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Hydrologic ecosystem services: water quality and quantity in the Magdalena River, Mexico City

Servicios ecosistémicos hidrológicos: calidad y cantidad del agua en el río Magdalena, Ciudad de México

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ABSTRACT

The increasing urbanization in big cities, that jeopardizes the ecosystems, makes it important to protect them as well as to recognize and manage the services they provide. In order to have the required scientific evidence to support conservation projects, an assessment of water quality and quantity seen as hydrological ecosystem services in the Magdalena River watershed, was carried out. Water quality was assessed in two annual cycles based on physicochemical, chemical, bacteriological and algal indicators, showing an abrupt change between the natural and urbanized areas. This has the potential to affect negatively the recreational activities practised in the area. The relevance of the indicators for water quality is that they show different aspects of the problem: physical and chemical parameters indicate variations across sites along the Magdalena River and point the places where domestic discharges occur. Algae reveal the natural conditions of the habitat and the risks to public health can be assessed with bacteriological indicators. To calculate the water quantity, balances were made in order to know the amount of water that runoff in the three dominant plant communities: the fir forest that generates 10,944,800 m^3 of water per year, the pine forest generates 6,878,000 m^3 and the mixed and oak forest generates 3,217,500 m^3. It is important to preserve the hydrological ecosystem services conserving the forests and rehabilitating the Magdalena River in order to enhance the provision of drinking water to the southern part of Mexico City.

Key words: Water balance, ecosystem management, physico-chemical and biological indicators.

RESUMEN

El crecimiento urbano en las grandes ciudades ha puesto en riesgo a los ecosistemas, por lo que es fundamental protegerlos así como reconocer y manejar los servicios que proporcionan. Con el objetivo de contar con la evidencia científica requerida para sustentar los proyectos de conservación, se llevó a cabo la evaluación de la calidad y cantidad de agua en la cuenca del río Magdalena, D.F., vistos como servicios ecosistémicos hidrológicos. La calidad se evaluó en dos ciclos anuales basada en indicadores fisicoquímicos, algales y bacteriológicos, mostrando que ésta cambia drásticamente en la transición entre la zona natural y la urbana, lo que podría generar consecuencias negativas para las actividades recreativas que se practican en la zona. La relevancia de estos indicadores radica en que muestran distintas perspectivas del problema: Los parámetros fisicoquímicos señalan variaciones entre los sitios y las áreas de descargas domésticas. Las algas revelan las condiciones naturales de hábitat y las bacterias muestran el riesgo para la salud pública. Para calcular la cantidad de agua se realizaron balances hídricos y se determinó el escurrimiento que generan las tres comunidades vegetales dominantes: El bosque de oyamel genera 10,944,800 m^3 de agua al año; el bosque de pino 6,878,000 m^3; y el bosque mixto 3,217,500 m^3. Para mantener la provisión de agua en el suroeste de la ciudad de México, es fundamental conservar los servicios ecosistémicos hidrológicos, través del manejo adecuado de los bosques de la cuenca del río Magdalena.

Palabras clave: Balance hídrico, manejo de ecosistemas, indicadores fisicoquímicos y biológicos.

INTRODUCTION

Ecosystem service (ES) is defined as a good and/or service that human populations obtain from ecosystems, i.e. from ecosystem functions including habitat, biological or system properties or ecosystem processes (Costanza *et al.*, 1997; MEA, 2003). There are other authors with similar definitions that include human welfare and name the ecosystems as the main providers of such services (Postel & Carpenter, 1997; De Groot *et al.*, 2002; Kremen, 2005; Quétier *et al.* 2007; Boyd & Banzaf, 2007; Dale & Polasky, 2007). This work is based on Millenium Ecosystem Assessment definition (2003) because is simple and widely used.

ES's are classified according to the way human needs are satisfied, such as provision, regulation, culture and support. Water supply is defined as a provision ES and includes extractive uses (domestic, agricultural, commercial) and non-extractive uses (hydroelectricity, recreation, transport); meanwhile water quality can be defined as a regulation ES.

As a result of population growth, industrialization and the increasing need for food, in addition to an increase of irrigation for agriculture, the demand for hydrological ES's has drastically increased. This happened in certain areas of the world, such as Latin America.

In 2008, for the first time in human history, urban population matched the rural population of the world. From now on the majority of the population will be living in urban areas (Uitto & Biswas, 2000; UNFPA 2007). The growth of cities is considered to be the largest influence on development in the 21st century. To protect the ecosystems and adequately manage ESs in the present and in the future, urban expansion requires to plan the use of natural resources in advance (UNPF, 2007).

Among the ecosystems that are most affected by human activities are those surrounding mega cities, defined as urban conglomerates that have reached 8 million inhabitants (Aguilar, 2004; Chen & Heligman 1999; Fuchs, 1999). In 2007 19 mega cities existed (UN, 2008), accounting for 4% of the world's population, and 9% of all urban inhabitants.

Water quality and availability is a challenge worldwide, especially for cities in developing countries (Brennan *et al.*, 1999; Gleick, 1998, 2004). Inadequate water supply and sanitation is a problem in areas with a high population density, such as megacities (Uitto & Biswas 2000; UNPF, 2007).

The Mexico City Metropolitan Area (after herein referred to as Mexico City) occupies a second place among mega cities, with around 18 million inhabitants (Garza, 2000). Mexico City changed from a self-sufficient urban area to a city that is highly dependent on resource provision. In particular, the amount of required water far exceeds the limits of sustainability (Kumate & Mazari, 1991; Mazari, 1996; Ezcurra *et al.*, 2006). Groundwater extraction started in 1847 and was significantly extended between 1950 and 1960, providing enough water to supply its inhabitants until the mid 1960s (Ramírez-Sama, 1990). Since then, groundwater and surface water has been extracted and pumped from two basins elsewhere: Lerma in the state of Mexico, and Cutzamala in the states of Mexico, Guerrero, and Michoacán. One of the elements that may limit growth and development of Mexico City is the quantity and quality of water that is available.

At present, Mexico City requires 59.96 m^3/s of which, 75% is supplied by groundwater extraction and 25% come from surface water. 14%of this water is imported from the Cutzamala system, and 5.4% is groundwater imported from the Lerma region (Sheinbaum, 2008).

Failing to achieve a water supply of 500-1000 m^3/person/year is interpreted as water scarcity (Falkenmark, 1995). Hence, Mexico City, with a natural mean water availability of 143 m^3/person/year (CONAGUA , 2008), is at a scarcity level taking into account the minimum water needs for basic human activities, and the pressure (155%) on the water resource is considered extreme (WHO *et al.*, 2000). Therefore, the study of hydrological processes in river basins that contribute its water to this urban conglomerate is of national interest and a security issue for the city.

Additional to water quantity, the quality is also compromised. Mazari-Hiriart *et al.* (2005) reported that the groundwater distribution network is susceptible to contamination by microorganisms. There are strong indications that some of these microorganisms are of fecal origin and represent a potential threat to human health, including common diseases such as acute gastroenteritis, urinary tract infections and nosocomial infections.

Water quality has also been affected by the release of ions from clay soils when intensive groundwater extraction has caused subsidence. Domestic, industrial and hospital wastewaters, too, have had detrimental effects, with environmental and health implications being particularly severe when wastewaters are discharged into water courses without previous treatment. A variety of potential sources related to organic contaminants have been described for the Basin of Mexico, associated to the permeability and vulnerability of groundwater systems (Mazari-Hiriart *et al.*, 2006).

Despite the critical situation regarding quality and quantity of water, there are still some places within the Basin of Mexico where ESs are still good and can potentially benefit a significant part of the population (Ezcurra, 2006). The sub-basins of the south-western area of Mexico City, are forested areas that contribute to groundwater recharge and have a rich biological diversity (Facultad de Ciencias-UNAM, 2008; Ávila-Akerberg, 2010). The case study presented in this paper is that of the Magdalena River sub-basin, hereinafter called the Magdalena River watershed (MRW) (Fig. 1). The MRW is among the most important watersheds that provide surface water to Mexico City (Jujnovsky, 2006). In spite of its relevance, the water of this basin has yet not been evaluated from the ES perspective. Moreover, understanding the functioning of the ecosystem would provide the basic knowledge to protect it (Brauman *et al.,* 2007).

The objective of this research was to integrate the information obtained to date of water quality and quantity to characterize the ESs of water provision that are generated by the watershed for the inhabitants in the southwest of Mexico City.

MATERIALS AND METHODS

Study area. The MRW (19° 15′ N, 99° 17′ 30′′ W) is located in the Sierra de las Cruces at the south-western limit of Mexico City, within the Basin of Mexico (Fig. 1); the surface area is around 30 km^2. The climate is temperate sub-humid in the lower part (2400-2800 masl) and semi-cold in the higher part (2800-3850 masl). As altitude increases precipitation too, from 900 to 1,300 mm. The annual mean temperature falls from 15 °C to 9 °C (García 1988; Dobler, 2010). Soils are mainly andosols (Álvarez, 2000), and there is a vegetation cover of 60%. Vegetation consists of oak *(Quercus* sp.*)*, fir (*Abies religiosa* (Kunth) Schleiden *et* Chamisso) and pine forests (*Pinus hartwegii* Lindley) (Rzedowski, 1978; Ávila-Akerberg, 2002; Nava, 2003).

Water quality field methods. Water quality assessment in the MRW was based on physico-chemical and biological indicators, such as diatoms (algal) and bacterial indicators. The Magdalena River crosses a natural area, and then flows through an urban area. Field stations were selected covering both of these areas, distributed in representative sites of the watershed, trying to represent the different environments and input of contaminants to the river.

The data were acquired from two sampling campaigns, with different scopes, therefore the sampling stations change. The first work included two sampling sites in the natural area, and two in the urban area, to evaluate if there was a difference. The second one focused on the natural area, with five stations from the river origin to the area of human influence, taking just one sample in the urban area.

The first campaign (Bojorge-García, 2006) gives a first approximation of the water quality during the cycle 2002-2003. Samples were taken and analyzed every two months during one year. A second campaign was performed during the 2007 annual cycle (Monges, 2009), covering the dry-cold, rainy and dry-temperate stations, representing the main seasonal changes in the area. Samples taken in the natural area corresponded to the sites with *Abies religiosa* and mixed-*Quercus* spp. forests.

Physicochemical determinations. During the first campaign pH, specific conductivity and temperature were measured *in situ* with a Conductronic pHmeter PC18, and dissolved oxygen was measured with an Oxymeter YSI 85.

In the second campaign 500 mL samples were taken for measurements *in situ*, and for subsequent physicochemical analysis. Measurements *in situ* were depth, pH, temperature, electrical conductivity, total dissolved solids and dissolved oxygen, measured with a Sension 156 Multiparameter (Hach, Loveland). Water samples were taken in polypropylene bottles and stored at 4ºC for subsequent biochemical oxygen demand (BOD_5) analysis, following standard techniques (APHA, 1998, 2005). Chemical parameters such as ammonia ($N\text{-}NH_4^+$), nitrates ($N\text{-}NO_3$), total nitrogen (TN), total phosphorus (TP) and total organic carbon (TOC) were measured, following Hach standard techniques (Hach, 2003), using a portable spectrophotometer (Hach DR/2400) and a digestor (Hach DR/200).

Bacteriological determinations and identification. One-liter samples were collected in wide-mouth polypropylene sterile flasks. Samples were transported and stored (4 ºC) according to standard procedures (APHA, 2005). Microbiological samples were processed within 24 h after collection, following standard membrane filtration procedures for enumeration of four bacterial categories: namely total coliform, fecal coliform, and streptococci/enterococci. Membrane filters (0.45 µm cellulose acetate, Millipore MF type HA) were placed on a pad with 2.5 ml of m-Endo broth MF for total coliform, M-FC broth for fecal coliform, and KF *Streptococcus* agar for streptococci and/or enterococci (APHA, 2005). Cultures were incubated at 35 °C for 24 h for total coliform, fecal streptococci and/or enterococci, and at 44.5 °C for 24 h for fecal coliform (APHA, 2005).

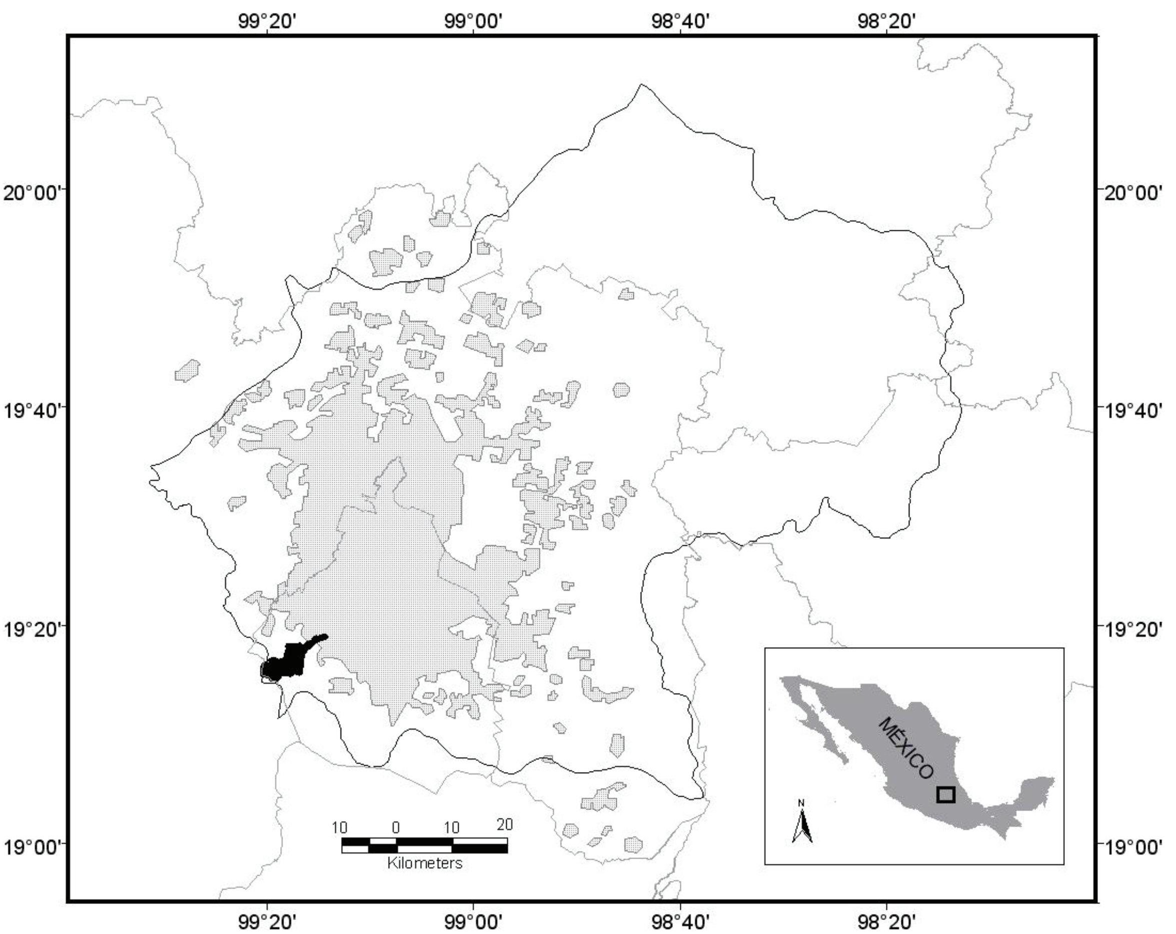

Figure 1. Location of the Magdalena River watershed (black), the Basin of Mexico (white) and the Mexico City Metropolitan Area (grey).

Gram-stain and biochemical tests were used to identify bacteria by a MicroScan, AutoSCAN-4 (Dade International, West Sacramento, CA). Organisms of the Micrococcaceae and Streptococcaceae, which include *Staphylococcus* and *Enterococcus* respectively, were identified, as well as those of the Enterobacteriaceae.

Positive samples from water filtration isolates were selected on the basis of different morphologies, and five colonies of each were placed on sheep blood 10% agar for differential Gram staining, and on McConkey agar for Gram-negative bacteria to differentiate between positive and negative lactose. Then, five colonies were selected for each morphology and were identified by negative COMBO22 micro plate (Dade-Behring, MicroScan). After the micro plate was inoculated with standard bacterial suspension, it was incubated for 18 h at 37 °C; subsequently, Vogues-ProsKauer and TDA indol were developed by addition of specific reagents. The COMBO22 micro plate was read on a MicroScan Auto SCAN-4 (Dade).

Gram-positive were distinguished from Gram-negative bacteria by a catalase test. The bacteria were identified in the Molecular Microbial Immunology Laboratory of UNAM's Faculty of Medicine.

A fecal coliform/fecal streptococci ratio was used to determine the possible origin of fecal contamination (Gerba, 2000; Toranzos *et al.*, 2007).

Diatom determination. Diatoms were collected only in the first campaign, by scraping an area of 100 cm^2 (10 × 10 cm) over the surface of the pebbles (Prygiel, 2005). The material was prepared according to Rushforth *et al*. (1984). Three permanent preparations were performed with Naphrax for the identification and quantification of 400 individuals (Kelly *et al.* 1995). Diversity was calculated by the Shannon-Wiener index using the PRIMER 5 v. 5.2.8 program. Three diatomological indexes were used to evaluate water quality: the pollution sensitivity index (IPS), the diatom biological index (IBD) and the diatom generic index (IGD), all using program OMNIDIA 7 v. 8.1.

Water quantity. Water quantity was defined as the amount of water runoff in the surface layers of soil and groundwater, contributing to the recharge of the river. The water quantity was calculated according to the three environmental units present in the watershed. These units were recognized according to topography and vegetation, in conjunction with geological and physical characteristics of the soil and their respective plant communities

(Jujnoksky, 2006). The highest environmental unit (*Pinus* forest) occupies an area of 943 ha. The relief of this unit is characterized by slopes with inclination less than 30º and the presence of pyroclastic material. It lies at an altitude between 3450-3870 masl. The soils are andosol of the humic and ochric types, with an average of 15-30% organic matter and a pH of 4.1-4.5.The depth is less than 40 cm. The vegetation that characterizes this area is the forest of *Pinus hartwegii.*

The middle environmental unit (*Abies* forest) occupies an area of 1469 ha at an altitude ranging from 3000-3500 m above sea level and corresponds to the middle parts of the watershed. The relief of this unit is characterized by sharp slopes, in most cases more than 45º. The soils are Andosols of humic type, with an average of 15-30% organic matter and a pH of 4.6-5.1. the soil depth is about 50 cm. The vegetation that characterizes this area is the forest of *Abies religiosa* (Nava, 2003).

The lowest environmental unit (mixed and oak forest) occupies an area of 482 ha. It distributes at altitudes between 2500-3000 masl and it is the lowest part of the watershed. It consists of foothills, erosive valleys and gentle slopes, with a lower inclination in the northeast (0-15°) and steeper (15-30°) in the SW. This area of the basin is characterized by being located in the area of human influence (Jujnovsky, 2003). The predominant soils are humic Andosols mixed with Lithosols with a low pH of 5.2-6.1 and a high amount of organic matter between 4-8%. The depth of these soils is around 40 cm. The dominant vegetation is mixed and oak forests.

Water quantity was calculated from the water balance estimated by the Thornthwaite-Mather method (Dunne & Leopold, 1978);

$$WB = P - Et - RO - \Delta SM$$

Where:

WB = water balance

P = precipitation

Et = evapotranspiration

RO = runoff

ΔSM = change in soil moisture

Were used data from 13 meteorological stations close to the study area (Table1; Fig. 2, for the years 1921-2007). We used this model because it is the simplest and most widely used, and most practical for the amount of information available. The data obtained from the water balance were correlated with the environmental units by weighting by the area. With the water balance data we estimated the amount of water runoff in the watershed and its availability for each environmental unit.

RESULTS

Water quality. According to the evaluated physicochemical and biological indicators, in the first campaign (Table 2) water quality in the Magdalena River diminishes as it enters the area with human influence. The FC/FE ratio (fecal coliforms to fecal enterococci) indicates contamination of predominantly animal origin in site I, a mixture of animal and human contamination in site II, and mainly contamination of human origin in sites III and IV. There is an inverse relationship between diatom species richness and bacterial abundance measured as colony forming units and nutrients (Fig. 3).

For the second campaign (Table 3, Fig. 4), the same pattern was observed for the physicochemical parameters. Ammonia and bacterial counts presents a gradual increase from the natural to the urban area. Bacteria drastically changes due to human discharges in the urban area, which is rapidly growing and presents wastewater discharges, fact that can be observed in both campaigns in stations III, IV and X.

Values were highest in the lower section of the river (sites VIII and IX), and in the urban zone (X), where water quality has been adversely affected by the presence of food stalls, trout ponds, domestic fauna, and increased numbers of visitors (VIII and IX). Site X is also subjected to a direct influx of wastewaters from irregular settlements, as well as the dumping of solid wastes on the banks and surroundings of the river.

The bacteria are shown in a similar way to that used for the algae. As the river enters the urban area, there is a decrease in diatom species richness, and an increase in the number of species tolerant of contamination, such as *Nitzschia palea*. The diatomological indices (IPS, IBD and IGD) showed oligotrophic (low level of nutrients) waters in site I, mesotrophic (medium level of nutrients) in site II, and eutrophic (high level of nutrients) in sites III and IV. The behavior of the bacterial indicators was the reverse of that of the algal indicators.

The bacteriological counts were similar during the two cycles studied for the stations in the natural area. In the urban area there was a variation in bacterial density.

In the Magdalena River, site V showed predominantly animal fecal contamination, while in sites VI and VII it seemed to be a mixture of animal and human contamination, and in sites IX and X predominantly human. This corresponds to the general degradation of water quality in terms of physicochemical parameters and bacterial coliforms, and the increasing human influence towards the urban sector of the Magdalena River.

Water quantity. Water balance calculations for *Pinus hartwegii* forest, where rainfall can reach 1175 mm/year, showed an annual runoff of 742 mm (without considering the water that infiltrated

Table 1. Meteorological stations used to estimate the water quantity.

Station	Key	Period	Latitude N	Longitude W	Altitude
Desierto de los Leones	9017h	1921-44-51-1988	19° 18' 51.117"	99° 18' 28.408"	3220
Dinamo No. 3	9019h	1932-1962	19° 16' 5.006"	99° 17' 0.035"	2920
Ajusco	38	1988-2007	19° 13' 12.994"	99° 12' 40.026"	3020
Bosque de Tlalpan	34	1988-2007	19° 17' 36.012"	99° 11' 42.024"	2330
Desierto de los Leones	56	2002-2007	19° 18' 52.017"	99° 18' 40.039"	2950
El Zarco	23	1988-2007	19° 17' 47.013"	99° 12' 11.025"	2400
Río Magdalena	25	1988-2007	19° 17' 25.011"	99° 15' 50.033"	2710
San Francisco	24	1988-2007	19° 18' 48.017"	99° 14' 20.03"	2480
Presa Anzaldo	9037	1954-1988	19° 19' 5.018"	99° 13' 0.027"	2400
Desviación al Pedregal	9020	1952-2005	19° 17' 54.013"	99° 10' 56.023"	2380
Monte Alegre	9067	1976-1983	19° 13' 52.997"	99° 17' 48.037"	3450
San Pedro Atlapulco	15242	1978-1991	19° 14' 40.00"	99° 23' 32.049"	2995
Coaxapa	15222	1977-1987	19° 9' 29.979"	99° 23' 40.049"	2940

into the aquifer).Weighting the absolute value of the runoff in the amount of hectares of forest, it was estimated that in this environmental unit the annual runoff approached 6´878,000 m^3. This is equivalent to 32% of the water quantity in the watershed.

The water balances for *Abies religiosa* forest, where annual rainfall can reach 1225 mm, showed an annual runoff of about 754 mm. Following the same criteria, the runoff in this unit is 10´944,800 m^3 of water per year, and therefore this area is generating 51% of the available water in the whole watershed.

The water balances for the mixed and oak forests, where annual precipitation amounts to 1100 mm, showed an annual runoff of 621 mm, so the annual runoff for this zone is 3´217,500 m^3, equivalent to 15% of the water generated in the watershed.

The remaining 2% of the water generated is derived from grasslands distributed along the watershed.

Therefore, on the basis of the water balance this watershed provides approximately 21 million m^3 per year, giving an average flow of 0.67 m^3s^{-1} (Table 2).

DISCUSSION

Water quality. The physicochemical quality of the water from the Magdalena River is generally very good in the natural area, since

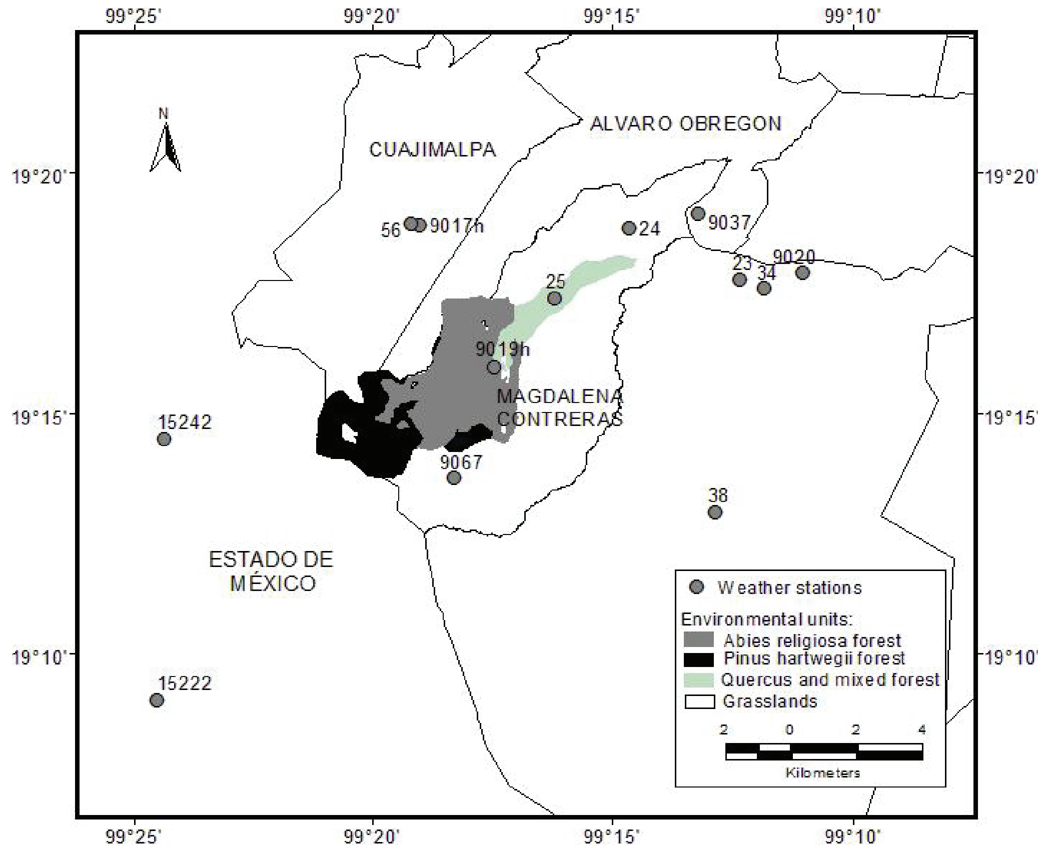

Figure 2. Location of the meteorological stations and the three environmental units described in the text and detail of the MRW crossing three counties; Cuajimalpa, Alvaro Obregon and Magdalena Contreras.

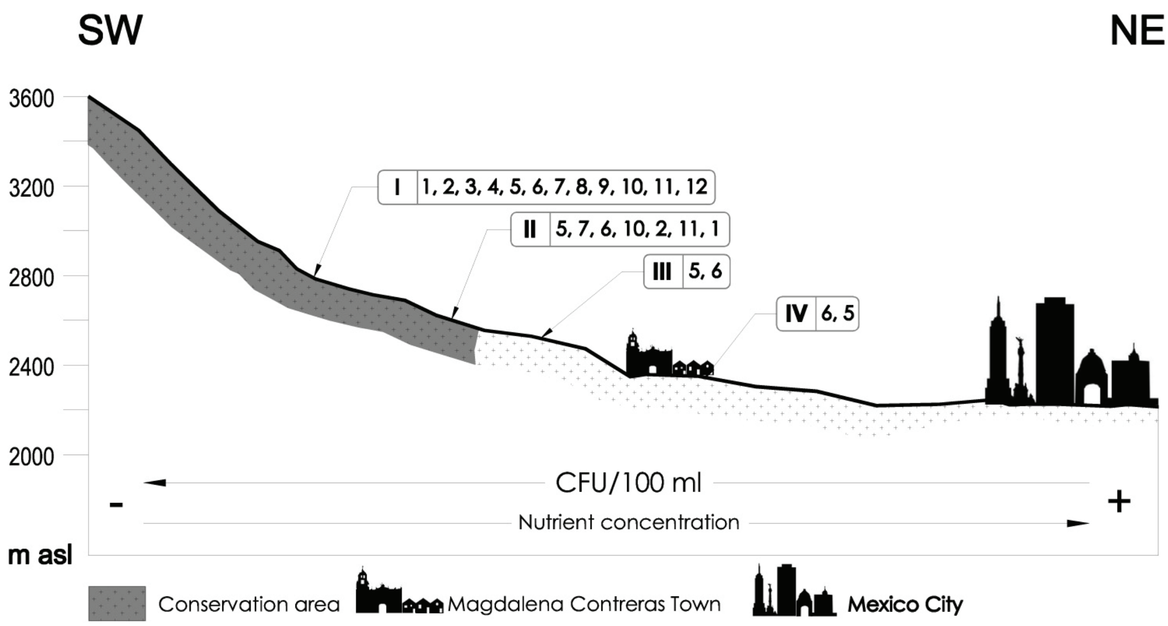

Figure 3. Variation of the diatom association and bacteria counts (CFU/100 mL) according to a degradation gradient. Sampling stations are at: I (2801 m asl), II (2530 m asl), III (2490 m asl) and IV (2308 m asl). Numbers represent the species, in order from higher to lower abundance. 1. *Cymbella silesiaca*; 2. *Achnanthes lanceolata*; 3. *Fragilaria capucina*; 4. *Navicula cryptocephala*; 5. *Nitzschia incospicua*; 6 *Nitzchia palea*; 7. *Rhoicosphenia abbreviata*; *8. Navicula subrynchocephala*; 9. *Cocconeis placentula*; 10. *Achnanthes minutissima*; 11. *Reimeria sinuata*; 12. *Gomphonema parvulum*.

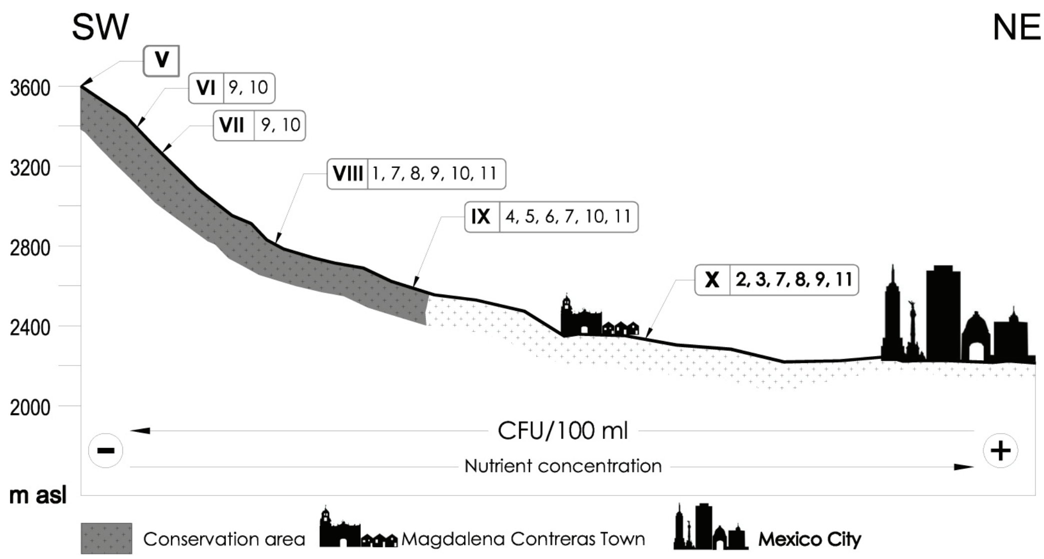

Figure 4. Bacteriological indicators (CFU/100 mL) variation, according to the altitude and degradation gradient. Sampling sites V (3600 m asl), VI (3370 m asl), VII (3250 m asl), VIII (2801 m asl), IX (2530 m asl) and X (2308 m asl). Numbers represent the bacteria species identified, and the (number) in the list the order from lower to higher abundance in isolate. Species in Bold are considered pathogens and the others opportunistic. 1. *Staphylococcus warneri* (1); 2. *Enterococcus casseliflavus* (2); 3. *Staphylococcus auricularis* (2); 4. *Salmonella paratyphi* (3); 5. *Enterobacter cloacae* (3); 6. *Klebsiella pneumoniae* (3); 7. *Enterococcus faecalis* (6); 8. *Pseudomonas stutzeri* (8); 9. *Enterococcus durans/hirae* (11); 10. *Enterococcus faecium* (14); 11. *Escherichia coli* (227).

these are temperate waters with low conductivity and circumneutral pH. The flow keeps a good oxygenation with a low BOD5 and a low nutrient balance. There is a gradual degradation of the water in the MRW by the return of residual domestic water into the river in the urban area.

Water at sites I and II is considered to be of good quality because the diatom composition showed waters with a low level of nutrients, and is similar to that reported in other countries with respect to diatom species richness and diversity, as well as the diatomological indexes (Stevenson, 1984; Rott & Pfister, 1988; Montesano *et al.*, 1999; Eloranta & Soinien, 2002). Also, the low nutrient concentrations, CFU/100 mL values recorded for bacterial groups are indicative of good quality (Wetzel, 1975; Calvo, 1999). In contrast, the quality of water at sites III and IV within the urban zone is poor, with an increase in nutrient concentration and high CFU/100 mL values for the bacterial groups. There is a dominance of two diatom species reported as tolerant to high concentrations of organic matter (Van Dam *et al.*, 1994; Asai & Watanabe, 1999; Lobo *et al.,* 2002), and low diatomological indexes (Eloranta & Soininen, 2002). Concentrations were higher during the dry season, this being attributable to the higher temperatures and the resultant higher evaporation: ions became more concentrated as the volume of water decreased (Lampert & Sommer, 1997; Seoánez, 1995).

Both biological indicators that were evaluated (diatoms and bacteria) were sensitive and showed an inverse response to the little modification of the environment by organic contamination that take place within the forested areas and the wastewater discharge and dumping of rubbish that happens in the urban area.

The physicochemical characteristics suggested that the water quality at all sampling stations was within the limits laid down by the Mexican Environmental Regulations, *Norma Oficial Mexicana* NOM-127-SSA1-1994 (DOF, 2000), and the Mexican National Commission of Water guidelines on water quality (CONAGUA, 2005); this water can be used for human consumption, with previous treatment such as disinfection (DOF, 2000). Nevertheless, in all sampling stations the concentrations of fecal coliform (FC) and total coliform (TC) bacteria exceeded the levels for human consumption permitted by the Mexican environmental regulations NOM-127-SSA1-1994 (DOF, 2000). Therefore, on the basis of this criterion, none of the water in any of the sampling stations can be considered suitable for human consumption. According to the general water quality guidelines recommended by CONAGUA (2005) and on the basis of permissible limits for FC, the water can be used for public supply if previously treated, for agricultural irrigation and for aquaculture. According to the water quality guidelines (CONAGUA, 2005) and the US EPA guidelines for freshwater (Gerba, 2000), only water from Site I can be used for recreational purposes that entail direct contact, and for public supply, agricultural irrigation and aquaculture, since it registered <126 CFU/100 mL. Since reliance on a single type of indicator may put human health at risk, more than one indicator should be used to evaluate water quality in these transition zones between cities and natural areas. Sampling stations in the natural area show increasing degradation along the course of the river, with no bacteria present where the river rises. There are only two identified bacterial species in the natural area at the higher part of the watershed. Then there is a clear increase starting from the recreational area at

Table 2. Physico-chemical and bacteriological indicators of water quality in the Magdalena River Basin during 2002-2003 annual cycle. All units are given in mg L^{-1} except where indicated. First line indicates minimum and maximum value, second line is the arithmetic mean and standard deviation; for bacterial indicators the geometric mean is given.

Variable	I	II	III	IV
Current velocity ms^{-1}	0.2-1.1 0.5 ± 0.3	0.1-1.1 0.4 ± 0.4	0.3-0.6 0.4 ± 0.1	0.3-0.7 0.4 ± 0.2
Light intensity μmol $cm^{-2}s^{-1}$	451-1857.3 1089 ± 535.3	433-1112.6 733 ± 230.4	114.7-965 419 ± 341.3	0-748 383.2 ± 280.5
Temperature ºC	8.7-18.5 13.2 ± 3.5	10.2-17.6 13.7 ± 2.7	10.2-17.8 13.8 ± 2.7	11.2-18.3 15 ± 2.9
pH	6.6-7.4 7 ± 0.3	6.5-7.6 6.9 ± 0.4	6.2-7.5 6.9 ± 0.5	6.9-7.6 7.3 ± 0.3
K_{25} μS cm^{-1}	72-128 93.3 ± 18.9	98.4-156 120 ± 22.6	100-435 189 ± 129.4	66.3-726 379.7 ± 220.3
Dissolved oxygen	7-9 8.3 ± .7	6.3-9 8 ± 1	4.4-8.8 6.5 ± 1.8	3.5-8.2 5.8 ± 1.6
BOD_5	1.6-4.6 3.2 ± 1.2	1.9-4.7 3.1 ± 1.2	2.8-7 5 ± 1.8	2.6-7 5 ± 1.7
$N\text{-}NH_4$	$< 2.8 \times 10^{-4}$ mg L^{-1}	$< 2.8 \times 10^{-4}$ mg L^{-1}	$< 2.8 \times 10^{-4}$ mg L^{-1}	$< 2.8 \times 10^{-4}$ mg L^{-1}-0.1
$N\text{-}NO_2$	$< 2.8 \times 10^{-4}$ mg L^{-1}	$< 2.8 \times 10^{-4}$ mg L^{-1}	$< 2.8 \times 10^{-4}$ mg L^{-1}	$< 2.8 \times 10^{-4}$ mg L^{-1}-0.1
$N\text{-}NO_3$	0.1-0.8 0.3 ± 0.3	0.1-1.3 0.6 ± 0.6	0.2-1.6 0.6 ± 0.5	0.2-6.9 2.2 ± 2.6
PON	0.1-1.2 0.3 ± 0.5	0.1-1.5 0.4 ± 0.6	0.3-3.4 1.5 ± 1.4	0.7-11.7 3.6 ± 4.1
DON	0.1-0.4 0.2 ± 0.1	0-1.2 0.5 ±0.4	0.3-10.6 3.1 ± 3.9	1.7-16.8 10.8 ± 6.4
TN	0.4-1.5 0.8 ± .4	0.7-2 1.4 ± .5	1.3-15.6 5.2 ± 5.4	5.8-28.7 16.6 ± 7.9
DRP	$< 2.8 \times 10^{-4}$ mg L^{-1}-0.1	0-0.5 0.1 ± 0.2	0.1-5 1.4 ± 2	0.7-12.2 4.5 ± 4.1
POP	$<2.8 \times 10^{-4}$ mg L^{-1}-0.1	0-0.2 .03 ± 0.1	0-0.9 0.3 ± 0.3	0.1-6 1.4 ± 2.3
DOP	$<2.8 \times 10^{-4}$ mg L^{-1}-0.1	0-0.3 0.1 ± 0.1	0.1-1 0.4 ± .4	0.3-2.1 1.1 ± 0.8
TP	0.1-0.2 0.1 ± 0.04	0.1-0.8 0.2 ± 0.3	0.3-6.1 2.1 ± 2.3	1.4-15.1 7 ± 5.5
$Si\text{-}SiO_2$	26.3-66.6 34.3 ± 15.9	27.5-60.1 34.6 ± 12.6	26-78.8 43.6 ± 22.4	25.4-38.3 30.9 ± 5
TN/TP	$< 2.8 \times 10^{-4}$ mg L^{-1}-10.7 1.8 ± 4.4	0-9.2 1.6 ± 3.7	0-5.2 0.9 ± 2.1	0-2.4 0.4 ± 1
H¨ $_{ln??}$	2.1	1.6	1.2	0.6
IPS	14.4	9.8	4.6	1.2
BDI	16.1	8.7	7.1	5.5
GDI	14.2	6.1	2.5	1.1
TC CFU/100 mL	23.93 ± 48.44	398.94 ± 1,197.70	1,824,769.79 ± 5,418,271.1	2,901,450.5 ± 11,733,559.7
FC CFU/100 mL	12.93 ± 19.94	435.11 ± 240.45	1,471,995.1 ± 14,862,494.0	5,780,003.7 ± 9,714,969.1
FE CFU/100 mL	36.43 ± 22.34	1,173.98 ± 2,788.80	1,278,848.5 ± 7,977,025.1	2,237,091.6 ± 1,049,020.8

Table 3. Physico-chemical and bacteriological indicators of water quality in the Magdalena River Basin during annual cycle 2007. All units are given in mg L^{-1} except where indicated. First line indicates minimum and maximum value, second line is the arithmetic mean and standard deviation; for bacterial indicators geometric mean is given.

Variable	V	VI	VII	VIII	IX	X
Current velocity ms^{-1}	0.09-0.19	0.59-0.85	0.68-0.83	0.38-0.90	0.33-0.93	0.35-0.53
	0.13 ± 0.05	0.71 ± 0.13	0.73 ± 0.09	0.60 ± 0.27	0.58 ± 0.31	0.43 ± 0.09
Temperature ^{0}C	9.1-11	9.1-13.7	9.5-15	5.6-16	7.1-14.5	12.1-14.8
	9.9 ± 0.97	10.5 ± 2.5	11.1 ± 2.35	10.6 ± 4.21	10.8 ± 3.7	13 ± 1.53
pH	6.30-6.76	7.30-7.34	6.83-7.92	6.91-7.93	7.32-7.78	7.49-7.51
	6.5 ± 0.24	7.3 ± 0.02	7.5 ± 0.56	7.4 ± 0.51	7.5 ± 0.24	7.5 ± 0.04
Conductivity	24.6-37.2	31.0-41.9	40.0-42.0	42.0-55.3	46.0-63.6	59.0-94.5
µS cm^{-1}	30.9 ± 6.30	37.0 ± 5.52	40.9 ± 1.0	48.1 ± 6.72	53.2 ± 9.23	72.2 ± 19.44
Dissolved oxygen	5.70-8.33	7.45-9.70	7.80-10.10	7.36-13.03	6.26-11.31	5.84-11.30
	6.7 ± 1.14	8.8 ± 1.20	9.2 ± 1.22	10.2 ± 2.84	8.2 ± 2.73	8.7 ± 2.85
Ca	3.96-4.69	3.23-4.32	3.86-4.16	3.79-4.13	3.49-3.77	4.30-4.75
	4.3 ± 0.37	3.9 ± 0.61	4.1 ± 0.17	4.0 ± 0.17	3.6 ± 0.16	4.5 ± 0.23
Mg	1.98-3.13	2.02-3.33	1.51-3.33	1.90-2.62	1.59-2.28	1.79-3.44
	2.5 ± 0.58	2.5 ± 0.74	2.2 ± 0.96	2.2 ± 0.39	1.9 ± 0.35	2.7 ± 0.83
TDS	15.4-24.9	23.2-28.3	22.8-27.7	27.3-31.8	29.8-34.1	63.9-80
	19.8 ± 4.78	26.1 ± 2.61	25.6 ± 2.51	30.0 ± 2.36	32.2 ± 2.21	72.8 ± 8.18
TSS	4.0-5.02	2.33-4.63	6.33-7.10	7.80-13.40	8.63-18.00	21.21-29.0
	4.5 ± 0.51	3.3 ± 1.18	6.1 ± 1.06	10.5 ± 2.80	12.7 ± 4.82	26.0 ± 4.9
TS	112.7-126.0	90.0-132.0	94.7-137.3	130.0-148.0	139.3-159.3	199.6-234.6
	117.6 ± 7.34	102.0 ± 26.15	109.1 ± 24.44	134.2 ± 12.23	152.0 ± 11.02	216.7 ± 17.51
$N\text{-}NH_4$	0.10-0.20	0.13-0.34	0.21-0.39	0.17-0.51	0.30-0.50	0.51-0.70
	0.14 ± 0.05	0.21 ± 0.12	0.28 ± 0.10	0.30 ± 0.18	0.41 ± 0.10	0.62 ± 0.10
$N\text{-}N0_3$	0.01-0.03	0.01-0.02	0.02-0.03	0.02-0.04	0.03-0.05	0.05-0.08
	0.022 ± 0.01	0.017 ± 0.01	0.024 ± 0.01	0.031 ± 0.01	0.041 ± 0.01	0.069 ± 0.02
TN	1.13-1.27	1.09-1.50	1.21-2.23	1.67-2.73	2.37-2.48	2.43-3.80
	1.18 ± 0.08	1.32 ± 0.21	1.71 ± 0.51	2.04 ± 0.60	2.74 ± 0.55	3.13 ± 0.68
TP	0.02-0.09	0.12-0.19	0.18-0.20	0.13-0.30	0.57-0.89	0.96-1.04
	0.05 ± 0.04	0.16 ± 0.04	0.19 ± 0.01	0.22 ± 0.08	0.71 ± 0.16	0.97 ± 0.07
TOC	1.23-2.50	0.47-1.57	0.67-1.63	0.77-1.77	1.27-2.53	2.30-5.30
	1.7 ± 0.70	0.9 ± 0.61	1.0 ± 0.53	1.2 ± 0.50	1.8 ± 0.65	3.5 ± 1.59
FC CFU / 100 mL	13 ± 11	25 ± 17	41 ± 29	101 ± 75	1,574 ± 353	507,250 ± 432,561
FE CFU / 100 mL	1 ± 1	4 ± 2	8 ± 7	38 ± 31	159 ± 37	19,834 ± 20,137

2308 masl to the urban area, with isolation of six bacterial species, representing at least three genera that may be considered human pathogens (Monges, 2009).

There is an inverse distribution and abundance of the two microbiological indicators used. In the upper parts of the watershed there is a high abundance of diatoms, and species typical of clean environments, whereas in the degraded area both abundance and diversity of the diatoms decrease. Counts of the bacterial indicators were low in the upper watershed, but they increased in abundance and diversity from the station that was influenced by recreational activities to the urban area. In the last three sampling stations, in the middle and lower watershed, the presence of pathogens such as *Escherichia coli*, *Klebsiella pneumoniae* and *Salmonella paratyphi* indicates the greater influence of fecal matter and the need for wastewater treatment.

Table 4. Characteristics of Environmental units and water provision of estimation.

Environmental Units	Extension (ha)	Altitude and topography	Vegetation	Annual precipitation (mm)	Runoff (m^3) per environmental unit	Percentage % with respect to total
Mixed forest and Quercus sp.	482	2500-3000 masl, piedmont, erosive valleys and smooth hillside (0-15º) and with larger slope (15-30º) in the SW portion	*Abies religiosa* *Quercus laurina*, *Quercus rugosa*	1000-1100	3,217,505	15
Abies religiosa forest	1469	3000-3500 masl, acute hillside >45º slope, Andosol humic soils	*Acaena elongata*, *Senecio angulifolius*, *Senecio cinerarioides* *Abies religiosa*	1050-1225	10 944 838	51
Pinus hartwegi forest	943	3500-3800 masl, hillside <30º slope, presence of piroclastic material	*Muhlenbergia quadridentata* *Festuca tolucensis* *Pinus hartwegii*	1125-1150	6 877 992	32
Grassland	6		Not identified			2
Estimated annual water production					21 538 250	100

In relation to this, there is a need to increase awareness among the authorities and the general public regarding the condition of the Magdalena River. Unless measures are taken to rehabilitate the waterway and establish a cultural ES, Mexico City may lose a source of water, the opportunities for recreation within the forested areas may decrease, and the health of people living in the surroundings, especially in the urban area, may be put at risk. This work also demonstrates the need to monitor the fluvial system to prevent the respiratory, gastrointestinal and skin diseases to which the population can be exposed as a result of ignorance of the potential effect of degraded water quality.

Water quantity. To characterize the ES as water provision in the MRW, the data for water balance give an idea of the volume of water involved. The order of magnitude indications of runoff for the main areas show the highest runoff from the *Abies religiosa* forest environmental unit, mainly due to its large area and high precipitation. Summing the runoff of the whole watershed, it is estimated that the total water generated per year is 21 million m^3, equivalent to 0.67 m^3s^{-1}. The annual average data reported by the Magdalena hydrometric station for 1999 is 0.58 m^3s^{-1}, although it has complete data for only one year, the similarity of the values reflects the accuracy of the model. Anyway this is a partial estimate, as there is little integrated information regarding geological formations, soil type and hydraulic conductivity of the different zones; there is also a need of updated weather and hydrometric information.

According to Maass (2003), the functioning of ecosystems is controlled in great measure by the hydrological flow, since the availability of water is one of the more decisive factors in the productivity of ecosystems. Compared with other rivers in the city, Magdalena River has a considerable hydrological flow (0.67 m^3s^{-1}). Temporal variation in flow must be taken into account, since water availability is not constant throughout the year. In silty-loam soils, as is the case in the MRW, vegetation has a substantial effect on runoff. Disturbance of the vegetation cover affects infiltration, evaporation and runoff indices and thus, the capacity to offer ecosystem services.

Thornthwaite method is based on general values for conifers. However, although conifers grow on more than two-thirds of the basin they do not all belong to the same community, and therefore the evapotranspiration may not be the same in the three environmental units; this should be taken into account in a more detailed interpretation of the water balance. Cienciala *et al*. (1997) have found that trees of the genus *Abies* transpire more than those of the genus *Pinus*; hence, water consumption by vegetation, should be higher in the middle parts of the MRW than in the higher ones. Inhabitants of the natural area of the watershed use water directly from the river for their food stalls in the recreation area, for trout ponds, and for business and domestic activities (bathrooms, dish washing, and cooking). In the urban area the water from the Magdalena River is consumed mainly by the inhabitants of two small suburbs, San Bernabé and San Jerónimo Lídice, in the NW of Magdalena Contreras. The purification plant operates at 200 L/s^{-1}, and the remaining water is piped through the drainage system to the Anzaldo Dam.

The estimated instantaneous mean flow of the river is 0.67 $m^3 s^{-1}$, which corresponds to approximately 1% of the Mexico city water demand (Sheinbaum, 2008), but this varies considerably between the months during the rainy season months (3.4 $m^3 s^{-1}$) and the dry season (0.2 $m^3 s^{-1}$), a fact that should be taken into account for water management. Because of the variable runoff, the purification plant (*La Magdalena*) does not filter all the river water, since the plant has a mean capacity of 170 $m^3 s^{-1}$ and a maximum of 200 L/s^{-1}. It serves to a mean population of 150,000 inhabitants or a maximum of 180,000. The real loss of "clean water" is during the rainy season, when the flow is more than 10 times the capacity of the plant and the excess water is directed to the sewage system down at the Anzaldo Dam (along side Periferico to protect the avenues).

The water management strategy should differ between the dry and rainy season; in the latter, action should be taken in order to collect water that could be distributed for human use in the south-western sector of Mexico City. Taking into account the water needs of the city, if the water were collected during the rainy season and transported through the distribution system, the Magdalena River could be contributing about 4.6% of the demand for water in Mexico City.

One of the most urgent measures that should be adopted if this zone is to continue generating ESs for the inhabitants of the southern parts of Mexico City is forest conservation. It is recommended that the *Pinus hartwegii* and *Abies religiosa* forests in the upper and middle parts of the watershed should be dedicated exclusively to conservation and restoration. This would increase soil retention and humidity in order to preserve the vegetation cover. This is important as these zones capture high amounts of water and have a high risk of landslides due to their steep slopes. In the mixed forest in the lower part of the watershed, some restoration should take place, but cultural and recreational activities could also be allowed. It is crucial to restore both sides of the river course, starting from its source to the lower reaches. According to Sweeney *et al*. (2002), to reestablish an ES such as water quality it is important to recover riparian vegetation and support directly the algal communities that provide oxygen to the water.

Recently, the local government built a second water treatment plant, La Cañada, at the border between the natural and urban areas, with the aim of supplying drinking water to 80,000 inhabitants. The main risk is that during the dry season the water could be insufficient for the needs of the local population. Also that river levels could fall and result in damage to the riverine ecosystem.

Beside taking measures to protect the forests, it is necessary to create efficient systems of water filtration to avoid contamination in the lower watershed, and a stronger control with regard to irregular settlements and wastewater systems is important.

It is very important to note that although the ecosystem service that is intended to conserve water supplies should be clear that failure to protect the entire ecosystem and related services, the population of the southwest of the city may not have sufficient quality and quantity water to meet their needs.

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