	26	29	16	22	29	24	25	24	28	21	+
Hydrology (H)	26	24	27	27	23	26	28	28	27	26	27	30	+
Stretch of the river (SR)	26	18	25	29	15	20	28	21	23	24	24	24	+
Riverbed (R)	25	23	27	30	26	22	29	22	25	24	28	28	+
Total hydromorphological quality (THQ)	105	86	105	115	80	90	114	95	100	98	107	103	+

(*): *NA* Non-available data, (+): not calculated due to inability to assess values

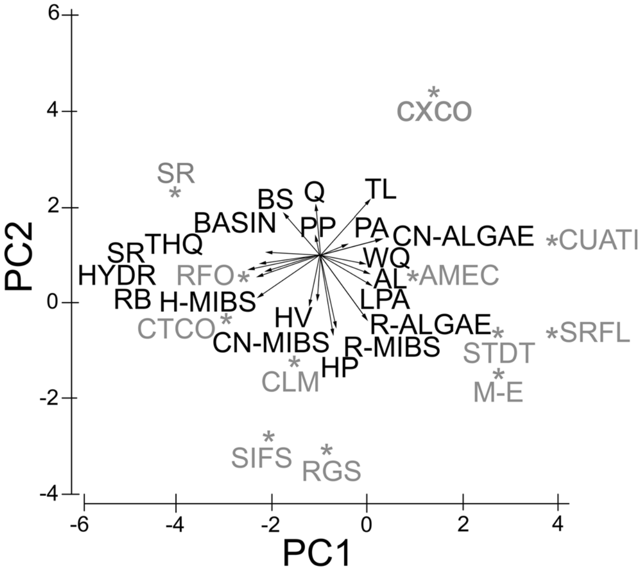

Fig. 2 Principal components analysis. The plot shows the distribution of the parameters and subbasins evaluated in two factors with an accumulated variance of 56.6%. Acronyms of the subbasins are according to Table 1, and ecosystem services indicators are according to Table 2

the second largest city in the world. In particular, the peri-urban rivers have physical and chemical characteristics, hydromorphological quality parameters and biological diversity that can be considered a reference for a good state of naturalness in aquatic rural-urban ecosystems (Encalada et al. 2011; Mendoza-Cariño et al. 2014; Caro-Borrero et al. 2015; Carmona-Jiménez and Caro-Borrero 2017). The use of the functional role of taxa highlights the importance of morphological and physiological data, that are rarely incorporated into aquatic ES analyses (Brill et al. 2017). However, our results shown that mountain river ecosystems are particularly vulnerable to the impacts associated with changes in land use, as usually occurs in streams with urban influence (Walsh et al. 2005; Mendoza-Cariño et al. 2014) We observed some alterations as indicated by the low values for riparian vegetation diversity, these modifications including extinction of native species bring important consequences for the benthic macroinvertebrates populations, because decrease the input of allochthonous organic matter (river continuum concept) and the heterogeneity of available habitats (Vannote et al. 1980; Merritt et al. 2008).

Our findings support the importance of maintaining not only the water quantity and quality as the most important ES derived from rivers in peri-urban areas, since this service is legally protected and socially valued, but also biological diversity (Maes et al. 2011; Sirakaya et al. 2018). In this sense, the proposal to use functional ecological value turned out to be an efficient and ecological way of supporting the potential and actual capacity to the ES provision, both in conserved conditions and in those with a certain degree of anthropogenic impact.

On the other hand, the protection and conservation of subbasins studied through some legal status, which turned out to be important for natural ecosystem functioning and, as a consequence, in the generation and maintenance of the aquatic ES evaluated. However, continuous urban sprawl threatens the permanence of these natural areas and has an impact on ecosystem function and structure, because even if these areas are protected, conservation regulation compliance is deficient (Aguilar and Santos 2011; López-Morales and Mesa-Jurado 2017).

Supporting services

Benthic macroinvertebrates proved to be useful indicators of organic matter incorporation from terrestrial to aquatic ecosystems and play a fundamental role in the connection of both systems to matter and energy interchange through the food network (Cummins et al. 2005; Brill et al. 2017). In some subbasins, the loss or seriously alterations of riparian vegetation were reflected in medium to low biodiversity values and the nutrient cycling function, thought the FFG ratios. These results imply a low density of shredders and therefore a high dependence of the aquatic system on river primary production, which is expected to be poor in the headwaters of the mountain rivers (Vannote et al. 1980; Cummins et al. 2005). In these sense, the modifications to the river banks, as evidenced by their hydromorphological quality, must be avoided because they are an important sources of alterations in aquatic food chain in peri-urban rivers (Vidal-Abarca et al. 2014).

In our study, the increased nutrient concentrations improve and increase algal diversity. However, such a stimulating effect on algal growth was limiting in subbasins with urban pollution, where algal diversity practically disappears as has been reported in other studies (Brill et al. 2017). Changes in algal diversity not always result in a reduction of richness and/or abundance of species; in some cases, changes in diversity can grow populations. In fact, abundant populations of tolerant species can proliferate, as occurs with the presence of cyanobacteria like *Phormidium* genera (Carmona-Jimenez et al. 2016). The algae species showed changes in diversity in the urbanization settlements close to the rivers, and this attribute can be used to comparing regional variation in response to land use change due to habitat fragmentation and loss (Caro-Borrero et al. 2015; Cai et al. 2017).

Provision services

Water provision was an ES metric that showed low values, which can respond to alterations within the river channels, such as extractions in situ, channeling, and damming (Rosenberg et al. 2000; Vidal-Abarca et al. 2014; López-Morales and Mesa-Jurado 2017). Despite the low values, in the case of the MIBs, they can increase their richness if the quantity and current velocity of water are stable (Alberti

2010). In ecological terms, a decline in water flow reduces the interaction between the river channel and the flood plain, affecting processes that regulate other aquatic ES, such as water quality, biodiversity, nutrient cycling and some cultural services, since all aquatic ES are controlled by the water flow regime (Gopal 2016; Gunderson et al. 2016). In Mexico the lack of long-term data on both the quantity of water and the change in land use is a predominant situation, so, determine its effects on river functioning make the evaluation and understanding of ES provision in peri-urban contexts more difficult (Eastwood et al. 2016; Brill et al. 2017).

In terms of human benefits, one of the greatest risks is the water decrease for consumption, which may be aggravated by seasonal changes during the dry season. In Mexico City, water extraction exceeds recharge by 1.73 times, compromising the sustainability of this ES at present (Oswald 2011; López-Morales and Mesa-Jurado 2017). This is in addition to other pressures, such as population growth, land use change, agricultural practices and political conflicts (Aguilar and Santos 2011; Oswald 2011). On the other hand, the regulation of water quantity during the rainy season has traditionally been managed through damming for flood control, which interrupts the natural river flow and therefore the biological interactions with repercussions in ES provision like nutrient cycling, biodiversity and other ES derived from biological interactions (Vidal-Abarca et al. 2014; Caro-Borrero et al. 2017).

The habitat provision service was related to medium and low MIBs and algal diversity values, respectively. These results were expected for mountain rivers, mainly due to the challenging natural conditions in parameters such as water temperature, current velocity and poor input of nutrients from the riparian zone. However, cases with low values could be related to river channel modifications and to the low ratio of natural shredders in association with the disappearance of species of algae typical of mountain rivers (Carmona-Jimenez et al. 2016).

Regulation services

Water quality is one of the most socially valued ES. In this case, most of the subbasins corresponded with oligo- to mesotrophic conditions, and few cases correspond to greater nutrient concentrations. Although this ES was evaluated through trophic status, it was also reflected in the macroinvertebrate communities and their functional groups, for example, filtering macroinvertebrates are typical inhabitants of streams with high organic enrichment (Merritt et al. 2008), but in the subbasins studied, they were not dominant. Taking into account the algal communities, the species registered suggests different strategies of carbon, phosphorus and nitrogen uptake and their fixation into organic compounds available to another organism. Nitrogen-fixing cyanobacteria were frequent and abundant in oligotrophic conditions and they could be established interactions with MIBs and employ them as food or refuge maintaining biological interactions within the ecosystem (Caro-Borrero and Carmona-Jiménez 2018). The emergence, replacement and increase of nutrient-tolerant species in our study suggests a potential risk in the middle and lower portions of the subbasins. Chemical pollution in association with hydromorphological disturbance generates a panorama that continually threatens the state of conservation of rivers; and ecosystem vulnerability is increasing (Gunderson et al. 2016).

Cultural services

The good status of ecological quality and easy accessibility to these areas due to their proximity to the city allow cultural ES to be widely appreciated along with the water provision in quantity and quality (Eastwood et al. 2016). However, alterations of the river channel and deforestation in the riparian zone were evident as a result of this rural-urban interaction in a city that is continuously expanding (López-Morales and Mesa-Jurado 2017). The results suggest that the declaration of protected areas must remain and be even more rigorous in ensuring compliance, since scenic beauty is not just a visual and spiritual ES for human populations but also has to do with the natural configuration of the landscape as an important function in the support of the other ES evaluated (Gopal 2016; Gunderson et al. 2016; Affek and Kowalska 2017).

Factors that affect the blue ecosystem services provision (principal components analysis)

In general, the ES provided by the rivers in the Mexico Basin respond positively to the physical characteristics, hydrological functioning and the functional ecology of organisms. Rather than being an individual aspect of the functioning of ecosystems, the provision of services is the combination of several factors that are positively related to supply capacity (Vidal-Abarca et al. 2014; Gopal 2016). The main factor that threatens the provision of aquatic ES is the transformation and /or loss of hydromorphological quality; mainly alterations in the channel, water diversions, and damming and the removal of riparian vegetation, are aspects that strongly influenced the status of ES provision in this study. In particular, the naturality of the subbasins and the hydrological cycle at local scale are affected by the presence of illegal human settlements in conservation soil of the Mexico City, which is related with the loss and/or reduction of ES (Vidal-Abarca et al. 2014). This is an important finding, since almost 59% of the actual river ecosystem configuration and function depends on hydrological factors and legal figure of conservation, and, an additional 13% of this configuration could be can be explained through morpho-functional bioindicators. The set of factors evaluated in this article are in the peri-urban context an approach very close to the actual state of ecological capacity in terms of ES potential.

In the current peri-urban scenario, and knowing the most important factors that support the ES provision, the conservation policies that are implemented in the wooded areas of the city in a river basin plan that includes some important aspects like as (Gopal 2016): a) characterization of the river basin at the ecological and biological level; for example, using the design of morpho-functional bioindicators of ES proposed here b) monitoring program of measures, for example, using the biological, algae and macroinvertebrates indicators and evaluating critical aspects of morphological deterioration such as number and location of dams and water diversions; c) implementation of water policies; using the information about the potential ES provision by subbasin is possible to design a conservation strategy at local level and establish areas with different ecological priority of permitted uses (BenDor et al. 2017; López-Morales and Mesa-Jurado 2017). and e) communication and public participation. Here is an important opportunity to enroll tourists, citizens and institutions through cross-scale interactions (Vidal-Abarca et al. 2014; Gunderson et al. 2016) since these conserved areas are unique in the midst of the extensive urban development of the Mexico City (Oswald 2011; Haase 2015; Gunderson et al. 2016).

Conclusions

The morpho-functional biological approach and hydromorphological indicators of blue ES proved to be an objective ecological tool to assess the state of river functioning. Additionally, they are a tool of rapid access that allows adaptation and flexibility in the conservations and management of aquatic natural resources in peri-urban context, an important aspect in developing countries, where it becomes necessary to reconcile economic and social growth with the maintenance of ecosystems with good ecological integrity.

The ES provision in rivers of the Mexico Basin mainly respond to three major factors: physical characteristics (nutrient enrichment, riparian zone alteration), hydrological functioning (dams' construction, water diverse) and the functional ecology of organisms (functional groups in algae and macroinvertebrates communities).

The aquatic ES most influenced in the peri-urban context was nutrient cycling through the incorporation of organic matter from the riparian ecosystem into the river course. Likewise, the water quantity was also influenced, due to local interventions for its extraction and the dam's construction to prevent floods in the urban area. The support and provision ES are very sensitive to changes in the geomorphology of the subbasins and are susceptible to the growing need for water by developing urban areas.

Classify the algae and macroinvertebrates organisms into functional groups, according to the ecological role that they fulfill within the ecosystem proving to be a good alternative to evaluate the ecological integrity and the potential provision of aquatic ES. The algae being the base of the food network and the macroinvertebrates as a connection with the other levels of the same, they offered key information on the rivers functioning.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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