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THE HYDROMORPHOLOGICAL QUALITY OF THE BASIN OF MEXICO: A PROPOSAL OF ITS INDICATOR VALUE OF THE ECOLOGICAL STATE IN THE RIPARIAN ECOSYSTEM

La calidad hidromorfológica en la cuenca de México: una propuesta del valor indicador de estado ecológico en el ecosistema de ribera

Raquel ORTIZ FERNÁNDEZ[1], Javier CARMONA JIMÉNEZ[1]*, Lisset Gabriela TEMIS GARCÍA[1], Ángela Piedad CARO BORRERO[1] and Beatriz GONZÁLEZ HIDALGO[2]

[1] Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México, Circuito Exterior s/n, Ciudad Universitaria, 04510 Ciudad de México, México.
[2] Departamento de Producción Agrícola y Comercial, División de Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana, Calzada del Hueso 1100, Colonia Villa Quietud, 04960 Ciudad de México, México.

*Author for correspondence: jcj@ciencias.unam.mx

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Key words: bioindicators, ecological quality, mountain rivers, riparian vegetation, reference conditions.

ABSTRACT

The characterization of hydromorphological quality is the evaluation of the physical structure and the flow regime associated with fluvial ecosystems. Its value indicates the state of ecosystem conservation, as well as the anthropogenic pressures that disturb it. The present study proposes an hydromorphological quality (HYQI) index that aims to establish reference conditions in the preserved rivers and springs in the Basin of Mexico, through: (*i*) the basin quality associated with the riparian zone's state, including the vegetation's naturalness, level of erosion, and land use in 13 sub-basins (63 sites); (*ii*) hydrology, related to natural or disturbance conditions in the channel; (*iii*) anthropogenic alterations in the riparian zone, and (*iv*) the characterization of the trophic level. The final evaluation is divided into five classes: high (> 100), good (76-99), moderate (51-75), bad (26-50), and poor (< 25). The HQYI evaluation showed that 44 sites have a high rating (120 to 100 points), where potential reference conditions for the Mexico Basin can be recognized. The remaining 19 sites have good to poor quality conditions. The vegetation cover was represented by 70% of native species in one of three types of forest: *Pinus, Abies,* and mixed forest dominated by *Quercus.* Modifications in the canal structure, extraction and retention of water, and introduced plant species were the causes that confirmed the moderate quality value in the middle and lower portions. The HQYI value was found to be significantly correlated with nutrient water enrichments with soluble reactive phosphorus and dissolved inorganic nitrogen. Therefore, this index is recommended for monitoring the Basin of Mexico and registering multiple environmental stressors.

Palabras clave: bioindicadores, calidad ecológica, condiciones de referencia, ríos de montaña, vegetación de ribera.

RESUMEN

La caracterización de la calidad hidromorfológica es la evaluación de la estructura física y el régimen de caudales asociados a los ecosistemas fluviales. Su valor indica el estado de conservación del ecosistema, así como las presiones antrópicas que lo perturban. El presente estudio propone un índice de calidad hidromorfológica cuyo objetivo es establecer las condiciones de referencia en los ríos y manantiales conservados en la cuenca de México. A través de *i*) la calidad de la cuenca asociada al estado de la zona ribereña, incluyendo la naturalidad de la vegetación, nivel de erosión y uso del suelo en 13 subcuencas (63 sitios); *ii*) la hidrología, relacionada con las condiciones naturales o de perturbación del cauce; *iii*) alteraciones antrópicas en la zona de ribera, y *iv*) la caracterización del nivel trófico. La evaluación final está dividida en cinco clases: alta (> 100), buena (76-99), moderada (51-75), mala (26-50) y pobre (< 25). La evaluación de la calidad hidrológica mostró 44 sitios con una calificación alta (120 a 100 puntos), donde se pueden reconocer las condiciones potenciales de referencia para la cuenca de México. Los 19 sitios restantes tienen condiciones de calidad buena a pobre. La cobertura vegetal estuvo representada por 70% de especies nativas en uno de los tres tipos de bosque: *Pinus*, *Abies* y bosque mixto dominado por *Quercus*. Las modificaciones en la estructura del canal, la extracción y retención de agua y las especies vegetales introducidas fueron las causas que confirmaron el valor moderado de calidad hidromorfológica en la parte media y baja. Se encontró que el valor del índice propuesto estaba significativamente correlacionado con los enriquecimientos de nutrientes con fósforo reactivo soluble y nitrógeno inorgánico disuelto. Por lo tanto, este índice se recomienda para el monitoreo en la cuenca de México y el registro de múltiples estresores ambientales.

INTRODUCTION

The hydrological basin is the geographical area where water flows towards a main current and then towards a common exit point. The hydrological cycle occurs in this territory, and the nature of climatic and geological origin, the kinetics and chemical composition of the water, the types of soil and sediment transport, and the biological communities confer a particular identity to the basin (Sabater et al. 2009). To determine the conservation status of a basin, it is necessary to evaluate a series of physical and chemical indicators of the water, such as biological, geological, hydromorphological, and socioeconomic descriptors, for instance legal status or ownership of the land (Hering et al. 2003, Stoddard et al. 2006). Together, these indicators allow us to recognize the reference conditions, and they serve as a basis for identifying the pressures for change promoted by anthropogenic action. Hydromorphological methods are used to understand the physical processes and causes of river alteration. For example, the Water Framework Directive (PE 2000) considers three types of indicators: (*i*) the hydrological regime through the flow state, the hydrodynamics of the river, and the connection with groundwater; (*ii*) the continuity of the river and its relationship with the riparian vegetation, and (*iii*) disturbances of anthropogenic origin. Other evaluation indices such as the Ecological Quality of the High Andean Rivers (CERA; Encalada et al. 2011), the Riverside Forest Quality (QBR; Munné and Prat 2004), and the Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers of the United States Environmental Protection Agency Index (USEPA; Barbour et al. 1999), have evaluation characteristics similar to the high mountain rivers of the Basin of Mexico. However, the reference conditions and disturbances that decrease the ecological quality of rivers are different for each region since they respond to a mosaic of socioeconomic conditions that function as drivers of change in different degrees. Because of this, indices are generally designed at the regional level and work well within the area for which they were designed, which means that they are subject to adjustment calibrations to represent the conditions of the study region since the indicators are built with the greatest spatial and temporal representativeness possible (Bouleau and Pont 2014). Given the rapid changes in riparian conservation status, reliable, swift, and low-cost methods must be developed (Kremen 1992, van Dam et al. 1994, McGeoch 1998).

As a solution to this problem, it has been proposed that conservation and management efforts focus on analyzing the hydromorphological structure and its relationship with biological communities, which should work as an environmental indicator under the assumption that the response to the change of the biological species is representative of a particular habitat (Andelman and Fagan 2000). The Water Framework Directive (PE 2000) proposes that the evaluation of hydromorphological quality must be continuously monitored and adjusted to identify the biotic and abiotic characteristics that indicate the state of conservation and/or deterioration of the environmental quality.

The evaluation of water quality in Mexico is developed under a utilitarian and little ecosystemic approach. Such is the case of the evaluation established by the Official Mexican Standard NOM-127-SSA1-1994 (SSA 1996), which focuses on the risk to humans from the concentration of nutrients and harmful bacteria. Also, the Mexican Standard NMX-AA-159-SCFI-2012 (SE 2012) establishes the procedure for environmental flow determination in hydrological basins, which is intended to preserve the aquatic ecosystem or carry out hydraulic works that modify the cause of the water body. For this purpose, as the norm establishes, it is necessary to evaluate the ecosystem health and its reference conditions.

This approach disregards aquatic ecosystems' structural and functional elements, including the hydromorphological and biological components. Due to the above, in recent years, comprehensive evaluations have been proposed in Mexico that include alternative biological indicators such as algae (Salinas-Camarillo et al. 2020, Carmona-Jiménez et al. 2022), macroinvertebrates (Caro-Borrero et al. 2021), and riparian vegetation (Mendoza et al. 2014). These indicators provide greater sensitivity to ecological evaluation, are low cost, and many of them are available in standardized protocol format.

To determine the state of conservation of the Basin of Mexico, this work aimed to estimate the hydromorphological quality of the rivers and springs through the physicochemical evaluation of the water, the hydromorphological elements, and the naturalness of the riparian vegetation. These were incorporated in the proposal of an index that allows for establishing the reference conditions of the riparian ecosystem.

MATERIALS AND METHODS

Study area

The basin of Mexico is located between 98-100º W and 19-20º N (**Fig. 1**). It was initially endorheic and was later artificially opened to the Pánuco River basin. It is surrounded by large mountains and/or volcanoes of the Trans-Mexican Volcanic Belt (the Ajusco to the south, the Sierra Nevada to the east, and the Sierra de las Cruces to the west). To the north, it is limited by a succession of mountains and hills (The Pitos, Tepotzotlán, Patlachique, and Santa Catarina), and to the southeast, the Popocatepetl and Iztaccihuatl volcanoes surround the basin. According to Ferrusquía-Villafranca (1993) and Legorreta (2009), 45 rivers that are still reported to exist descend from this system of mountains. The basin has an approximate area of 9600 km^2, encompassing territories of the State of Mexico (50%), Hidalgo (26.5%), Mexico City (13.8%), Tlaxcala (8.7%), and Puebla (1%). Of the total area, 5136 km^2 (53.5%) are flat terrain and hillslopes (2250-2400 masl), and low slopes (2-12º). The remaining 4464 km^2 (46.5%) are mountainous terrain (> 2400 masl) with a steep slope (2-12º) (Lugo-Hubp 1990). In the latter, about 2000 km^2 (44.8%) are occupied by human settlements, in most cases irregular because they are located in mountainous areas of ecological importance (Perló and González 2005, Aguilar 2008). From a biogeographical point of view, the rivers and springs in the basin are classified as subtropical mountain rivers (altitudes greater than 2200 masl). The rainfall (total annual precipitation of 600-1200 mm) and temperature (5-25 ºC) variation throughout the year generate a biological community with greater affinity to temperate or boreal regions (Bojorge et al. 2010). Ninety-two percent of the sites were located in the upper basin (> 2800 masl) and 8% in the lower basin (< 2800 masl). According to Legorreta (2009), the rivers and surface springs are born and run through superficial stretches between 5600 and 3200 masl altitudes before being piped in the lower basin. According to the Instituto Nacional de Geografía y Estadística (National Institute of Statistics and Geography; INEGI 2013), 70% of the land in the Basin of Mexico is used to develop primary activities (livestock, agriculture, and forestry), and 20% of the land is urban, covering most of the territory of Mexico City and some areas of the State of Mexico. Forests of *Pinus*, *Abies*, and mixed represent the vegetation. The rivers and springs of the basin originate in the mountainous areas surrounding the Basin of Mexico and are mostly modified with hydraulic infrastructure, such as small dams, diversion channels, and extraction with hoses, among others (Legorreta 2019). Other springs are owned by private agencies or used for local domestic and economic needs. The rivers circulate on different slopes for stretches of several kilometers before mixing with sewage that originates from anthropogenic activities in the urban area of the city (Legorreta 2019).

Sampling and data analysis

In this research, 63 sites (50 rivers and 13 springs) distributed in 13 sub-basins were evaluated between 2012 and 2020. Sampling was carried out

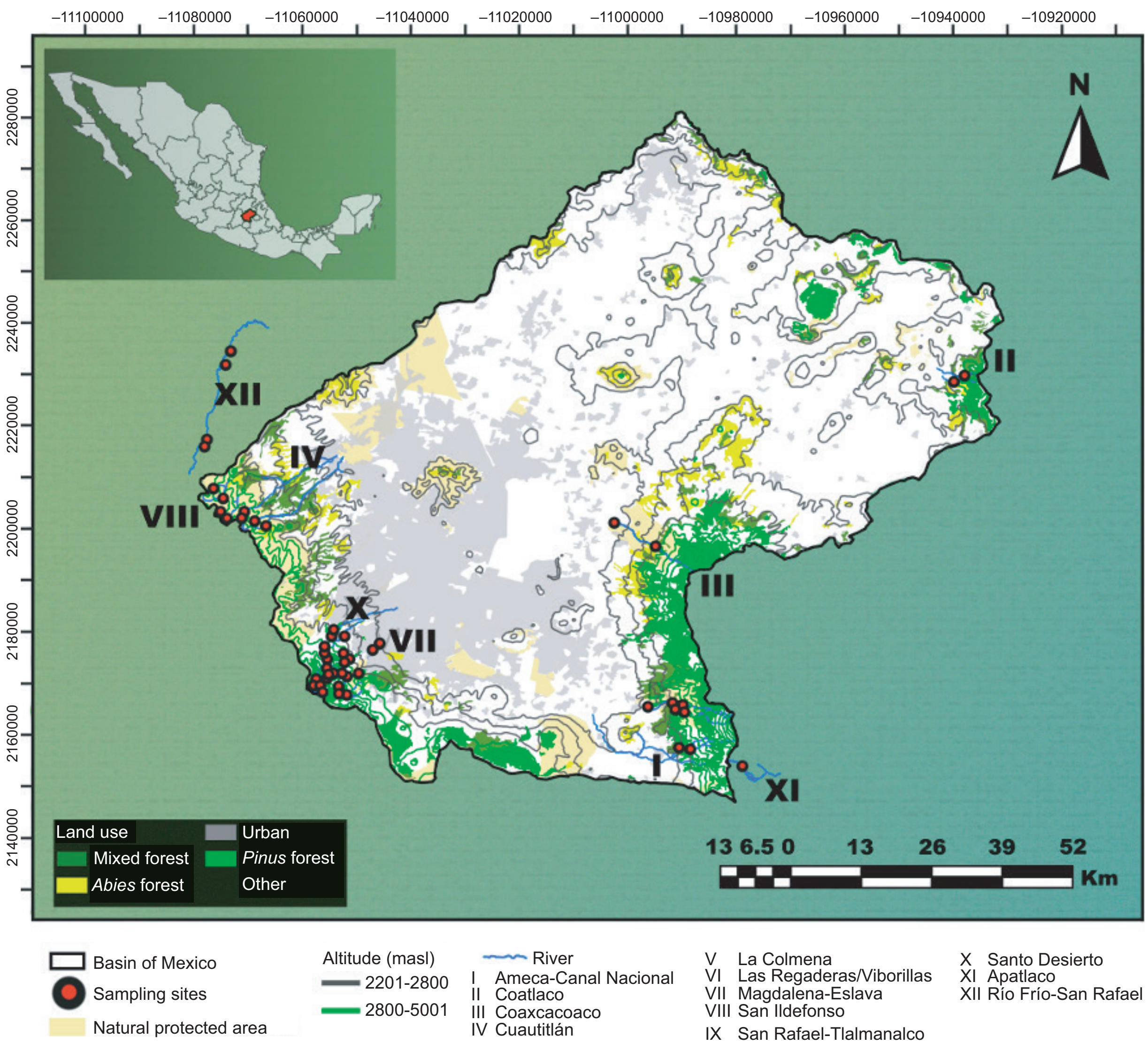

Fig 1. Basin of Mexico limits, protected areas, use land, and altitudinal and hydrological distribution of the 13 sub-basins and 63 sample sites.

in the most contrasting climatic seasons of the year (García 2004): dry winter (December to February, temperature of –2 to 25 °C and total annual precipitation of 600 mm); dry spring (March and early June, temperature of 12 to 26 °C and total annual precipitation of 1000 mm), and rainy summer (July to November, temperature of 13 to 23 °C and total annual precipitation of 1200 mm). The sites were selected under the following criteria: (*i*) altitude greater than 2800 masl; (*ii*) representative of the headwaters, middle and lower zones of the rivers, including the springs, and *(iii)* in territorial terms that were representative of the Protected Natural Area or Conservation Soil of Mexico City. At each site, a 10-m-long stretch was selected where the following physicochemical parameters of the water were recorded in situ: temperature (°C), hydrogen ions (pH), and specific conductivity (µS/cm) measured with a YSI-85 meter (YSI-85 meter, YSI, Ohio, USA). Likewise, 500 mL of water were filtered and analyzed in the laboratory according to the criteria established by the Official Mexican Standard and international water quality standards (SSA 1996, APHA 2005). The following nutrient concentrations were determined in the laboratory with a DR 3900 spectrophotometer (Hach, Loveland, CO; Hach 2003): nitrite (NO_2-N), nitrate (NO_3-N), ammonium (NH_4-N), dissolved inorganic nitrogen (DIN), and soluble reactive phosphorus (SRP, which theoretically is mainly in the form of orthophosphate [PO_4-P]). The discharge (Qm^3) was calculated from the current velocity and depth date following Gore (1996).

The hydromorphological quality (HQ) of the rivers and springs, as well as the anthropogenic activities, were evaluated and adapted from the ecological quality index of the high Andean rivers (Acosta et al. 2009, Encalada et al. 2011), which evaluates 22 parameters divided into four sections (basin, hydrology, river section, and bed). Each section has a value of 30 points, totaling 120 points. Likewise, the HQ was evaluated using the riparian vegetation quality index, which includes detailed evaluation categories on riparian vegetation structure and its indicator value (Munné et al. 2004).

The hydro morphological quality index proposal for the Basin of Mexico was adapted from the above assessments. It included the diversity and status of riparian vegetation, whether native or introduced, as well as elements of regional environmental disturbance, such as the construction of dams in the spring or the canal, tourism, the opening of trails, trout farming, and the typification of native riparian vegetation. We incorporated the size and heterogeneity of the substrate, the current velocity regimes, and the erosion of the shore bank as an element of spring evaluation (**Table I**). The final evaluation is divided and interpreted according to the total score in five classes of hydromorphological quality: high (> 100), good (76-99), moderate (51-75), bad (26-50), and poor (< 25). For a site to be considered a reference, more than 100 points are required. The taxonomic identity of the vegetation was recognized using Rzedowski and Calderón (2005) and Ávila-Akerberg (2010), and those species that present more than 10% abundance in at least one site were included in the index. The Shannon-Winner index was calculated to estimate differences in biological diversity between sites (Addinsoft 2021). To recognize the physicochemical and hydromorphological affinity between sites (including the characterization of the riparian vegetation), the Hierarchical Classification Analysis was performed with standardized data using the ln(x + 1) algorithm and the XLSTAT program (Addinsoft 2021).

We used a new test set to validate the HYQI proposed, which consisted of 26 sites collected in the cool, dry season (February 13-21, 2019) spanning three of the largest sub-basins within the Basin of Mexico, at altitudes of 2333 to 3379 masl. The HYQI, physicochemical parameters, and riparian vegetation were calculated for each site.

RESULTS

The 13 sub-basins are originally associated with different legal conservation statuses within the basins. The rivers and springs were defined as: 1. Natural state: inside or outside a conservation area and 2. Canalized section: inside or outside a conservation area. The Cuautitlán, La Colmena, Las Regaderas, San Ildefonso, Apatlaco, and Río Frío-San Rafael rivers were registered as natural (**Table II**). In accordance with the Consejo Nacional de Áreas Naturales Protegidas (National Council of Natural Protected Areas; CONANP 2016), the shapefile was obtained with the polygons of the protected natural areas. These data were processed in a geographic information system to delimit the length and percent of the segment of each sub-basin. The rivers with the highest proportion in a natural state (**Table III**) were Coatlaco (85%), Amecameca-Canal Nacional (63%), Magdalena (61%), and Eslava (61%). The rivers that had the lowest proportion in a natural state were Coaxcacoaco (49%), San Rafael-Tlalmanalco (37% in a natural state and 63% channeled), and Santo Desierto (23%). According to their in situ validation, the state of permanence of the 50 rivers and 13 springs studied is perennial. In contrast to our validation, the hydrological chart prepared by INEGI (2013) only considers five permanent rivers (Santo Desierto, Magdalena, San Rafael, and Cuautitlán rivers, as well as the upper area of the Ameca-Canal Nacional); the rest were indicated in an intermittent condition. Springs are not referenced within the hydrological charts.

Reference conditions

The reference conditions in the rivers and springs of the Basin of Mexico were characterized by having a temperate affinity with temperatures between 5 and 17 °C, slightly acidic to neutral pH between 5 and 7.5, located in an altitude gradient between 2800 and 4700 masl, with three types of vegetation including *Pinus* (3400 to 3800 masl), *Abies* (2750- 3500 masl) and mixed forest dominated by *Quercus* (2620 to 3370 masl). We identified 75 plant species (**Table IV**). The richness and diversity were heterogeneous between sites, with a 0.4 to 15.6 diversity index value of native species. In general, this wide margin between both values is related to the sites with the greatest disturbance and the most conserved sites. The highest specific diversity was recorded in the *Pinus* forest, followed by the *Abies* and the mixed forest. On the other hand, in the mixed forest, the largest number of introduced species was recognized, associated

TABLE I. PARAMETERS AND SCALES TO EVALUATE THE HYDROMORPHOLOGICAL QUALITY INDEX (HYQI) IN THE BASIN OF MEXICO.

Section	Parameter	Description	Scale	Value
I. Quality of the surrounding area	Riparian cover (Native)	Percent of native riparian cover: right and left bank.	> 70% of native species 69-50% of native species 49-30% of native species < 29% of native species	10 7 4 0
	Bank stability	Percentage evidence of erosion or exposure of the substrate.	<10%, minimal evidence 10-50%, moderate bank 50-80%, unstable bank > 80%, eroded areas	10 7 4 0
	Pool substrate characterization and conditions	Mixture of loose stone, gravel, sand and rooted aquatic plants. Percent of disturbed substrate	< 20% of disturbed substrate 20-40% of disturbed substrate 41-80% of disturbed substrate > 80% of disturbed substrate	10 7 4 0
	Riparian zone with presence of agriculture, livestock	Percent of riparian zone used for agriculture and livestock: right and left bank	Absence of farming < 20% used 21-60% used > 60% used	10 7 4 0
II. Hydrology	Dam present	Percent of water flow containment	Dam absence 50% of water flow through 20% of water flow through containment of water flow	10 7 4 0
	Velocity/ estimated stream depth (only for rivers)	Presence of four velocity regimes: slow-deep, slow-shallow, fast-deep and fast-shallow	Four velocity regimes: slow-deep, slow-shallow, fast-deep and fast-shallow 3 of the 4 regimes presents 2 of the 4 regimes presents 1 of the 4 regimes presents	10 7 4 0
	Channel alteration	Percent of channelization or water extraction pipes	Channelization or water extraction pipes absent > 40% of the stream channelized 41-60% of the stream channelized > 60% of the stream channelized	10 7 4 0
II. Alterations caused by human activities	Presence of effluents from household use	Absence or presence	Absence Presence	10 0
	Urban development	Percent of riparian zone with infrastructure (houses or roads)	Absence of settlements 20% with infrastructure 50% with infrastructure >60% with infrastructure	10 7 4 0
	Human activities	Presence and number of human activities (agriculture, livestock, fish farming, houses or shops)	Absence of human activities At least one human activity Three human activities More of three activities	10 7 4 0
	Presence of organic contamination, garbage and debris.	Percent of organic or inorganic garbage in the riparian zone	<10% garbage 20-40% garbage 50-80% garbage >80% garbage	10 7 4 0
	Water body protection (only springs)	Presence of bars or fences that limit access to the body water	Water body protected (limit access) Water body protected (free access) Partial infrastructure protected Absence of protection	10 7 4 0

TABLE II. PHYSICOCHEMICAL AND HYDROMORPHOLOGICAL CHARACTERISTICS OF SAMPLING SITES IN THE BASIN OF MEXICO.

Sub-basin	Sites	Condition	Stream order	Land use	HQ[3]	HQ[4]	Protected area	Temperature (°C)	pH	Specific conductivity (µS/cm)	Q_3 (m^3s^{-1})	TL[5]
I. Amecameca-Canal Nacional	1. La Castañeda AM1	P	4	BM	104	104	No	4.9	6.49	80	0.272	O-M
	2.La Castañeda II AM2	P	4	BM	104	104	No	9.3	7	175	0.255	O-M
	3.La Castañeda III AM3	P	4	BM	104	104	No	6.6	7.1	178	0.348	O-M
	4.La Castañeda IV AM4	P	4	BP	120	113	No	8.3	7.3	255	0.39	O-M
	5.La Castañeda V AM5	P	4	BM	96	91	No	11	7.16	201	0.29	O-M
II. Coatlaco	6.Rancho nuevo I CT1	ND	1	BM	100	91	No	11.2	7.4	61	0.013	O-M
	7.Rancho nuevo II CT2	ND	2	AP	82	66	No	13.5	6.8	68	0.014	O-M
III. Coaxcacoaco	8.Miraflores CX1	P	4	AP	74	60	No	16.7	7.7	441	0.330	M-E
	9.Santa Catarina CX2	P	3	BM	98	72	Yes	12.3	7.5	92	0.335	M-E
IV. Cuautitlán	10.Los organillos CU1	P	1	AP	108	96	Yes	10.7	6.65	124	0.013	O-M
	11. Capoxi spring CU2	P	1	BM	114	110	Yes	13	6.6	45	0.007	O-M
	12. San Pedro spring CU3	P	1	AP	118	110	Yes	9	6.7	54	0.007	O-M
	13. Iturbide dam, spring CU4	P	1	AP	108	97	Yes	11.73	6.89	51	0.053	O-M
	14. Capoxi CU5	P	1	BM	114	110	Yes	11.35	6.8	46	0.018	O-M
V. La Colmena	15.La Caldera LC1	P	4	BE	116	111	Yes	8.1	6.7	35	0.019	O-M
	16.Xopachi LC2	P	2	BM	115	108	Yes	8.63	7.10	35	0.027	O-M
VI. Las Regaderas	17.Monte Alegre1 LR1	P	3	BP	77	77	Yes	11.60	7.42	49	0.07	O-M
	18.Monte Alegre2 LR2	P	3	Pa	77	74	Yes	17.65	7.16	62	0.05	O-M
VII. Magdalena-Eslava	19.Chautitle ME1	P	1	Pa	116	111	Yes	5	6.7	64	0.151	O-M
	20.Chautitle waterfall ME2	P	2	BP	120	117	Yes	6	7	64	0.214	O-M
	21.Confluencia ME3	P	4	ZU	54	36	No	12	7.1	86	0.20	M-E
	22. Eslava spring ME4	P	1	BP	110	117	Yes	8.75	5.7	112	0.019	O-M
	23.Santa Teresa ME5	P	5	ZU	52	25	No	12.8	7.6	80	0.30	M-E
	24.Truchero ME6	P	4	BP	88	68	Yes	7.6	7.2	63	0.421	O-M

P: perennial; I: intermitent; MF: mixed forest; PA: primary activity; PF: *Pinus-Abies* forest; Pa: grassland; UZ: urban zone; HQ: hydromorphological quality; TL: trophic level.
[1]Hydromorphological quality (CERA; Encalada et al. 2001): very good (>100), good (76-99), moderate (51-75), bad (26-50), poor (< 25).
[2]Hydromorphological quality (HYQI): high (120-100), good (76-99), moderate (51-75), bad (26-50), poor (< 25).
[3]Trophic level: O: oligotrophic; M: mesotrophic; E: eutrophic (SSA 1996).

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VIII. San Ildefonso	25.Las Palomas SI1	P	1	BM	120	117	Yes	11.75	7	48	0.06	O-M
	26.Truchero SI2	P	4	BM	107	88	Yes	10.25	7.15	54	0.114	O-M
IX. San Rafael-Tlalmanalco	27.Agua dulce SR1	P	4	BM	100	88	Yes	9	6.57	138	0.57	M-E
	28. San Rafael channel1 SR2	P	4	BM	94	85	Yes	11.3	6.83	136	0.35	O-M
	29.Compañía waterfall high SR3	P	4	BE	66	51	Yes	14.9	6.98	137	0.046	O-M
	30.Compañía waterfall SR4	P	4	BM	112	95	Yes	10.65	7.15	153	0.06	O-M
	31.Cosamala high SR5	P	4	BM	92	87	Yes	8.8	7	50	0.528	M-E
	32.Cosamala low SR6	P	4	BM	104	94	Yes	14.6	7	99	0.49	O-M
	33. UAM station SR7	P	5	AP	72	60	No	0	0	0	0.35	M-E
	34 San Rafael channel2 SR7	P	4	BM	118	114	Yes	9.85	7.5	137	0.388	O-M
	35.San Rafael SR8	P	1	BP	85	79	Yes	11.95	5.52	71	0.056	O-M
	36.San Rafael channel3 SR9	P	4	BE	96	94	Yes	11.55	7	137	0.028	O-M
	37.San Rafael Vereda SR10	P	4	BE	96	94	Yes	11.55	7	137	0.02	O-M
X. Santo Desierto	38.Arroyo desierto SD1	P	2	BM	120	120	Yes	9.6	7	89	0.20	O-M
	39.Convento SD2	P	2	BM	65	65	Yes	9.4	6.6	77	0.027	M-E
	40.La capilla Sta. Rosa SD3	P	1	AP	104	94	Yes	13	7.3	150	0.019	O-M
	41.Santa Rosa 1 SD4	P	2	BM	110	107	Yes	11.75	7.5	77	0.14	O-M
	42.Santa Rosa spring SD5	P	1	BM	114	114	Yes	13.3	7.04	86	0.018	O-M
	43.Santa Rosa 2 SD6	P	2	BM	114	110	Yes	10	6.48	78	0.258	O-M
	44.Truchero SD7	P	3	BM	79	65	Yes	7.4	6.6	100	0.038	M-E
	45.Valle de monjas SD8	P	2	BM	89	82	Yes	5.5	7.3	83	0.045	M-E
XI. Apatlaco	46.Apatlaco A1	P	3	BM	111	94	Yes	10.7	6.92	58	0.238	O-M
XII. Río Frío- San Rafael	47.El llano1 RF1	P	4	BM	102	93	Yes	15.6	7.2	34	0.204	O-M
	48.El llano2 RF2	P	4	BM	104	99	Yes	13.05	6.65	62	0.426	O-M
	49.La cabañita RF3	P	5	BM	114	103	No	13.85	6.8	78	1.03	O-M
	50.La planta RF4	P	5	BM	100	62	No	15	7.2	81	0.972	O-M
Magdalena	51.Spring ME7	P	1	BP	96	79	Yes	9.7	5.7	65	0.002	O-M
	52.Cañada de cuervos ME8	I	1	BP	102	91	Yes	11	6.5	72.5	0.004	O-M
	53.Cieneguillas dam ME9	P	1	BP	104	97	Yes	10	6.5	68	0.025	O-M
	54.Magdalena spring	P	1	BE	110	103	Yes	10	6.6	58.9	0.015	O-M
	55. Cieneguillas1 ME10	P	2	BP	104	99	Yes	10	6.8	69.5	0.033	O-M
	56.Presa Cieneguillas2 ME11	P	1	BP	114	102	Yes	10	6.4	72	0.033	O-M
	57.Temascalco ME12	P	1	BP	96	93	Yes	11	6.4	95.5	0.015	O-M
	58.Las Rosita alto ME13	P	1	MB	114	110	Yes	10.1	6.3	129	0.021	O-M
	59.La rosita spring ME14	P	1	BE	102	90	Yes	10.4	6.8	113	0.003	O-M
	60. Ermita spring ME15	I	1	MB	114	92	Yes	10.8	6.9	118	0.007	O-M
	61.San José spring ME16	P	1	BP	96	92	Yes	11	6.5	97.5	0.019	O-M
	62.La Bodega spring ME17	P	1	BE	92	72	Yes	12	5.9	68.5	0.001	O-M
	63.Potrero spring ME18	P	1	BP	98	78	Yes	10.8	6.1	78.5	0.013	O-M

P: perennial; I: intermitent; MF: mixed forest; PA: primary activity; PF: *Pinus-Abies* forest; Pa: grassland; UZ: urban zone; HQ: hydromorphological quality; TL: trophic level.
[1]Hydromorphological quality (CERA; Encalada et al. 2001): very good (>100), good (76-99), moderate (51-75), bad (26-50), poor (< 25).
[2]Hydromorphological quality (HYQI): high (120-100), good (76-99), moderate (51-75), bad (26-50), poor (< 25).
[3]Trophic level: O: oligotrophic; M: mesotrophic; E: eutrophic (SSA 1996).

TABLE III. LENGTH OF THE SUB-BASIN AND ITS PROPORTION INSIDE OR OUTSIDE PROTECTED AREAS OF THE BASIN OF MEXICO.

Sub-basin/river	Total river longitude (km)	Channelized segment (km)			Natural segment (km)		
		Out of protected area	Under protected area	Total	Under protected area	Out of protected area	Total
Ameca-Canal Nacional	51.1	29.9	2.0	32	4.8	14.1	19
Coatlaco	25.1	21.3	—	21.3	—	3.8	3.8
Coaxcacoaco	37.5	1.8	16.6	18.4	—	—	19
Cuautitlán	64.2	28.9	41.9	70.8	—	—	—
La Colmena	27.1	22.7	4.4	27.1	—	—	—
Las Regaderas	10.6	0.64	10.0	10.6	—	—	—
La Magdalena	21.7	—	13.3	13.3	—	8.4	8.4
Eslava	8.7	—	5.4	5.4	—	3.3	3.3
San Ildefonso	8.4	1.8	6.7	8.4	—	—	—
San Rafael-Tlalmanalco	53.4	7.4	12.0	19.5	—	33.8	33.8
Santo Desierto-Mixcoac	34.2	—	7.9	7.9	4.3	21.9	26.2
Apatlaco	27.2	23.3	3.8	27.2	—	—	—
Río Frío-San Rafael	15.9	12.1	3.7	15.9	—	—	—
TOTAL	391.3	150.4	127.8	277.8	9.2	85.6	113.5

with physical alteration of the channel structure, damming and extraction of the riverbed and springs, and deforestation. However, the decrease in richness was also naturally linked to the altitude of 3400 m. Four vegetation types were recorded, composed mainly of *Abies religiosa*, *Prunus persica*, *Pinus teocote*, *Quercus laurina,* and *Cupressus lindleyi*. Due to its elevation, the *Abies* forest can be differentiated at an altitude range of 3000 to 3500 masl (sharp slopes), the mixed forest at an altitude of 2500 to 3000 masl (mountain foothills, erosive valleys, and slopes), and the *Pinus* forest at an altitude range of 3500 to 3800 masl (slightly inclined slopes). These types of temperate forests are important and representative of Mexico (Ávila-Akerberg 2010). The type of vegetation defines the reference conditions, and the disturbances that decrease the ecological quality in the CERA and QBR indices differed by 50 % and were not representative of all the drivers of change present in the study area.

The Basin of Mexico Hydromorphological Quality Assessment Index (HYQI)

The index was divided into three sections, and each section added 40 points, so the index accumulated 120 points (**Table I**; also see **Table SI** in the supplementary material). The three evaluation sections are as follows: (*i*) basin quality, which evaluates the state of the riparian zone, including the quality of the vegetation, its level of erosion, and land use; (*ii*) hydrology, which evaluates the natural conditions of the river and the alterations that exist in the natural flow of water in the channel, and (*iii*) anthropogenic alterations, which evaluates the human activities that take place in the riparian zone and reduce the ecological quality. The basin quality section evaluates the native plant cover in percentage, for which a guide to plant species was developed as an appendix to the HYQI. Forests of *Abies religiosa*, *Pinus hartwegii* and *Quercus* spp. grow in the upper areas of the watershed, with mixed forests in the middle and lower areas. Each vegetation type has a subdivision of native and introduced species and their way of life.

The HYQI evaluation showed 44 sites with an optimal rating (120 to 100 points) where potential reference conditions for the Mexico Basin can be recognized. The remaining 19 sites were rated as having medium to poor quality conditions. The hydromorphological quality generally decreases with altitude, urbanization, and silvopastoral activity. The vegetation cover was represented by 70 % of native species (or more) in the reference sites. The riparian vegetation was modified in general by the invasion of irregular human settlements that alter and destroy the river's bank through the following activities: (*i*) opening of trails for tourism or cattle, (*ii*) construction of bridges, (*iii*) channeling of the river through canals or tubes that carry water for on-site activities, (*iv*) reforestation with exotic plants, and (*v*) accumulation of organic and inorganic waste.

The evaluated sites were grouped into two sets by hierarchical agglomerative clustering, the first one including those that registered the potential reference conditions (**Figs. 2** and **3**), and the second one

TABLE IV. FLORISTIC RICHNESS AND LIFE FORM IN THE RIPARIAN ECOSYSTEM OF THE BASIN OF MEXICO.

Species	Life form
Pinus forest (3420-3800 masl)	
Native species	
Alchemilla vulcanica Schldtl. and Cham.	Perennial grass
Cestrum nocturnum L.	Tree
Conyza sophiifolia Kunth.	Annual grass
Cyperus seslerioides Kunth.	Perennial grass
Drymaria leptophylla (Cham. and Schltdl.) Fenzl ex Rohrb.	Annual grass
Epilobium ciliatum Raf.	Perennial grass
Equisetum hyemale L.	Perennial grass
Erigeron pubescens Kunth.	Perennial grass
Eryngium carlinae F. Delaroche.	Perennial grass
Eupatorium sp. L.	Perennial grass
*Gamochaeta americana (*Mill.) Wedd.	Annual grass
*Lobelia cardinalis (*L.) Batsch.	Perennial grass
Lopçezia racemosa Cav.	Annual grass
*Malvastrum coromandelianum (*L.) Garcke.	Annual grass
*Melampodium divaricatum (*Rich.) DC.	Annual grass
Oenothera pubescens Willd. ex Spreng.	Perennial grass
Pinus hartwegii Lindl.	Tree
Ranunculus peciolares Humb., Bonpl. and Kunth ex DC.	Annual grass
Salvia mexicana L.	Annual grass
Solanum nigrescens M. Martens and Galeotti.	Grass
Stevia jorullensis Kunth.	Annual grass
Verbena teucriifolia M. Martens and Galeotti.	Annual grass
Veronica peregrina subsp. *xalapensis* (Kunth) Pennell.	Annual grass
Introduced species	
Plantago major L.	Annual grass
Poa annua L.	Annual grass
Reseda luteola L.	Annual grass
Taraxacum officinale F.H. Wigg.	Perennial grass
Abies forest (2750-3500 masl)	
Native species	
*Abies religiosa (*Kunth) Schltdl. and Cham.	Tree
Acaena elongata L.	Grass
Alchemilla pectinata Kant.	Perennial grass
*Alchemilla pringlei (*Rydb.) Fedde	Perennial grass
Alnus jorullensis Kunth	Tree
*Ageratina glabrata (*Kunth) R.M. King and H. Rob.	Bush
*Ageratina mairetiana (*DC.) R.M. King and H. Rob.	Bush
Ageratum corymbosum Zuccagni.	Grass
Arctostaphylos pungens Kunth.	Bush
Arenaria bourgaei Hemsl.	Perennial grass
Bidens pilosa L.	Annual grass
Geranium seemannii Peyr.	Perennial grass
Salix paradoxa Kunth.	Tree
Sigesbeckia jorullensis Kunth.	Perennial grass
Introduced species	
Achillea millefolium L.	Perennial grass
Chenopodium murale L.	Annual grass
Sambucus nigra L.	Tree

TABLE IV. FLORISTIC RICHNESS AND LIFE FORM IN THE RIPARIAN ECOSYSTEM OF THE BASIN OF MEXICO.

Species	Life form
Mixed forest-*Quercus* (2620-3370 masl)	
Native species	
Adiantum braunii Mett. ex Kuhn.	Perennial grass
Alchemilla procumbens Rose.	Perennial grass
Alnus acuminata Kunth subsp. *glabrata* (Fernald) Furlow.	Tree
Arachniodes denticulata (Sw.) Ching.	Perennial grass
Arbutus xalapensis Kunth	Tree
Argemone ochroleuca Sweet.	Annual grass
*Arracacia aegopodioides (*Kunth) J.M. Coult. and Rose.	Annual grass
Asplenium formosum Willd.	Grass
Baccharis conferta Kunth.	Bush
Baccharis salicifolia (Ruíz Pav.) Pers.	Bush
Baccharis sordescens DC.	Bush
Begonia gracilis Kunth.	Grass
*Bidens aurea (*Ait.) Sherff.	Perennial grass
*Brachypodium mexicanum (*Roem. and Schult.) Link.	Perennial grass
Bromus dolichocarpus Wagnon.	Perennial grass
Bromus carinatus Hook. and Arn.	Perennial grass
Erigeron longipes DC.	Perennial grass
Montanoa tomentosa Cerv.	Bush
Oxalis corniculata L.	Perennial grass
Oxalis latifolia Kunth.	Grass
*Phacelia platycarpa (*Cav.) Spreng.	Perennial grass
*Pseudognaphalium semiamplexicaule (*DC.) Anderb.	Perennial grass
Quercus spp	Tree
Salvia gesneriflora Lindl. and Paxton.	Bush
Sicyos microphyllus Kunth.	Annual grass
Solanum americanum Mill.	Annual grass
Solanum corymbosum Jacq.	Perennial grass
*Tridax trilobata (*Cav.) Hemsl.	Annual grass
*Tripogon spicatus (*Nees) Ekman.	Perennial grass
Urtica dioica L.	Perennial grass
Verbena gracilis Desf.	Perennial grass
Introduced species	
Adiantum andicola Liebm.	Perennial grass
*Conyza bonariensis (*L.) Cronquist.	Annual grass
Eleusine indica (L.) Gaertn.	Annual grass
*Erodium cicutarium (*L.) L'Hér. ex Aiton.	Annual grass
Eruca sativa Mill.	Annual grass
*Melinis repens (*Willd.) Zizka.	Perennial grass
Mentha sp. L.	Perennial grass
Prunella vulgaris L.	Perennial grass
Rumex acetosella L.	Perennial grass
Rumex obtusifolius L.	Perennial grass

encompassing those where channeling of the river, presence of crops, lack of vegetation cover in the riparian zone, and a high percentage of introduced species were recorded. In addition, an increase in the concentration of phosphorus and nitrogen dissolved in the water was recorded, making it unfit for human consumption (SSA 1996). Concerning the evaluation of springs, specific characteristics of human disturbance related to the creation of dams, installation of water extraction pipes, deforestation, and

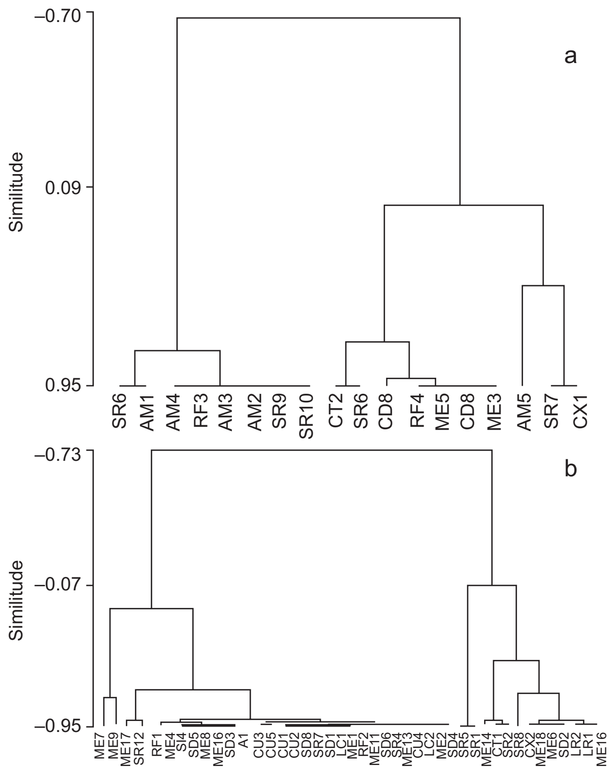

Fig. 2. Hierarchical agglomerative cluster recognizing two clusters of sites: (a) over 2800 masl, and (b) under 2800, based on the hydromorphological quality index, dissolved inorganic nitrogen, and soluble reactive phosphorus data. (AM1: La Castañeda, AM2: La Castañeda II, AM3: La Castañeda III, AM4: La Castañeda IV, AM5: La Castañeda V, CT1: Rancho Nuevo I, CT2: Rancho Nuevo II, CX1: Miraflores, CX2: Santa Catarina, CU1: Los Organillos, CU2: Capoxi spring, CU3: San Pedro spring, CU4: Presa Iturbide spring, CU5: Capoxi, LC1: La Caldera, LC2: Xopachi, LR1: Monte Alegre 1, LR2: Monte Alegre 2, ME1: Chautitle, ME2: Chautitle waterfall, ME3: Confluencia, ME4: Eslava spring, ME5: Santa Teresa, ME6: Truchero, SI1: Las Palomas, SI2: Truchero 2, SR1: Agua Dulce, SR2: San Rafael channel, SR3: Compañía 1, SR4: Compañía 2, SR5: Cosamala 1, SR6: Cosamala 2, SR7: UAM station, SR7: San Rafael channel 1, SR8: San Rafael, SR9: San Rafael channel 2, SR10: San Rafael path, SD1: Arroyo Desierto, SD2: Convento, SD3: La Capilla Santa Rosa, SD4: Santa Rosa 1, SD5: Santa Rosa spring, SD6: Santa Rosa 2, SD7: Truchero, SD8: Valle de Monjas, A1: Apatlaco, RF1: El Llano 1, RF2: El Llano 2, RF3: La Cabañita, RF4: La Planta, ME7: Cañada de Cuervos spring, ME8: Cañada de Cuervos, ME9: Cieneguillas dam, ME10: Cieneguillas 1, ME11: Cieneguillas 2, ME12: Temascalco, ME13: La Rosita Alto, ME14: La Rosita spring, ME15: Ermita spring, ME16: San José spring, ME17: La Bodega spring, ME18: Potrero spring.)

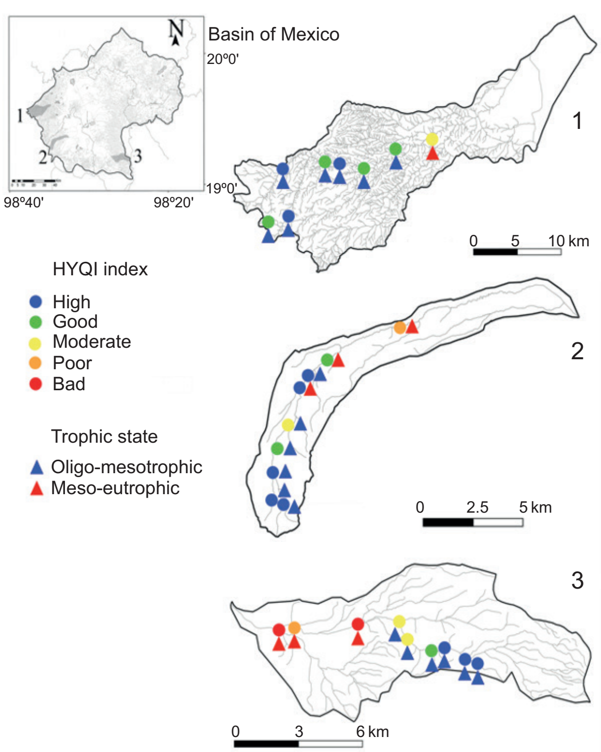

Fig. 3. Physical and chemical quality, and hydromorphological quality index (HYQI) validation score in (a) Cuautitlán, (b) Santo Desierto-Mixcoac, and (c) San Rafael-Tlalmanalco sub-basins of the Basin of Mexico.

the presence of fecal organic matter from sheep and cows were detected.

HYQI validation

In general, the hydromorphological quality was consistent with the trophic status (**Table V**). Headwaters presented good and high qualifications, while an evident decrease in the value of hydromorphological quality was related to the lowland sites. The HYQI value was found to be significantly correlated with nutrient enrichments with DIN and SRP. Modifications in the canal structure and the extraction and retention of water in the rivers were the causes that confirmed the moderate HQ value in the middle and lower portions of the three sub-basins.

DISCUSSION

Within the Basin of Mexico, factors such as topography, high altitude, slope orientation, slope, and soil units are conducive to the development of a wide range of environments and a diverse plant community. The physicochemical, hydromorphological, and biological data analyzed in this study showed that, in general, the upper basin areas of the rivers

TABLE V. PHYSICAL, CHEMICAL, AND HYDROMORPHOLOGICAL CHARACTERISTICS, AS WELL AS HYQI VALUES OF VALIDATION SAMPLING SITES IN THE BASIN OF MEXICO.

Sub-basins and sites	Altitude (masl)	K_{25} (µS/cm)	DO (%)	SRP (mg/L)	DIN (mg/L)	HYQI
1. San Rafael-Tlalmanalco						
Diamantes waterfall	3266	174	8.1	0.45	0.05	120
Negro waterfall	3094	161	8.4	0.31	0.04	120
Vereda	2956	151	8.1	0.31	0.04	102
Canal	2915	142	7.9	0.38	0.04	95
Agua Dulce	2788	151	8.2	0.33	0.09	63
Dos Aguas	2676	123	7.7	0.34	0.12	55
San Rafael	2525	261	5.8	2.58	21.52	18
UAM	2429	415	3.0	3.24	15.4	37
Tlalmanalco	2400	677	2.7	2.52	52.06	24
2. Cuautitlán						
Spring*	3379	39	7.6	0.15	0.13	111*
Iturbide spring*	3317	60	7.7	0.14	0.23	72
Iturbide	3205	59	8.4	0.13	0.16	104
El Paraíso	2703	51	8.0	0.36	0.21	120
El Polvorín	2612	70	7.2	0.21	0.21	76
Cantera	2578	72	7.5	0.15	0.38	65
Transfiguración	2515	70	7.6	0.29	0.23	92
Yondese	2396	113	7.6	0.42	0.32	85
Nicolás Romero	2333	175	6.8	1.75	1.94	53
3. Santo Desierto						
San Miguel	3310	57	7.7	0.26	0.06	117
Conejos	3314	72	7.4	0.13	0.11	111
Confluencia Alta	3123	75	7.5	0.17	0.15	108
Camino	2840	82	8.2	0.14	0.42	93
Convento	2907	115	5.7	0.36	0.29	66
Escuela	2702	110	7.79	0.14	0.24	102
Truchero	2734	130	7.8	0.08	0.24	91
Cancha	2719	369	5.7	2.48	2.12	46
Guadalupe Victoria	2491	347	1.6	2.49	30.04	37

K_{25}: specific conductivity; DO: dissolved oxygen; SRP: soluble reactive phosphorus; DIN: dissolved inorganic nitrogen.

maintain a good ecological quality status, partly due to the declarations of protection under the denomination of Conservation Soil or Protected Natural Area, which prevents the massive establishment of human activities within each sub-basin and the excessive extraction of water for urban areas. However, the existence of springs and rivers exposed to different transformations, mainly due to water extraction, agricultural activities, and urbanization, was recorded. It is important to identify the volumes of water that circulate in each sub-basin, and maybe a policy of maximum volume extraction by hoses can be established, especially in springs and first-order rivers in the upper portions of the basin, where the discharge is minimal. The 391.3-km total length of the studied rivers suggests an important contribution of water for environmental conservation and its potential human use in the basin. Of these, 71% are channeled for their historical or current use. However, the lack of supervision and resource management strategies prevents reliable data on the quantity and quality of available water. Among the most frequent disturbances are gabion dams and hydraulic diversions through hoses of different materials and thicknesses. These disturbances are widely scattered throughout the basin and there are no studies on their real impact on biological communities and the consequences on the functioning of aquatic ecosystems. These alterations are frequent and are not limited to a particular section of the basin; they can be found in the upper basin which, in theory, should be the best preserved and exempt from this infrastructure. The flow rate and precipitation in the Magdalena River sub-basin have shown a slight increase in the flow trend and a decrease in precipitation amount in the last 20 years (Caro-Borrero et al. 2017). This may result from a higher runoff caused by the presence of non-porous material, a sign of urban expansion in the conservation soil. Therefore, sub-superficial and deep-water infiltration may be compromised, affecting the perennial character of the system (Caro-Borrero et al. 2017).

The deterioration in the middle section of the Basin of Mexico responds to activities with a greater impact in terms of pollution since there are urban or garbage discharges directly related to the contributions of nutrients, detergents, insecticides, and waste from agricultural activity. According to the Official Mexican Standard NOM-127-SSA1-1994 (SSA 1996), the nutrient concentrations in the rivers and springs were within the maximum permissible limits for dissolved inorganic nitrogen and soluble reactive phosphorus in terms of water for human consumption. However, according to Dodds (2003), the sections of the rivers within the middle basin are oligo-mesotrophic, and in the lower basin area, they are meso-eutrophic. This shows a lack of standardization in the concentration levels allowed according to international parameters.

The characterization of the hydromorphological quality had some drawbacks that are frequent in Mexico and, in general, in Latin America. Government mapping information is incomplete, and/or no updates are available. In the in-situ validation of land use, there was no consistency with the presence of agricultural, livestock, trout farms, human settlements, and commercial areas present in the riparian zone. This reflects the rapid and uncontrolled advance of economic activities within forest areas and the most worrying within areas with some conservation status. Regarding the type of vegetation, it was represented in a general way by the main types of forest that make up the basin: *Pinus*, *Abies*, and mixed, with the dominance of *Quercus* spp. (Espinosa and Sarukhán 1997; Rzedowski and Calderón 2005, Ávila-Akerberg 2010). However, hydromorphological evaluation indices require spatial and temporal recognition of the richness and diversity of the vegetation associated with the riverbank (Munné et al. 2003, Barbour et al. 1999, Encalada et al. 2011). This vegetation is not represented in the cartography due to the low-resolution spatial scale available (1:50 000), and this lack of specificity could lead to a lack of knowledge of the endangered plant diversity, which has potentially been lost given the reported activities.

The hydrological condition of permanence of the rivers is undervalued in the hydrological chart of the INEGI (2013) since only five of the 13 sub-basins studied are registered as perennial. The representation of infrastructure such as embankments, gabion dams, piping, and channeling of rivers is not indicated and much less updated. Some of these channels are even evident in the urban area of Mexico City, where water currents are indicated in the hydrological chart with natural flow or without artificial modifications. This point is important because many current public policies with a socio-environmental focus, such as the temporary employment program, finance the construction of infrastructure, such as small dams within the riverbeds, without taking into account the works of previous interventions. In this sense, the information available from INEGI (2013) does not record or update the changes that the naturalness of rivers and land use in the Basin of Mexico. The advance of the urban sprawl within the conservation soil of Mexico City in recent years is a main factor in the decline of the water capacity to recharge the aquifers, and it increases the risk of converting the basin into a potential input of contaminants to the aquifer (Cram et al. 2008).

On the other hand, architectural remnants were found that date back to the 19th century and recall the operation of an active and prosperous textile and wood industry within the basin. Especially, diversion channels and electricity-generating turbines (dynamos) were found in the sub-basin of the San Rafael-Tlalmanalco, Magdalena-Eslava, and San Rafael-Río Frío rivers (Caro-Borrero et al. 2015). This may indicate that despite a historical hydraulic intervention, the structural and functional components of the aquatic ecosystem can be partially recovered (Carmona-Jiménez and Caro-Borrero 2016).

All the points previously exposed denote the government's outdatedness with respect to environmental data. It implies that an additional effort for the selection of potential sampling sites has to be made, since every time that monitoring is needed, it is necessary to go to the field without the certainty that the sites have conditions of little anthropogenic disturbance (Bordallo and Casado 2011). The land use and hydrological charts work as a general reference but are not punctual for the location of potentially natural areas. Based on the results of the in-situ validation, we propose that potential reference sites should be selected in accordance with the altitudinal gradient, the zoning of protected areas, and the evaluation of the reference hydromorphological conditions, and not only based on the government cartographic information.

Rivers and springs are influenced by different biotic and abiotic factors, as observed in the Basin of Mexico, where all surface waters are subject to human activity at the local or regional level, causing pressure on the entire ecosystem. For example, if the rivers/springs can have a good physical-chemical quality and a degraded physical structure, the result will be a habitat that is not suitable for benthic community development (Río and Bailey 2006, Ollero et al. 2007, Garófano-Gómez et al. 2011, Villamarín et al. 2014).

The foregoing shows that government urban planning has not considered the maintenance of natural areas and ecological flow as a source of ecosystem services for the Basin of Mexico. These services include the provision of water, carbon capture and storage, climate regulation, buffering against floods and droughts, and the possibility of developing productive activities such as agriculture, livestock, recreation, and tourism. In the last 50 years, with the accelerated urbanization of Mexico City, a great extension of the forested area has been lost in order to solve the social pressures of housing and mobility. Although the Basin of Mexico has areas with steep slopes > 20º, which are considered natural barriers, they are no longer an obstacle to human settlement. The Sierra de Guadalupe to the north of the basin; the Sierra de Santa Catarina, Ajusco, and Chichinautzin to the south; Lake Texcoco, to the east, and the mountainous area of the Sierra de Las Cruces and Monte Alto, are examples of this phenomenon of urbanization, (Gutiérrez and González 2010). Many of these areas have irregular settlements that greatly reduce the possibility for soils to allow aquifers to regenerate and maintain their own riparian vegetation (Cram et al. 2008).

CONCLUSIONS

According to the hydromorphological quality protocol proposed for the Basin of Mexico, conditions of high and good quality were recognized, related to the protected natural area of the headwaters of the basin where the rivers originate. However, these conditions are not always present due to human interventions related to the extraction of water from springs and rivers, destruction of riparian vegetation, and alteration of the riverbed. Hydromorphological quality should be associated with water quality in the official Mexican protocols that protect the health of the riparian ecosystem, as in other legislations in the world. The evaluation and validation should be based on an updated census of the springs and rivers of the Basin of Mexico.

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SUPPLEMENTARY MATERIAL

TABLE SI. HYDROMORPHOLOGICAL QUALITY INDEX (HYQI) ASSESSMENT PROTOCOL OF THE BASIN OF MEXICO RIVERS AND SPRINGS.

Sub-basin		Station	
North Latitude		Date	Time
West Longitude		Altitude	
Collector name(s)			
	WATER QUALITY ASSESSMENT		
Physical	Water temperature (°C) pH Specific conductivity (µS/cm) Dissolved oxygen (mg/L) Oxygen saturation (%) Discharge (*Q*)= Σ *A.V* (m^3 /s) A=partial area each 0.2m; V= partial current velocity each 0.2m A_1 riverbank= $depth_1$*0.2m/2 A*n* river column=$depth_1$*$depth_2$*0.2/2 Orthophosphate (mg/L) Nitrite (mg/L) Nitrate (mg/L) Ammonium (mg/L) Dissolved Inorganic Nitrogen (mg/L)		
Inorganic substrate size (%)	Roks (up to 256 mm) Pebble (64-256 mm) Loose stone (2-64 mm) Sand (0.06-2 mm) Clay (0.004 mm)		
Riparian cover	Forest type	Dominant life form	
	Abies Pinnus Mixed	tree shrub grass herb	

I. SURROUND QUALITY AREA

Parameter	Optimal	Medium	Bad	Poor
Riparian cover (Native)	> 70% of native ripiaran cover	69-50% of native riparian cover	49-30% of native riparian cover.	< 29% of the bank covered with riparian vegetation
Right bank (Score)	5	3.5	2	0
Left bank (Score)	5	3.5	2	0
2. Bank stability	Stable bank, little or minimal evidence of erosion (<10%) or exposed substrate	Moderate stable bank, small areas of erosion (10-50%)	Moderate unstable bank, with areas of erosion, high erosion potential during floods (50-80%).	Unstable bank, many eroded areas and “raw” areas (> 80%)
Score	10	7	4	0
3. Pool substrate characterization and conditions	Mixture of loose stone, gravel, sand and rooted aquatic plants. <20% of disturbed substrate	Mixture of soft sand, clay or mud, some root mats and submerged vegetation. 20-40% of disturbed substrate.	Clay at the surface, no submerged roots, no aquatic. 41-80% of disturbed substrate.	Hard-pan clay or bedrock, no root mat or submerged vegetation. > 80% of disturbed substrate.
Score	10	7	4	0
4. Riparian zone with presence of agriculture, livestock	Absence of farming or zones for livestock, absence of branches for agriculture and livestock use.	<20% of the riparian zone used for agriculture and livestock.	21-60% of the riparian zone is used for agriculture and livestock use.	> 60% of the riparian zone is used for agriculture and livestock. Presence of branches for household and industry use
Right bank (Score)	5	3.5	2	0
Left bank (Score)	5	3.5	2	0

II. HYDROLOGY

5. Dam Present	Absence of a dam upstream	Presence of a dam made from material that lets 50% of water flow through	Presence of a dam made from material that lets 20% of water flow through.	Presence of a dam made from material that does not let water flow through
Score	10	7	4	0
6. Velocity/ estimated stream depth (m) (Only for Rivers)	All four velocity regimes: slow-deep, slow-shallow, fast-deep and fast-shallow	3 of the 4 regimes presents	2 of the 4 regimes presents	1 of the 4 regimes present (usually slow-deep)
Score	10	7	4	1
7. Channel Alteration	Channelization or water extraction pipes absent (included traditional channelization)	Evidence of past or recent channelization or water extraction pipes in >40% of the stream	41-60% of the stream channelized or water extraction pipes,	Banks shored water extraction pipes, gabion or cement. >60% of the stream is channelized
Score	10	7		0

III. ALTERATIONS CAUSED BY HUMAN ACTIVITIES

8. Presence of effluents from household use	Absence		Presence	
Score	10		0	
9. Urban development	Absence of settlements, roads or roadbeds	20% of the riparian zone with the presence of roadbeds or settlements	50% of the riparian zone with infrastructure (i.e., houses or roads)	>60% of the riparian zone with infrastructure (i.e., houses or roads)
Score	10	7	4	0
10. Human activities	Absence of human activities	Presence of at least one human activity (i.e., agriculture, livestock or fish farming)	Presence of at least 3 human activities (i.e., agriculture, livestock, fish farming, houses or shops)	Presence of several human activities (i.e., agriculture, livestock, fish farming, houses or shops)
Score	10	7	4	0

11. Presence of organic contamination, garbage and debris.	<10% organic or inorganic garbage in the riparian zone	20-40% with organic or inorganic garbage in the riparian zone	50- 80% with organic or inorganic garbage in the riparian zone	>80% with organic or inorganic garbage in the riparian zone
	10	7	4	0
12. Water body protection (only springs)	Presence of bars or fences that limit access to the body water (restricted area)	Presence of bars or fences protection (free access)	Partial presence of bars or fences (free access)	Absence of protection
Score	10	7	4	0
TOTAL SCORE				

Hydromorphological quality index interpretation	Score
High	> 100
Good	76-99
Moderate	51-75
Bad	26-50
Poor	< 25