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PROPUESTA PARA LA EVALUACIÓN DEL SERVICIO ECOSISTÉMICO DE PROVISIÓN DE AGUA: EL CASO DE LA CUENCA DEL RÍO MAGDALENA, MEXICO, D.F.

T E S I S

QUE PARA OBTENER EL GRADO ACADÉMICO DE

DOCTORA EN CIENCIAS

P R E S E N T A

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P r e s e n t e

Me permito informar a usted que en la reunión ordinaria del Comité Académico del Posgrado en Ciencias Biológicas, celebrada el día **4 de junio de 2012**, se aprobó el siguiente jurado para el examen de grado de **DOCTORA EN CIENCIAS** del (la) alumno (a) **JUJNOVSKY ORLANDINI JULIETA** con número de cuenta **98770234** con la tesis titulada: **"Propuesta para la evaluación del servicio ecosistémico de provisión de agua: El caso de la cuenca del río Magdalena, México D.F"**, realizada bajo la dirección del (la) **DRA. LUCIA ALMEIDA LEÑERO:**

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M. del Coro Arizmendi

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INDICE

RESUMEN

En la ciudad de México, después de 500 años de manejo inadecuado del agua, se debe reconocer a las cuencas hidrográficas como elementos claves en la transición hacia la sostenibilidad. Por lo que es necesario visualizar a la urbe como un socio-ecosistema donde se relacione lo social y lo ambiental. De tal forma que si el manejo del agua se hace desde el enfoque de servicios ecosistémicos, las autoridades podrán reconocer e integrar los ecosistemas naturales a las ciudades, ya que es una manera de entender como los procesos que ocurren en las áreas naturales generan beneficios a las áreas urbanas. Se escogió como modelo a la cuenca del río Magdalena por ser el abastecimiento de agua superficial más importante de la ciudad y presentar excelente calidad en la zona alta. A su vez, el estado de conservación de sus bosques permite que tenga una alta biodiversidad. Con el fin de desarrollar una metodología para la evaluación del servicio de provisión de agua, se reconocieron los principales procesos ecosistémicos que determinan la provisión de agua en la cuenca del río Magdalena; se ubicaron espacialmente las zonas donde se generan los servicios, se identificaron los beneficiarios reales y potenciales del servicio. Finalmente, se integró la información recabada y se desarrolló una propuesta de manejo, misma que plantea los lineamientos que deben seguirse para la evaluación de la provisión de agua, como son: evaluar la cantidad y la calidad del agua con métodos de monitoreo y análisis, considerar los actores sociales que tengan mayor injerencia en la zona y proponer una valoración económica del servicio acorde con la función ecosistémica que se esté valorando. Finalmente se proponen intervenciones de manejo para que el servicio se siga generando. Se espera que si estos lineamientos son incorporados en las políticas públicas para la gestión integrada del agua puedan servir como modelo para otras cuencas rural-urbanas con características similares.

Palabras claves: *Ciudad de México, agua, servicios ecosistémicos, cuenca del río Magdalena, propuesta de manejo.*

ABSTRACT

After nearly 500 years of mishandling water in Mexico City, we must begin to see the rivers and their watersheds as key elements to its sustainability. Therefore, it is necessary to view Mexico City as a socio-ecological system; in which people strongly depend on the ecosystem services. It is expected that if water management were done from the ecosystem services approach, it would be easier to influence the authorities to integrate natural ecosystems into city management programs. Magdalena River Watershed was chosen as a model because is the most important surface water supply in the city and the river has excellent quality at the top of the watershed; also their forests host high biodiversity. In order to develop a methodology for evaluating the water supply service, the ecosystem processes related to water balance were recognized and the generation zones and the beneficiaries were located. Finally, with all the information collected the management proposal was developed. The proposal states that the guidelines to be followed for the evaluation of water supply are: assessing the water quantity and quality using monitoring and analysis methods, considering the stakeholders that have greater influence in the area and propose an economic valuation according to ecosystem function that is being valued. Finally, management interventions are proposed in order to maintain the ecosystem service. We expect that if these guidelines are incorporated in public policies for integrated water management, this study could serve as a model for other rural-urban watersheds with similar characteristics.

***Key words**: Mexico City, water, ecosystem services, Magdalena River Watershed, Management proposal.*

C A P I T U L O 1

INTRODUCCION

MARCO CONCEPTUAL

Las megaciudades y el agua

Por primera vez en la historia de la humanidad, la población urbana mundial rebasó a la población rural. Por lo tanto, la expansión hacia las ciudades será cada vez mayor y las zonas rurales serán desplazadas por pueblos o ciudades pequeñas (Uitto & Biswas, 2000; UNFPA, 2007). Se calcula que para el año 2050, el 70% de la población mundial vivirá en ciudades (WWF, 2011). En los países desarrollados, esta urbanización se ha caracterizado por el crecimiento de una gran cantidad de ciudades de tamaño mediano. En contraste, en países en desarrollo, el crecimiento urbano se concentró en una o en pocas ciudades grandes, frecuentemente mencionadas como megalópolis o megaciudades. Estas se definen como centros urbanos, que han alcanzado o superado los 10 millones de habitantes (UN Habitat, 2008).

Durante la segunda mitad del siglo XX el "éxodo" de las poblaciones rurales hacia las ciudades transformó de manera radical el paisaje de los países del Tercer Mundo. La relación entre las ciudades y el agua es crucial; las grandes urbes requieren grandes cantidades de agua para abastecer a los pobladores y a su vez, sus desechos, impactan negativamente a los sistemas de agua dulce (UNESCO, 2010). Otro de los mayores problemas hídricos que enfrentan las megaciudades en los países en desarrollo es la disponibilidad (Fuchs *et al*., 1999; WWF, 2011). A escala mundial, las aguas subterráneas representan la fuente de agua potable más importante y el rápido crecimiento poblacional acelera en gran medida la explotación de acuíferos (Llamas & Custodio, 2003; WWF, 2011). Por lo tanto, a medida que se incremente el porcentaje de población urbana mundial, la protección de acuíferos será una necesidad crítica dentro de las políticas públicas en países en vías de desarrollo (Mazari-Hiriart *et al.*, 2006).

De acuerdo con la UNESCO (2010), una gestión urbana del agua sostenible, eficiente y equitativa debe ser un tema prioritario. Las ciudades deben garantizar a sus pobladores un acceso confiable al agua potable y a un saneamiento adecuado. Por lo tanto, hacer frente a estas necesidades es uno de los temas más urgentes de este siglo.

La problemática del agua en Ciudad de México

La ciudad de México, actualmente una de las mayores urbes del planeta, permite analizar temas de sustentabilidad ambiental ya que los problemas que esta ciudad enfrenta son similares a los de muchas megaciudades de países en desarrollo (WWF, 2011). Esta urbe se encuentra dentro de una cuenca endorreica donde la disponibilidad natural de agua ha sido modificada por cuatro siglos de obras hidráulicas (Rojas, 2004; Legorreta, 2010. Históricamente ha enfrentado graves problemas relacionados a la escasez de agua, los cuáles se han agudizado debido al incremento de la población y la contaminación de sistemas acuíferos (Uitto & Biswas, 2000).

La creciente urbanización de la cuenca ha resultado en la creación de la Zona Metropolitana de la Ciudad de México (ZMCM); constituida por 16 delegaciones del Distrito Federal, 39 municipios del Estado de México y 1 municipio del Estado de Hidalgo. Corresponde a la extensión territorial que incluye la antigua ciudad central en el Distrito Federal y aquellas unidades político-administrativas urbanizadas contiguas a él, que forman parte de una unidad funcional (Ezcurra *et al*., 2006). El agua subterránea en la ZMCM es la principal fuente de abastecimiento para uso doméstico e industrial (Soto-Galera *et al.*, 2000) y la demanda de espacios para la creciente población han forzado cambios de uso de suelo, cubriendo áreas que son esenciales para la recarga de los acuíferos (Uitto & Biswas, 2000). La extracción de agua subterránea empezó en 1847 y se extendió significativamente entre 1950 y 1960. Desde entonces se ha extraído agua adicional de dos cuencas externas, la de Lerma y la de Cutzamala (Ezcurra *et al.*, 2006; GDF, 2007). En los últimos 30 años la demanda de agua prácticamente se duplicó, pasando de 40 a 72.5 m3/s. El 72% se extrae del subsuelo, 18% proviene del sistema Cutzamala, 8% del Lerma y 2% de manantiales y escurrimientos superficiales propios de la cuenca. De esta cantidad, 10 m3/s se usan directamente en riego (Guerrero-Villalobos et al., 1982; Jiménez Cisneros et al., 2004). De acuerdo con Sheinbaum (2008), se estima que ingresan al sistema de distribución de agua potable 64 m^3/s, de los cuales aproximadamente 35 m^3/s son para el D.F. y el resto, 29 m^3/s, corresponden a los municipios conurbados del Estado de México. El 70% de este suministro proviene de fuentes subterráneas; 24% de fuentes superficiales y 6% restantes de agua de reuso.

Además de los problemas de desabasto, la infraestructura de expulsión de aguas pluviales y residuales ha desecado la cuenca y las políticas públicas que se han aplicado no contemplan una estrategia de tratamiento, separación y reuso al interior de la cuenca. El suelo de la ciudad presenta hundimientos diferenciales ocasionados por la extracción excesiva de agua subterránea y la mayoría de los ríos de la ciudad han sido entubados y/o utilizados como drenajes, ya que ahí descargan las aguas residuales y se utilizan además como tiraderos de basura (González-Reynoso *et al*., 2010). De tal manera que a medida que fue avanzando la urbanización de la cuenca de México, los ríos comenzaron a ser vistos como un problema para la seguridad de sus habitantes, tanto por cuestiones de salud como por las inundaciones que pueden ocasionar.

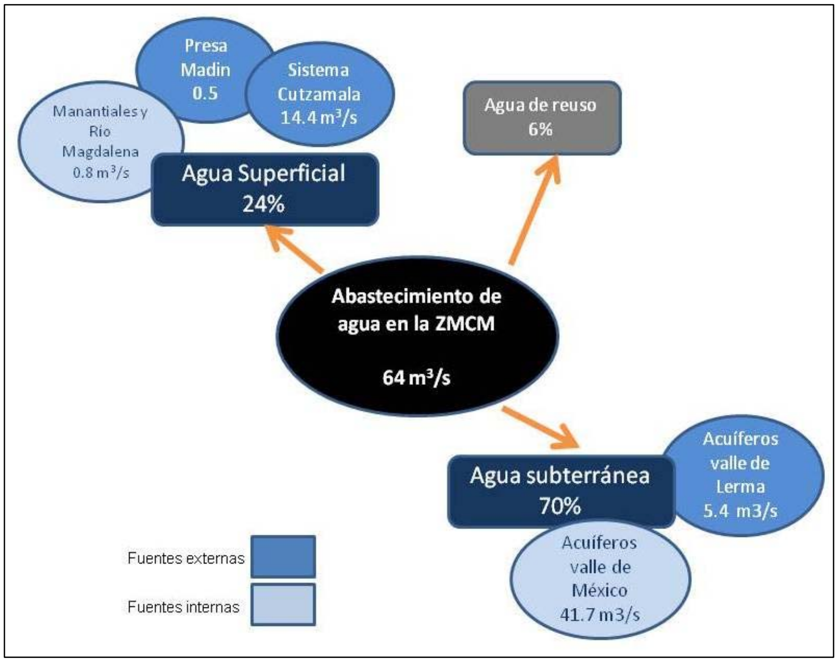

Figura 1.1- Fuentes de abastecimiento de agua potable para la zona metropolitana de la ciudad de México, elaboración propia, a partir de datos de Sheinbaum, (2008).

El estudio de los sistemas socio-ecológicos y los servicios ecosistémicos

La comprensión de los procesos que conducen a cambios en los ecosistemas es limitada, porque las disciplinas científicas utilizan diferentes conceptos y lenguajes tanto para describir como para explicar los sistemas socio-ecológicos (Ostrom, 2009). El conocimiento científico es necesario para mejorar los esfuerzos de conservación de sistemas socio-ecológicos, pero las ciencias sociales y ambientales se han desarrollado de manera independiente y no es fácil combinarlas. Ostrom (2009) afirmó que si no se construye un marco conceptual común entre la esfera social y la ambiental, únicamente se seguirá generando conocimiento de manera aislada. Afortunadamente, desde inicios de este siglo se están realizado esfuerzos conjuntos entre diferentes científicos, países e instituciones para tratar de aplicar la información científica básica y las consecuencias que el uso de los recursos naturales trae sobre el bienestar humano (MA, 2003; GLP, 2005; IGBP, 2006; Ostrom, 2009).

Uno de los mayores esfuerzos de colaboración internacional para evaluar el estado de salud de nuestro planeta, es el *Millennium Ecosystem Assessment* (MA, 2003). Esta iniciativa surgió en la Asamblea General de las Naciones Unidas en el año 2000 debido a la creciente preocupación sobre el incremento de la pobreza mundial y el deterioro global del ambiente. Debido a ello, se generó un documento elaborado por científicos de todo el mundo y avalado por la Organización de las Naciones Unidas que busca el equilibrio entre la conservación de los ecosistemas y el bienestar humano. El marco conceptual del MA se publicó en el 2003 y los primeros reportes de evaluación sobre cómo se encuentran los ecosistemas del mundo se inició en el 2005.

Otro proyecto para realizar estudios integrales es el *Global Land Project* (GLP), el cual representa la agenda de investigación conjunta del *International Geosphere-Biosphere Programme* (IGBP) y del *International Human Dimensions Programme on Global Environmental Change* (IHDP) para mejorar el entendimiento de la dinámica de los sistemas terrestres en el contexto del funcionamiento del Sistema Terrestre Global (GLP, 2005; IGBP, 2006). Este plan representa un primer paso, fundamental para abordar la interacción entre las personas y su ambiente, es parte de los esfuerzos más amplios para comprender cómo estas interacciones han afectado y podrían afectar la sustentabilidad de la biosfera terrestre. Se espera que el GLP desempeñe un papel claro en mejorar el entendimiento de los sistemas terrestres a escalas regionales y globales, así como fomentar una fuerte sinergia científica en los programas para enfrentar el cambio global. Desarrolla un nuevo paradigma enfocado en dos aspectos conceptuales fundamentales para el socio-ecosistema: contempla la interfase entre personas, biota y recursos naturales, combinando estudios detallados con una perspectiva global. Finalmente, toma a los servicios ecosistémicos, como punto de partida para la toma de decisiones (GLP, 2005; IGBP, 2006).

A pesar de los esfuerzos internacionales para evaluar el sistema terrestre de manera global, al momento de tratar de aplicarlo a un ecosistema en particular, surgen una serie de complicaciones. Principalmente, en países en desarrollo, donde falta generar información básica y lo que hay está a distintas escalas tanto temporales como espaciales, por lo que se hace muy complicado realizar proyectos integrales. Los estudios desde la perspectiva de los servicios ecosistémicos (SE) pueden ser un marco de referencia común al permitir visualizar integralmente, los beneficios que el hombre obtiene de los sistemas socio-ecológicos.

El concepto de SE surgió en los años 60 y resalta la relación del ser humano con su entorno natural (Daily *et al.*, 1997; MA, 2005; Balvanera & Cotler, 2007). Sin embargo, la noción de recibir beneficios por parte de los ecosistemas no es nueva, ya que se remonta a la época de los griegos (Mooney & Ehrlich, 1997; Fisher *et al*., 2009). Los SE han sido definidos en múltiples ocasiones y cambian en función del contexto en el que son empleados. Daily (1997), una de las primeras autoras en usar el término, los define como las condiciones y procesos a través de los cuales los ecosistemas naturales y las especies que los conforman, sustentan la vida humana. Hay otros autores que han generado definiciones parecidas cuyas implicaciones abarcan el bienestar humano y a los ecosistemas como proveedores principales de dichos servicios (Costanza *et al*., 1997; De Groot *et al*., 2002; Kremen, 2005; Quétier *et al*. 2007; Boyd & Banzaf, 2007; Dale y Polasky, 2007). Una definición sencilla y ampliamente usada es la del MA (2003), que concibe a los SE como los beneficios que los seres humanos obtienen de los ecosistemas. No solo hay diversas definiciones, sino también se han propuesto varias clasificaciones (Postel & Carpenter, 1997; De Groot *et al.*, 2002; MA, 2003; Brauman *et al*., 2007) y aunque han habido varios intentos para generar una clasificación "universal", no han podido establecerse acuerdos (Fisher *et al*., 2009). La clasificación que se tomará en cuenta en este trabajo es la del MA (2003), donde los clasifica en servicios de provisión, regulación, culturales y de soporte.

Existen factores que afectan a los ecosistemas y por lo tanto a los servicios que éstos proporcionan. Dichos factores se conocen como *impulsores de cambio* y son cualquier factor natural o antropogénico que causa un cambio directo o indirecto al ecosistema e inciden como fuerzas naturales o inducidas por el ser humano (MA, 2005). Aún no se conoce a profundidad cuál es el impacto que las distintas técnicas de manejo ocasionan en los ecosistemas, por lo que un tema prioritario del GLP es conocer cómo un cambio en los SE afecta el medio de vida de los seres humanos (GLP, 2005; Carpenter *et al.*, 2009).

Lo antes mencionado no es un problema reciente; en diferentes ocasiones se ha manifestado la falta de coordinación entre el desarrollo socio-económico, cultural y la protección ambiental. Sin embargo, éste problema ya no se restringe a una población local, sino que ha adquirido un carácter global (Leff, 2004). De ahí la importancia de saber manejar a los ecosistemas y sus recursos para garantizar que sigan existiendo en el futuro, sin minar la posibilidad del desarrollo de la sociedad.

Un esquema con preguntas relevantes para el entendimiento, evaluación y manejo de servicios ecosistémicos es el propuesto por Brauman *et al.*, (2007); en el que se enfatiza la generación biofísica de servicios en sus dimensiones social, económica e institucional (Figura 1.2).

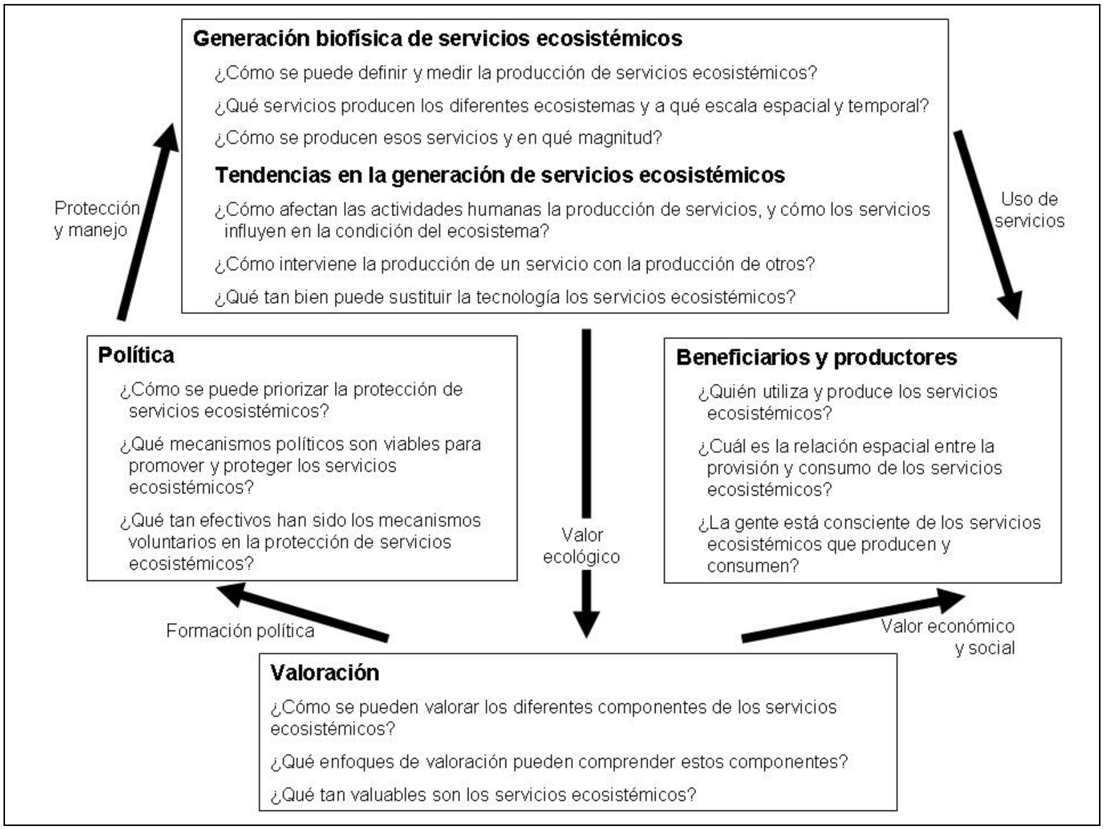

Figura 1.2- Preguntas relevantes para el entendimiento, evaluación y manejo de los servicios ecosistémicos de acuerdo con Brauman, *et al.*, 2007.

Dentro de los elementos claves del ecosistema, el agua es quizá el servicio mejor reconocido por la especie humana (Falkenmark & Folke, 2003). Los SE relacionados con el agua se conocen como servicios de corte hidrológico; y son fundamentales para que exista la vida como la conocemos. Están relacionados con el agua pero son producidos por ecosistemas terrestres (Brauman *et al.*, 2007). Los servicios se relacionan unos con otros y con los procesos que los regulan, por lo que muchas veces es difícil encasillarlos en una clasificación (MA, 2003). Por ejemplo, la provisión de agua dulce, depende de la cantidad y calidad de agua, que son servicios de regulación y del ciclo hidrológico, que es un servicio de soporte (Figura 1.3).

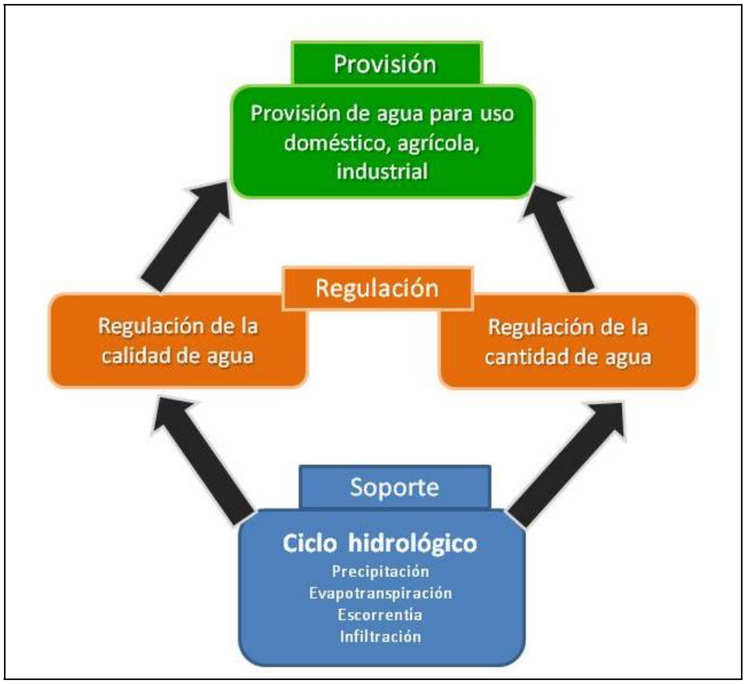

Figura 1.3 Servicios ecosistémicos hidrológicos que se relacionan con la provisión de agua, elaboración propia, basada en la clasificación del MA (2003).

JUSTIFICACIÓN Y OBJETIVOS

Después de casi 500 años de un manejo inadecuado del agua en la ciudad de México es necesario considerar a las cuencas y sus ríos como elementos claves para la sustentabilidad de la urbe. Es necesario visualizar a la ciudad de México como un sistema socio-ecológico donde se consideran tanto los ecosistemas como la sociedad. Se espera que si el manejo del agua se hace desde el enfoque de servicios ecosistémicos, sea más sencillo, lograr que los tomadores de decisiones integren los ecosistemas naturales a las ciudades, ya que es una manera de entender como los procesos que ocurren en estos ecosistemas generan beneficios a la población.

Por lo tanto el objetivo general de este trabajo es desarrollar una propuesta para la evaluación del SE de provisión de agua que sea aplicable a cuencas periurbanas. Se seleccionó como modelo a la cuenca del río Magdalena, debido al estado de conservación de sus bosques, a su alta biodiversidad (Ávila-Akerberg *et al.*, 2008; Cantoral *et al.*, 2009) y por ser el abastecimiento de agua superficial más importante de la Ciudad de México (Jujnovsky *et al.*, 2010).

Para cubrir el objetivo general se reconocieron los principales procesos ecosistémicos que determinan la provisión de agua en la zona de estudio, se ubicaron espacialmente las zonas donde se generan los servicios, se identificaron los beneficiarios reales y potenciales del servicio; finalmente, se integró la información recabada y se desarrolló una propuesta de manejo del agua en la zona de estudio, utilizando el enfoque de servicios ecosistémicos, la cual se espera que sea aplicable a otras cuencas periurbanas.

ZONA DE ESTUDIO: LA CUENCA DEL RÍO MAGDALENA

Características generales

A pesar de la problemática ambiental que ha sufrido la ciudad de México en los últimas décadas, todavía cuenta con áreas boscosas catalogadas como Suelo de Conservación del Distrito Federal (SCDF); las cuales comprenden zonas rurales y forestales (Sheinbuam, 2008). De acuerdo con el Programa General de Ordenamiento Ecológico del Distrito Federal, este tiene una extensión de 88,442 ha. Al sur, abarca hasta las sierras de las Cruces, del Ajusco y del Chichinautzin; al oriente, la sierra de Santa Catarina, la planicie lacustre de Xochimilco y el Cerro de la Estrella. Hacia el norte se extiende el territorio de la Sierra de Guadalupe y el Cerro del Tepeyac. La importancia de este territorio radica en que suministra servicios ecosistémicos fundamentales para la supervivencia y el mantenimiento de la ciudad. La vegetación arbórea en particular, cumple una importante función reguladora, ya que influye en la cantidad, la calidad y la temporalidad del flujo del agua, protege a los suelos de ser erosionados y de la consecuente sedimentación, previene la degradación de los ríos y la afectación, en general, de los ecosistemas acuáticos (Cotler, 2004). Además de la provisión de agua, otros servicios ecosistémicos relacionados son, la captura de carbono, la retención de partículas y el mantenimiento del microclima. Así mismo, la zona tiene una alta diversidad de especies y endemismos (Ávila-Akerberg *et al*., 2008); además es el territorio de los principales ejidos y comunidades de la entidad (Sheinbaum, 2008).

No todo el SCDF presenta el mismo estado de conservación, esto se debe a su ubicación geográfica, a las condiciones del relieve y a como ha crecido la mancha urbana. Una de las porciones mejor conservadas son las cuencas que se localizan en la porción suroeste de la entidad, una de ellas es la cuenca del río Magdalena (Figura 1.4). El uso de suelo de esta cuenca es boscoso en su mayoría, seguido por pastizales y matorrales y unos pequeños manchones de agricultura. La vegetación predominante es el bosque de coníferas (*bosque de Abies religiosa* y *Pinus hartwegii*) en las altitudes entre 3000 y 3800 msnm y de encino (*Quercus* sp.) en las regiones más bajas de 2500 a 3000 msnm (Nava-López, 2003).

El río que le da su nombre a la cuenca del río Magdalena, es uno de los escurrimientos más importantes de toda la urbe ya que contribuye con el abastecimiento del 50% del agua superficial de la Ciudad de México, generando un promedio de 0.67 m^3/s (Jujnovsky *et al.*, 2010).

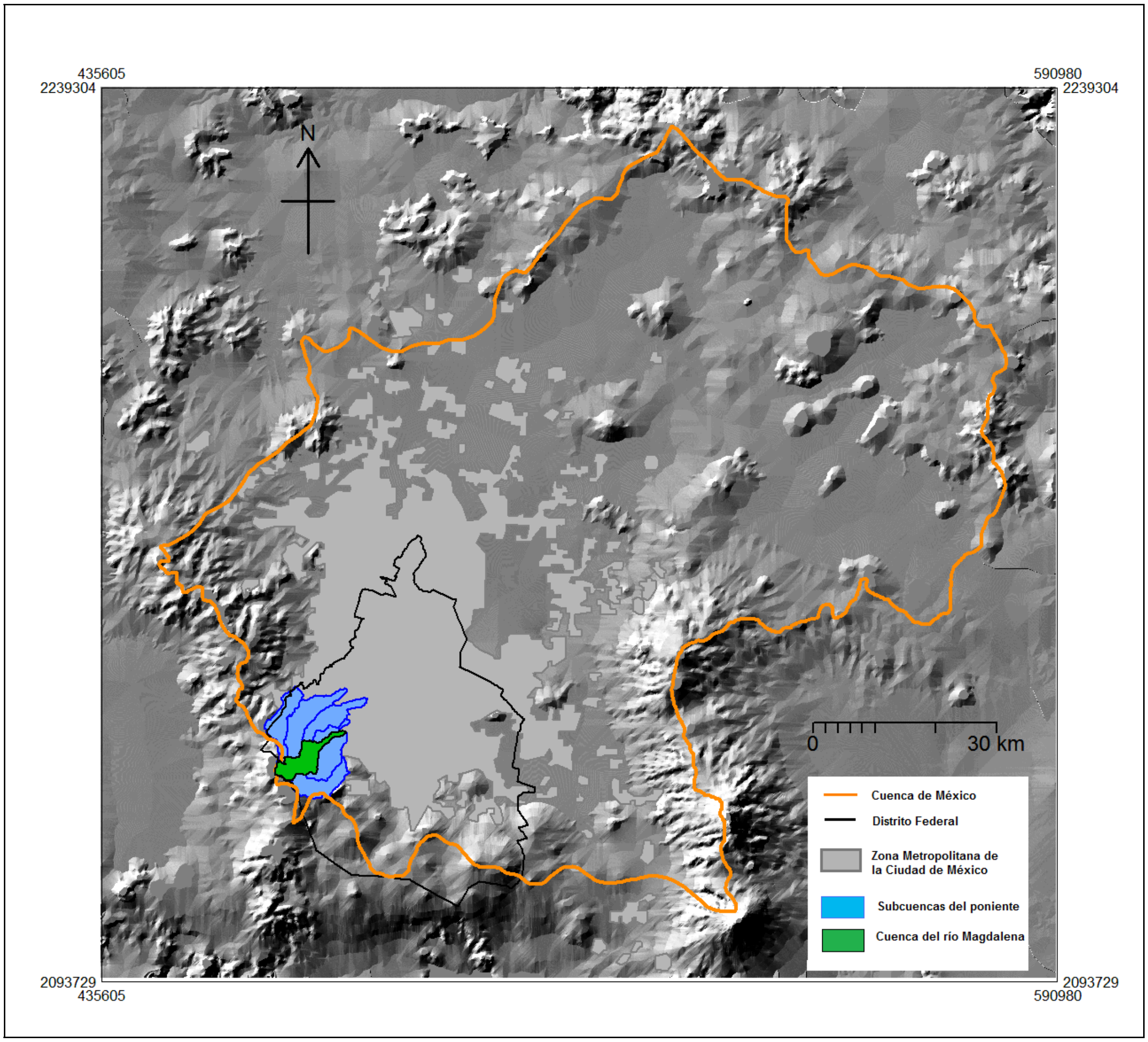

Figura 1.4.- Localización de la cuenca del río Magdalena y las cuencas del suroeste del Distrito Federal.

Problemática social

Las cuencas del suroeste y en particular, la cuenca del río Magdalena, son regiones prioritarias debido a los servicios ecosistémicos que brindan a la población. Sin embargo, las zonas forestales que circundan la ciudad de México han sido sometidas a fuertes presiones derivadas de la actividad humana (Hernández & Bauer, 1989).

A pesar de que estas zonas se localizan dentro del SCDF, la urbanización ha aumentado considerablemente en los últimos 50 años. Mientras que en la década de 1950 la única urbanización, en ese momento, era en la partes bajas de las cuencas de San Ángel y en la Barranca del Rosal. Para la década de 1980 ya había crecido hacia las cuencas del río Magdalena, río Eslava y una pequeña fracción del Santo Desierto. El avance de la mancha urbana hacia las partes más altas de las cuencas del suroeste continuó hasta el año 2000 y para el año 2005 a pesar del decreto del ordenamiento ecológico del D.F. donde se prohíben asentamientos urbanos en el SCDF, se da un crecimiento de asentamientos irregulares; afectando principalmente la cuenca de río Leones, Santo Desierto, Eslava y Viborillas, las cuales hasta esa fecha no habían estado sujetas a la urbanización. A partir de la década de 1970 se dio un crecimiento exponencial de la población en la delegación Magdalena Contreras, diez veces más que en el resto de la entidad, las viviendas se asentaron principalmente en parcelas de cultivo colindantes a las zonas boscosas (Fernández-Eguiarte, 2002). La evolución del crecimiento de la mancha urbana de 1950 a 2005 se muestra en la Figura 1.5. Los asentamientos irregulares, al no tener servicios de drenajes, han propiciado que las descargas residuales sean vertidas directamente al río Magdalena.

Otra problemática importante para la zona es su indefinición legal. En México, la tradición conservacionista moderna se inició a finales del siglo XIX con la implementación de lo que podría considerarse la primer Área Natural Protegida (ANP) del país, el “Desierto de los Leones”, estrategia que tuvo un gran auge y que siguió el modelo de Parque Nacional, proceso que se continuó hasta la década de 1960. Ésta fue durante mucho tiempo la principal herramienta de conservación, pero se limitó a ciertas áreas. A partir de la implementación de los primeros parques nacionales, se decretaron diversas ANP con un sin número de categorías diferentes, característica que ocasionó gran confusión, un ejemplo son las Zonas Protectoras Forestales.

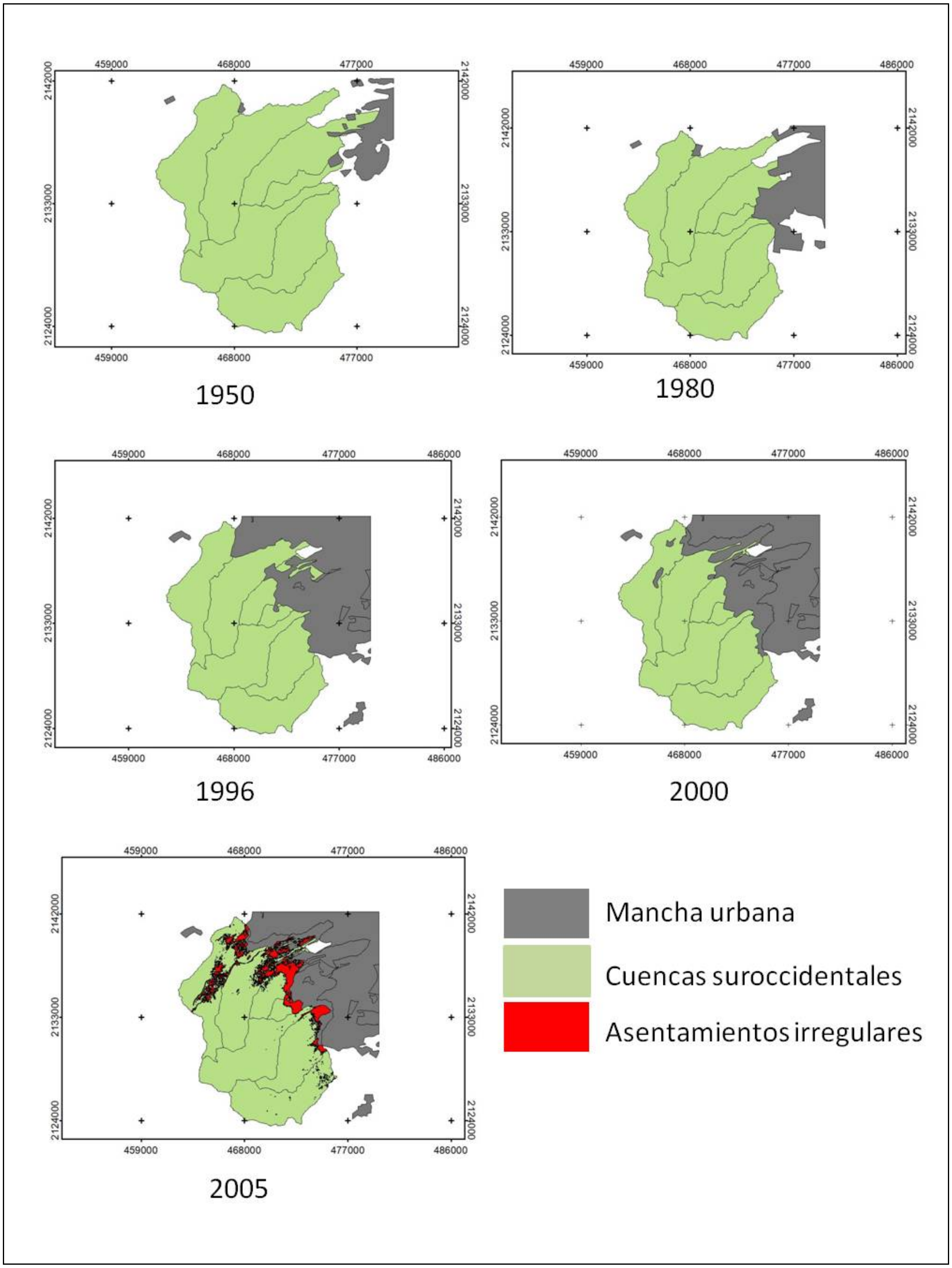

Figura 1.5- Crecimiento de la mancha urbana en las subcuencas suroccidentales de 1950-2005

Estas ANP constituyeron una importante categoría de conservación originada en la década de 1920 mediante decreto presidencial. Las zonas protectoras forestales son áreas bajo régimen de administración especial, establecidas por el poder ejecutivo en terrenos con vegetación forestal y en las cuales, según su decreto de creación, se restringen, se condicionan o se prohíben algunas actividades de manejo o uso de los recursos naturales forestales (Fernández, 1997). Bajo esta categoría fueron decretadas un gran número de áreas, pero el decreto sólo les dio legitimidad, ya que en la práctica no contaron con protección (Ramos, 2008). Este es el caso de la cuenca del río Magdalena, donde existe un acuerdo de 1932 que corresponde con la declaratoria de Zona Protectora Forestal los Bosques de la Cañada de Contreras, que establece una superficie de 3,100 ha. En 1947 mediante un decreto presidencial, se declara Zona de Protección Forestal del río Magdalena a una franja de 12 kilómetros de longitud desde el nacimiento del río hasta aguas abajo en la parte urbana, cubriendo 500 metros a cada lado del cauce (1,200 ha). Finalmente, el Programa General de Ordenamiento Ecológico del Distrito Federal publicado oficialmente en el año 2000, contradice el acuerdo y el decreto mencionados ya que establece como Área Natural Protegida una superficie de 215 ha con categoría de Zona Protectora Forestal, la cual abarca desde el cuarto dinamo hasta el inicio de la mancha urbana. A raíz de esta indefinición legal ha resultado muy confusa la administración y regulación de la zona (Almeida-Leñero *et al*., 2007).

La tenencia de la tierra, también es un factor problemático para la conservación. De acuerdo con el Registro Agrario Nacional existen 31 ejidos y comunidades dentro del SCDF, casi el 70% de su superficie (Sheinbaum, 2008). Dentro de ellos hay cerca de 25 mil hectáreas que presentan conflictos agrarios sin solución. La cuenca del río Magdalena no es la excepción; a pesar de que casi toda la superficie pertenece a la comunidad agraria Magdalena Atlitic, existen dos litigios importantes; hacia el sur se diputan 693 ha entre Magdalena Atlitic y el ejido San Nicolás Totolapan; y en la parte alta, lo que corresponde casi en su totalidad al bosque de *Pinus hartwegii*, 357 ha entre Magdalena Atlitic y el ejido de San Mateo Tlaltenango (Ávila-Akerberg, 2004). Esto último ha dificultado la restauración de zonas del bosque que se encuentran quemadas. Además, existe un traslape importante con el predio la Cañada de 118 ha, presunta propiedad privada de una compañía constructora (Ramos, 2008).

No solamente los litigios entre pueblos vecinos pueden llegar a ser un factor importante que altera indirectamente los ecosistemas, también los litigios internos. La Magdalena Atlitic es la comunidad agraria que posee la mayor extensión dentro de la cuenca del río Magdalena, pero a pesar de ello, aún siendo de la misma comunidad, existen conflictos internos que dificultan la toma de decisiones. La comunidad cuenta con títulos de propiedad otorgados desde 1535; los cuales fueron reconocidos como "bienes comunales" en el siglo XX con el reparto agrario. Las primeras solicitudes se hicieron en 1945, sin embargo la Resolución Presidencial de Confirmación de Bienes Comunales se dió hasta 1975 a 1779 comuneros donde se restituyen 2,393 ha que corresponden casi en su totalidad a la cuenca del río Magdalena. En este documento se reconocen los derechos ancestrales de la comunidad sobre su territorio y sus recursos. Sin embargo la comunidad Magdalena Atlitic se caracteriza por la falta de organización y poca participación en las asambleas ya que de 1779 comuneros censados, hay aproximadamente 300 activos. Esos mismos grupos tienen desconfianza hacia sus propias autoridades y hay grupos con conflictos de intereses. Estas características dificultan la formación de acuerdos para el manejo del bosque (Almeida-Leñero *et al.*, 2007).

Problemática ambiental

Una de los principales impactos que sufre esta zona es la tala clandestina, la cual se da principalmente hacia los límites comunales, que coinciden en su mayoría con los de la cuenca (Nava, 2006). El turismo no controlado también es un problema ya que no existen restricciones en cuanto al número de personas que ingresan desde la parte baja hasta la parte media de la cuenca, que es la zona más visitada. Así también, no hay suficiente vigilancia y control sobre las actividades que los visitantes realizan y las áreas a las que pueden ingresar. La agricultura se da en baja proporción y en forma artesanal, principalmente en la parte baja de la cuenca; la ganadería se desarrolla esencialmente en la zona media y alta de forma desordenada (Instituto de Geografía-UNAM, 2008).

Otro factor que pone en riesgo a los ecosistemas son los incendios forestales. Se tienen registros que en el SCDF se registraron en promedio alrededor de 322 incendios por cada 10 mil ha. Para la cuenca del río Magdalena, en un período de 10 años, el número de incendios forestales fue de 457 afectando un total de 584.7 hectáreas. De este periodo el año 1998 fue el que mayor número de incendios, reportando con un total de 385 hectáreas siniestradas, aproximadamente el 66% de la superficie total siniestrada en 13 años. Los incendios se presentan con mayor frecuencia en las comunidades de *Pinus hartwegii* y de *Abies religiosa* (Flores-Rodríguez, 2006; Almeida-Leñero *et al.*, 2007; Facultad de Ciencias-UNAM, 2008).

Dada la severa crisis ambiental que sufre la ciudad de México, debido a su crecimiento desordenado y al mal manejo de sus recursos hídricos resulta fundamental cuidar las áreas verdes que le quedan a esta gran urbe. El riesgo de perder estas áreas es muy alto debido a la importancia que tienen como proveedoras de servicios ecosistémicos, por ser de las zonas mejor conservadas y servir como reservorios de agua para la población.

En resumen, dada la relevancia que tiene la cuenca del río Magdalena por los servicios ecosistémicos que provee, aunado a la vulnerabilidad que presenta por su problemática tanto social como ambiental, convierten a esta zona como un lugar idóneo para proponer alternativas para el manejo del agua desde la perspectiva de servicios ecosistémicos.

Antecedentes de estudios en la zona

La Facultad de Ciencias ha trabajado en la cuenca del río Magdalena desde hace más de 10 años. Primero con proyectos aislados, después con un Censo de Biodiversidad para la delegación Magdalena Contreras y posteriormente con el Macroproyecto Manejo de Ecosistemas y Desarrollo Humano. En el año 2008 se firmó un Convenio entre el Gobierno del Distrito Federal y la UNAM para elaborar el Plan Maestro Integral y Aprovechamiento Sustentable de la cuenca del río Magdalena. En este estudio, además de la Facultad de Ciencias, participaron otras entidades de la UNAM. Dicho proyecto plantea acciones de manejo, conservación, uso y restauración de la cuenca del río Magdalena, con el objetivo de no poner en riesgo su potencial como prestadora de servicios ecosistémicos, especialmente de carácter hídrico para la ciudad. Un año después se realizó junto con el Programa Universitario de Medio Ambiente, el estudio sobre “Sistema de Indicadores para el rescate de los ríos Magdalena y Eslava”. El objetivo del informe era dotar al Gobierno de la Ciudad de una herramienta que le permitiera monitorear el avance en el cumplimiento de los objetivos planteados en el Plan Maestro. Además de los proyectos institucionales, se han realizado diversas tesis tanto de nivel licenciatura como maestría, los trabajos tienen diferentes enfoques, en la Tabla 1.1 se presentan los orientados a la recuperación ambiental del bosque y del río Magdalena.

Estos trabajos han sido un parteaguas fundamental para la realización de esta tesis doctoral, ya que sin la información previa no hubiera sido posible la realización de este estudio.

Tabla 1.1- Tesis realizadas en la cuenca del río Magdalena en los últimos 6 años.

Autor	**Tesis realizadas**
Jujnovsky, 2006	Servicios ecosistémico relacionados con el recurso agua en la cuenca del río Magdalena, Distrito Federal, México.
Bojorge-García, 2006	Indicadores biológicos de la calidad del agua en el río Magdalena, D.F.
Gómez, 2007	Redefinición de los ríos de la Ciudad de México como solución hidráulica y urbana: caso de estudio rio de la Magdalena.
Flores, 2008	Evaluación de la calidad del agua en el río Magdalena.
Ramos, 2008	Propuesta de reclasificación y zonificación participativa de la Zona Protectora Forestal Cañada de Contreras, Distrito Federal, México
González-Martínez, 2008	Modelación hidrológica como base para el pago por servicios ambientales en la microcuenca del río Magdalena, Distrito Federal.
Monges, 2009	Calidad del agua como elemento integrador para la rehabilitación del río Magdalena, Distrito Federal.
Velázquez, 2009	Propuesta de plantas de tratamiento para el saneamiento del río Magdalena
Ávila-Akerberg, 2009	Forest quality southwest Mexico City. Assessment towards ecological restoration of ecosystem services.
Morales-Luque, 2010	Evaluación de la calidad del agua en el río Magdalena, D.F. como servicio ecosistémico
Caro-Borrero, 2012	Evaluación del pago por servicios ambientales hidrológicos: Una perspectiva socioambiental en la cuenca del río Magdalena, México, D.F

C A P I T U L O 2

SERVICIOS ECOSISTÉMICOS HIDROLÓGICOS

Hidrobiológica 2010, 20 (2): 113-126

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 southwestern 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 subbasin, 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).

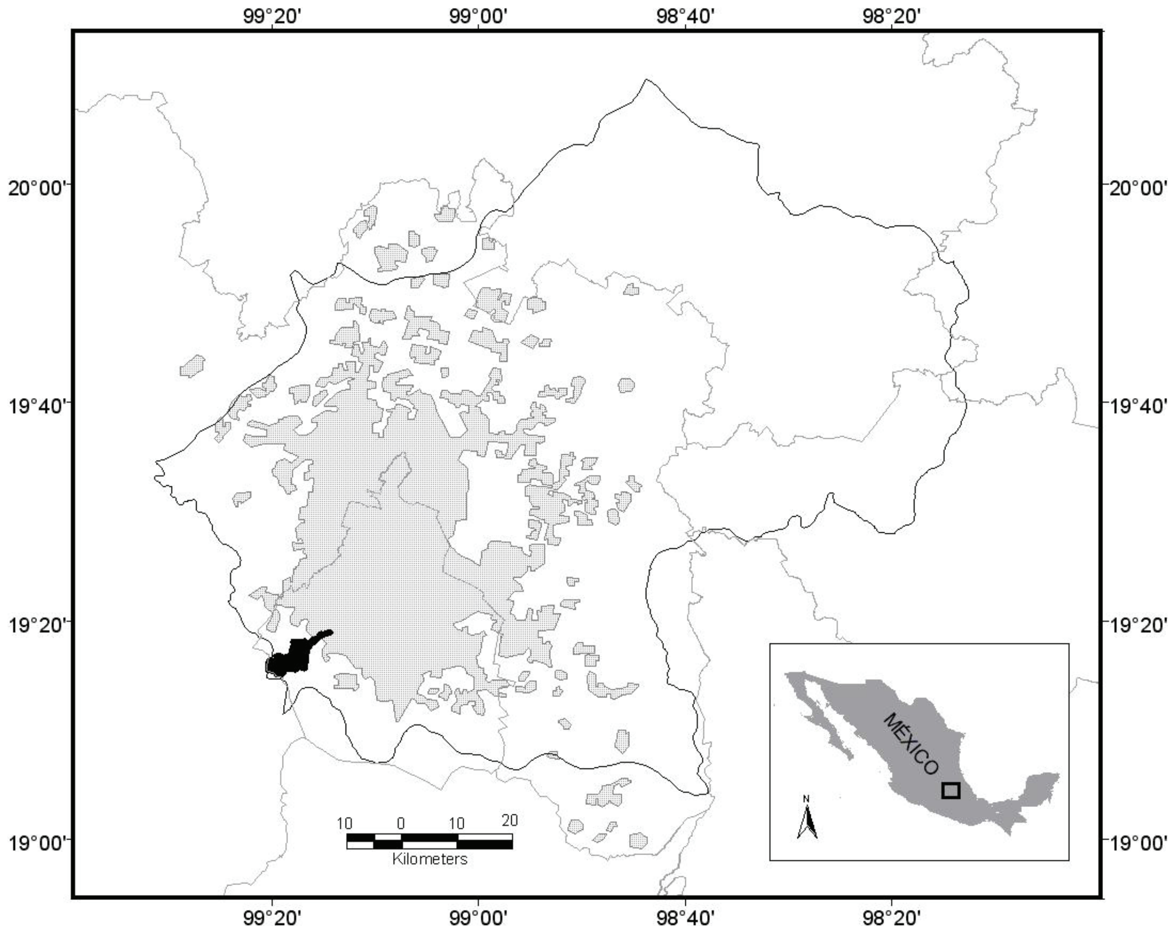

Figure 1. Location of the Magdalena River watershed (black), the Basin of Mexico (white) and the Mexico City Metropolitan Area (grey).

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^{3}s^{-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

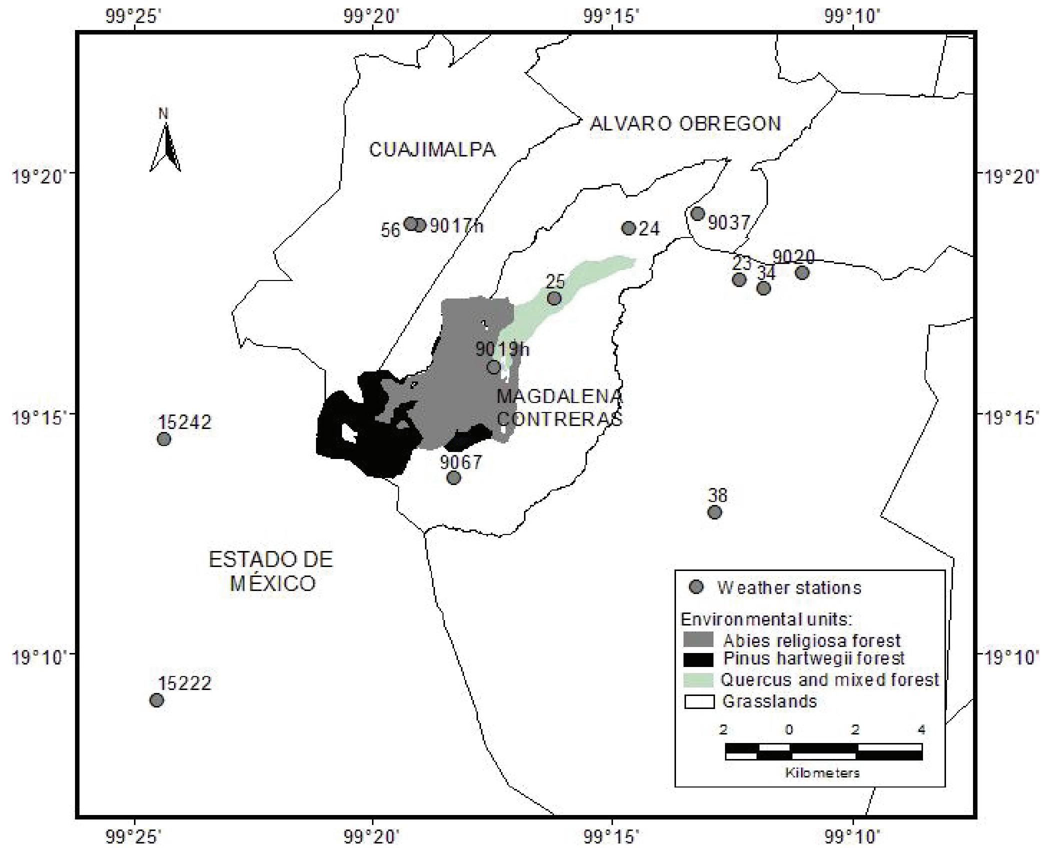

Figure 2. Location of the meteorological stations and the three environmental units described in the text and detail of the MRW crossing three counties; Cuajimalpa, Alvaro Obregon and Magdalena Contreras.

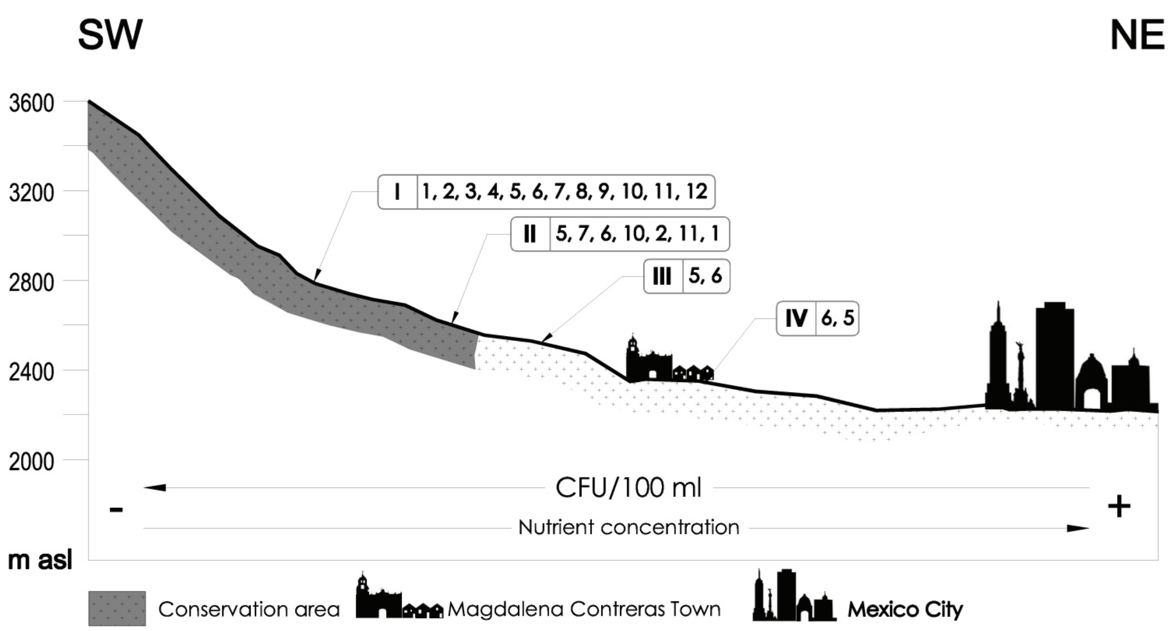

Figure 3. Variation of the diatom association and bacteria counts (CFU/100 mL) according to a degradation gradient. Sampling stations are at: I (2801 m asl), II (2530 m asl), III (2490 m asl) and IV (2308 m asl). Numbers represent the species, in order from higher to lower abundance. 1. *Cymbella silesiaca*; 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*.

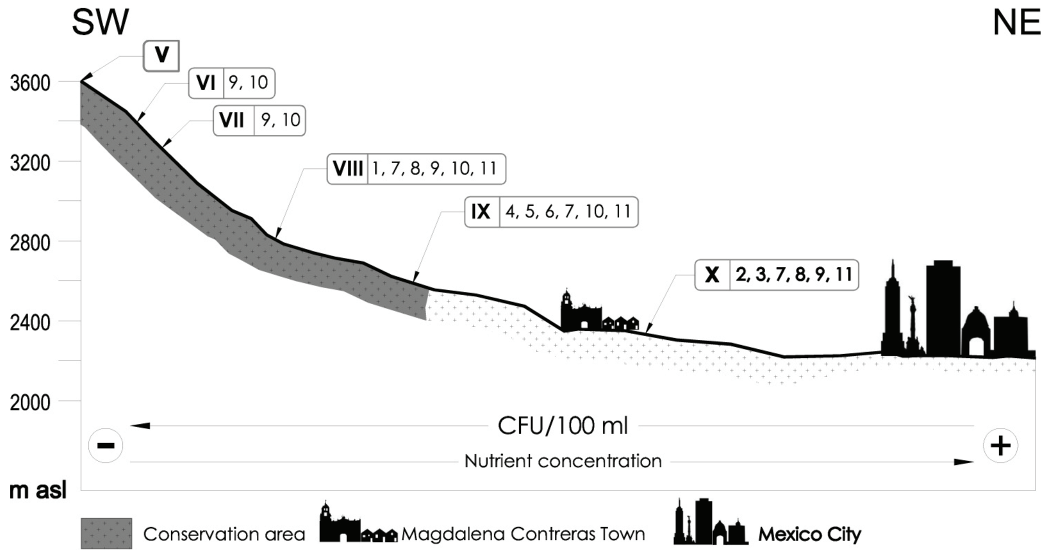

Figure 4. Bacteriological indicators (CFU/100 mL) variation, according to the altitude and degradation gradient. Sampling sites V (3600 m asl), VI (3370 m asl), VII (3250 m asl), VIII (2801 m asl), IX (2530 m asl) and X (2308 m asl). Numbers represent the bacteria species identified, and the (number) 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 0.13 ± 0.05	0.59-0.85 0.71 ± 0.13	0.68-0.83 0.73 ± 0.09	0.38-0.90 0.60 ± 0.27	0.33-0.93 0.58 ± 0.31	0.35-0.53 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
$N-NH_4$	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
$N-N0_3$	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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Assessment of Water Supply as an Ecosystem Service in a Rural-Urban Watershed in Southwestern Mexico City

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Abstract Studies from the ecosystem services perspective can provide a useful framework because they allow us to fully examine the benefits that humans obtain from socio-ecological systems. Mexico City, the second largest city in the world, has faced severe problems related to water shortages, which have worsened due to increasing population. Demand for space has forced changes in land cover, including covering areas that are essential for groundwater recharge. The city has 880 km^2 of forest areas that are crucial for the water supply. The Magdalena River Watershed was chosen as a model because it is a well-preserved zone within Mexico City and it provides water for the population. The general aim of this study was to assess the ecosystem service of the water supply in the Magdalena River Watershed by determining its water balance (SWAT model) and the number of beneficiaries of the ecosystem services. The results showed that the watershed provides 18.4 hm^3 of water per year. Baseflow was dominant, with a contribution of 85%, while surface runoff only accounted for 15%. The zone provides drinking water to 78,476 inhabitants and could supply 153,203 potential beneficiaries. This work provides an example for understanding how ecosystem processes determine the provision of ecosystem services and benefits to the population in a rural–urban watershed in Mexico City.

Keywords Ecosystem services · Magdalena River Watershed · SWAT model · Water balance · Mexico City

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Introduction

The severe environmental crisis caused by the transformation of natural ecosystems and the human dependence on the services they provide was recognized a few decades ago (Ehrlich and Ehrlich 1991; Urquidi 1994). The understanding of the processes that drive these changes in ecosystems is limited because scientific disciplines use different concepts and languages to describe and explain the socio-ecological systems. For example, in a protected area, ecologists and sociologists face the problem of deforestation in very different ways; the ecologists would like to combat soil degradation processes and encourage natural regeneration, while the sociologists would like to combat the problems of marginalization and poverty. As Ostrom (2009) advised, if we do not build a common conceptual framework of the social and environmental fields, we will only generate isolated knowledge. Since the beginning of the 21st century, joint efforts have been made among scientists, countries and institutions to apply basic scientific information to understanding the consequences of the use of natural resources for human welfare. Examples of these efforts are the Millennium Ecosystem Assessment (MA) (2005), the Global Land Project (GLP) (2005) and the

International Geosphere-Biosphere Programme (IGBP) (2006). However, despite all international efforts to assess the Earth's systems as a whole, a number of complications arise when trying to assess a particular ecosystem. Studies from an ecosystem services (ES) perspective can generate a common framework between the social and environmental fields, and this combined/integrated approach may allow us to realize the benefits that humans obtain from socio-ecological systems. ES have been defined many times, and the definition changes depending on the context in which it is employed (Daily and others 1997; Costanza and others 1997; De Groot and others 2002; Kremen 2005; Quétier and others 2007; Boyd and Banzhaf 2007; Dale and Polasky 2007; Stanton and others 2010). We used the definition of Millennium Ecosystem Assessment (2003) as "the benefits that humans obtain from ecosystems" because of its simplicity, broad coverage and suitability for environmental management purposes. This concept adds a new perspective to the problem of natural resource management, in which interconnected ecological processes and the management of nature and its services must be properly integrated. Also, by recognizing that ecosystem processes are services that benefit humans, the task of conserving and managing them properly becomes easier because the benefits that they entail are evident. These benefits include, for example, the water supply, air purification, scenic beauty and soil erosion control (Millennium Ecosystem Assessment 2003).

The links between human welfare and ecosystems for most of the planet's ecosystems are not fully known due to a variety of socio-economic factors and the multiple scales on which environmental information is applied, from global to local. This lack of knowledge results in bad decisions for the management of ecosystem services (Balvanera and Cotler 2007). One of the challenges in developing countries, such as Mexico, is that there is very little information upon with to make management decisions. Researchers often require "further investigation" before giving suggestions, and politicians make decisions without knowing the dynamics of ecosystems and the consequences of the inadequate management of them. Given that environmental problems need immediate solutions, it is necessary to propose guidelines for ecosystem management based on the available scientific information, which can then be used to make informed decisions according to the functioning of the ecosystem.

Many regulating, provisioning, supporting and cultural services are related to water. Some of the services that people benefit from most directly include the provision of drinking water, irrigation water, hydropower, fish, and opportunities for recreation, and flood mitigation (Brauman and others 2007). Among these services, the water supply is likely the most crucial for the maintenance of cities; therefore, understanding ecosystem processes that generate this benefit is critical to creating sustainable programs for megacities.

Mexico City, the second largest in the world (Mazari and others 2001, UNESCO-WWAP 2003, United Nations 2009), has faced severe problems related to water shortages, which have worsened due to increasing population and the pollution of aquifers (Uitto and Biswas 2000). Increasing urbanization has resulted in the creation of the Metropolitan Area of Mexico City, and demand for space for the growing population has forced changes in land cover, including areas that are essential for groundwater recharge (Uitto and Biswas 2000). The total volume of water used by Mexico City is estimated to be 60 m^3/s, of which approximately 70% is obtained from the Basin of Mexico and 30% from external sources, such as the Lerma and Cutzamala basins, which are more than 100 km away from the city (Jujnovsky and others 2010). Most of the water consumed within Mexico City is obtained from underground sources, and some springs and the Magdalena River are among the few surface water systems that have survived (Ezcurra and others 2006; Sheinbaum 2008). Mexico City still has 880 km^2 of forested area that is classified as a "preservation zone" (Sheinbaum 2008). Because these forests are crucial for the water supply, it is essential to take immediate measures to prevent their urbanization. The development of short-, medium- and long-term programs for ecosystem management, both regionally and locally, is needed to meet the challenge of providing water to the inhabitants of the metropolitan area. Some of the priority sites for the implementation of these programs are the watersheds located in the southwest of the preservation zone. An example is the Magdalena River Watershed (MRW), which was chosen as a model for this study because it is a well-preserved zone in the southwest of Mexico City, provides water for the population and has been studied by the National University of Mexico (UNAM) for nearly a decade (Ávila-Akerberg 2010).

Previous studies have attempted to estimate the volume of water that the Magdalena River Watershed (MRW) provides (González–Martínez TM 2008; Jujnovsky and others 2010). However, due to the lack of environmental information available in the area when these studies were conducted, greater precision is still needed to understand the value of the benefits generated by this ecosystem. It is therefore necessary to obtain a more robust value for the amount of water in the watershed using the preliminary studies as a baseline and to improve the model by incorporating new information with a socio-ecological approach.

Although much has been written on ecosystem services in recent years, there are few studies that show the relationship between ecosystem processes and their direct benefit to the population (Egoha and others 2007). Therefore, the general aim of this study was to assess the ecosystem service of the water supply in the MRW. It was necessary to determine the water balance to understand the ecological processes related to the hydrological cycle and to calculate the population benefiting from the ecosystem service.

Methods

Study Area

The MRW is home to one of the major rivers in Mexico City and has high biodiversity; it hosts a high percentage of the endemic species to the Basin of Mexico (Jujnovsky 2006; Almeida and others 2007; Ávila-Akerberg and others 2008). It is located at 19° 15′ 00″ N and 99° 17′ 30″ W inside the Basin of Mexico (Fig. 1). The entire watershed covers about 33 km^2, the climate is temperate humid in the lower parts (2400–2800 masl) and semi-cold in the higher parts (2800–3850 masl), the annual precipitation is 900 mm in the lowlands and 1300 mm in the highlands, and the annual temperature ranges are between 9 and 15 °C (García 1988; Dobler 2010). There are three different soil units, Litosol, Feozem, and Andosol. The humic Andosol subunit is the most widely distributed (Álvarez 2000). Given the conserved status of its forests, the MRW is considered to be the most important continuous mass of vegetation and one of the more diverse temperate ecosystems of central Mexico (Facultad de Ciencias-Universidad Nacional Autónoma de México (UNAM) 2008).

The Magdalena River is the main surface water body in Mexico City; it has good water quality in the higher portion, which deteriorates as it flows down to the urban area, mainly because it is mixed with sewage water (Jujnovsky and others 2010). The Magdalena River has its headwaters at the base of Palma Hill (3650 masl) and has a total length of approximately 22 km, along which it is fed by various springs. It flows through 12 km of natural area where the predominant vegetation community is *Pinus hartwegii* (pine) and *Abies religiosa* (fir) at higher altitudes and mixed and *Quercus* forest (oak) at lower altitudes. At 2770 masl, a water treatment plant distributes 200 L/s to the Delegación Magdalena Contreras, while two-thirds of the remaining water continues its path into the city, where it is used as sewage and receives inputs from several collectors (Jujnovsky and others 2010). Within the city, the river runs for 10 km until it is piped into the Churubusco River (a larger river which flows out of the Basin of Mexico).

For the purposes of this study, the watershed was divided into two zones to evaluate water provision as an ecosystem service: (1) the source where the service (fresh water) is generated and (2) the location where the water is consumed, this means where potentially beneficiaries are. The ecosystem service generation zone covered an area of 28.8 km^2 and was defined as beginning at the natural watershed and ending at the Magdalena River Hydrometric station, which is the point where the channel measurements reflect the hydrological function of the watershed. Because it is very difficult to follow the natural boundaries of a watershed in urban areas, the ecosystem service consumer area was determined using a polygon of influence. The polygon was proposed in

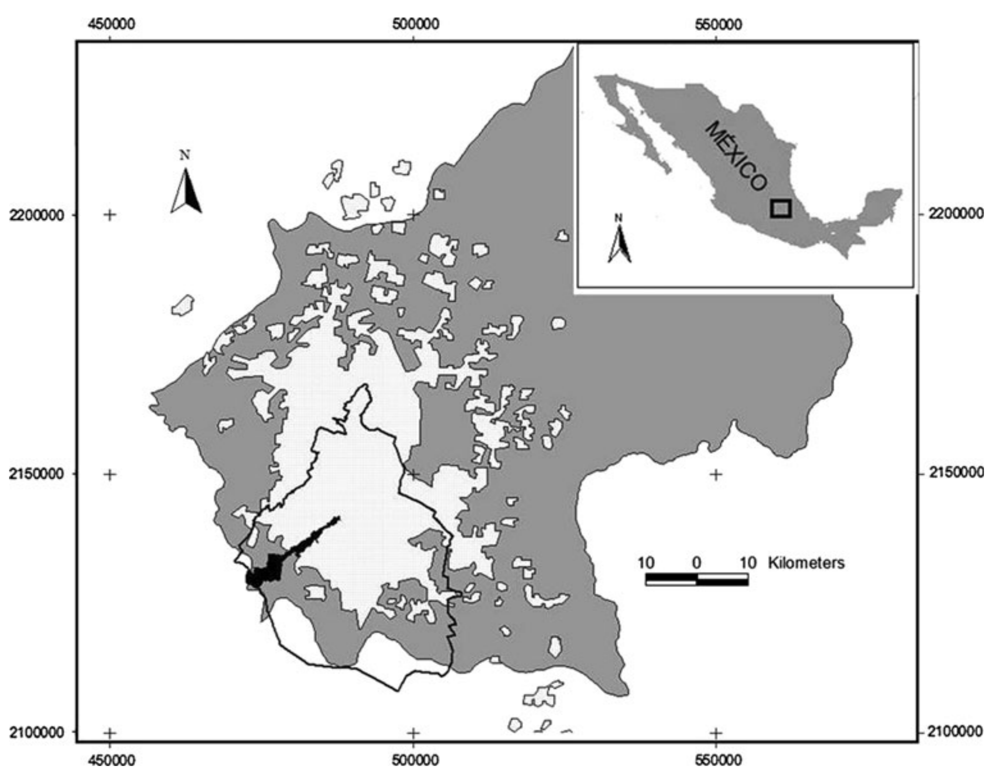


Fig. 1 Location of the Magdalena River Watershed (*in black*), the Basin of Mexico (*in dark grey*), the metropolitan area of Mexico City (*in light grey*), Distrito Federal (*thin blackline*)

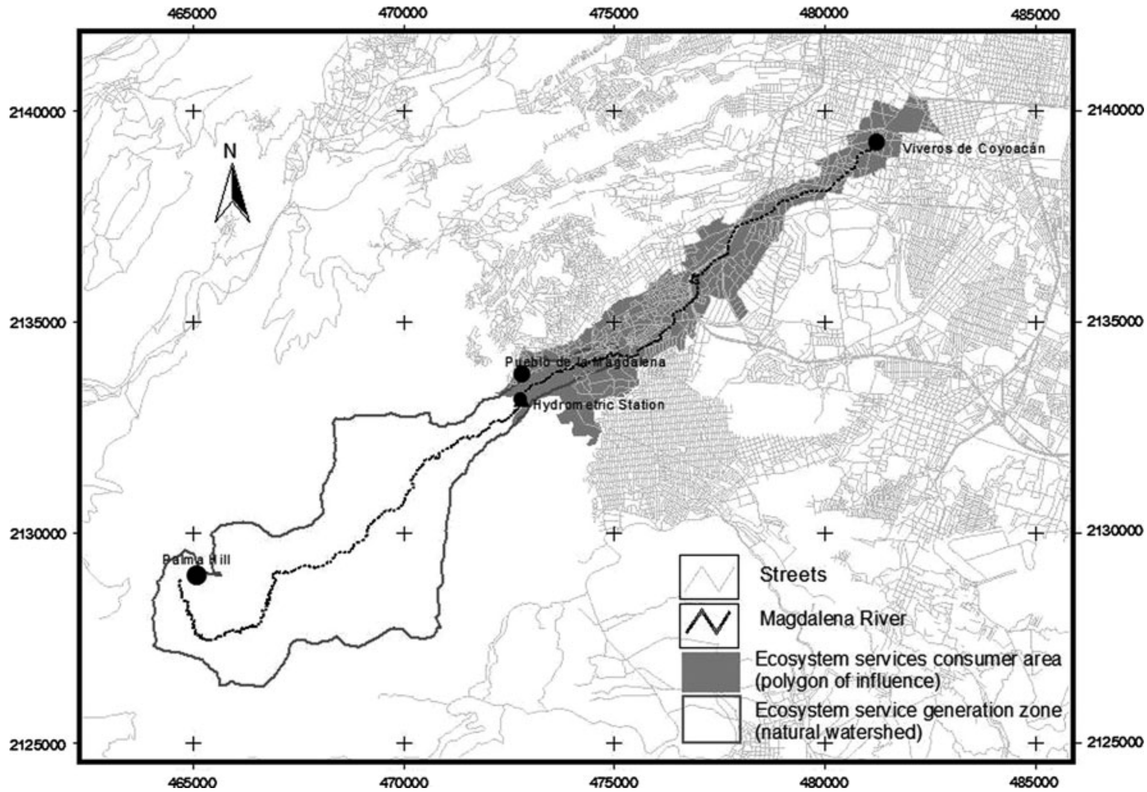


Fig. 2 The Magdalena River Watershed divided into two zones, the zone where the service is generated and the zone where it is consumed

the "Master Plan for Integrated Management and Sustainable Use of the Magdalena River Watershed" by a collaboration agreement between the government of Mexico City and the National University of Mexico (Programa Universitario de Estudios Sobre la Ciudad (PUEC-UNAM) 2008). The delimitation was performed according to the basic geostatistical areas (AGEBs) that cross the river within a radius of 500 m of each side of the channel. The AGEBs are units of information used by the "National Institute of Statistics, Geography and Informatics" (INEGI) to integrate socio-economic data. The polygon extends from the natural area (town of Magdalena) to the "Viveros de Coyoacán", where the Magdalena River is completely piped (Fig. 2).

Water Supply Determination

To determine the water supply, it is necessary to assess the water balance of the Magdalena River. The water balance is defined as $WB = P - Et - RO - \Delta SM$, where WB = water balance, P = precipitation, Et = evapotranspiration, RO = runoff (surface runoff + baseflow + water recharge of the confined aquifer), and ΔSM = change in soil moisture (Neitsch and others 2002).

Runoff is an element of the water balance that can be considered to be a water provision ecosystem service because it can be used by people. To assess the runoff generated by this watershed, hydrologic modeling was conducted using the SWAT model (Soil and Water Assessment Tool), which is the AvSWAT interface 2003 for ArcView 3.2 developed by the US Department of Agriculture (Neitsch and others 2002). It uses water balance as its baseline to determine the input, output and storage of water in the basin. The model works at various scales, including basins and sub-basins which are defined by the hydrological network. Which are them divided into smaller units, using the intersection of two factors that are essential to define the behavior of water in the soil, land cover and soil type, resulting in hydrological response units (HRUs).

The basic steps for using the SWAT model are data entry, calibration of parameters, validation and statistical analysis. The modeling process starts with the collection of data from previous studies (González–Martínez TM 2008; Facultad de Ciencias-Universidad Nacional Autónoma de México (UNAM) 2008; Jujnovsky and others 2010) that can be fed into the model and, in conjunction with parameters derived from field work, used to create a more robust and representative model. The data that were fed the program were the land cover, soil and vegetation type characteristics, hydrologic network type, location of weather stations and weather parameters (Table 1); SWAT requires daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity.

Table 1 Basic information used to run the SWAT model

Information	Source	FORMAT
Digital elevation model	Instituto Nacional de Estadística, Geografía e Informática (INEGI) (2000)	Grid
Land cover Map	Ávila-Akerberg (2005)	Grid
Soil units Map	Registro Agrario Nacional (RAN) (2000) (Only took into account the major soil units)	Grid
Hydrology	Ávila-Akerberg (2002)	Shape
Weather stations	ERIC III (Instituto Mexicano de Tecnología del Agua (IMTA) 2007) (daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity)	dBase
Zarco		
San Francisco		
Río Magdalena		
Monte Alegre		
Desviación Alta al Pedregal		

The SWAT model needs to be calibrated in order to adjust the calculated and observed data. It is necessary to have the actual flow data of the drainage networks in order to compare it with the flows simulated by the SWAT model. We used the Magdalena River hydrometric information for 1999 based on the hydrograph separation filter (Lyne and Hollick 1979) previously made by González–Martínez TM (2008). The model was calibrated adjusting the simulated data to observed. The adjustment was made using the Nash-Sutcliffe index and the coefficient of determination until statistical analysis showed acceptable values. The parameters modified during calibration can be seen in Appendix 1.

For the validation process the model was run again but using climatological and hydrometric data from 2000.

Components of the Hydrologic Cycle and Vegetation Relationships

The SWAT model provides information regarding the components of the hydrologic cycle (Table 2), so the variables involved in calculating the water balance were *precipitation*, *water content in soil*, *actual evapotranspiration*, *potential evapotranspiration*, *surface runoff*, *baseflow, recharge*, and *total water yield*. With the information generated from the modeling in the calibration step, we identified the components of the hydrologic cycle for each vegetation type, and therefore their role in ecosystem services generation, i.e., the amount of water produced. With this information, we determined how the hydrological cycle processes were involved in generating the ecosystem service of water supply in the forest.

Identification of Beneficiaries

The identification of beneficiaries was conducted according to the polygon of influence and to the areas of river water distribution. The real beneficiaries for this study were defined as the current users of the water that is generated in the watershed and potential beneficiaries as people who lived within the polygon of influence but received water from sources other than the Magdalena River.

Table 2 Description of the components of the hydrologic cycle

Components Of Hydrologic Cycle	Description
Precipitation	Amount of water that falls on a region
Content of soil water	Moisture that remains in the soil at the end of a period of time
Water yield	Total amount of water that contributes to the recharge of the main channel of the river. It is the sum of the surface, lateral subsurface and groundwater flow
Actual evapotranspiration	Loss of surface moisture by evaporation and by transpiration by vegetation that occurs under the current conditions
Potential evapotranspiration	Maximum amount of water that can evaporate from soil completely covered with vegetation under optimal conditions
Surface runoff	Amount of water runoff on the soil surface layer
Baseflow	Amount of water that infiltrates into the ground as subsurface or groundwater flow and contributes to the recharge of the river
Recharge	
Unconfined aquifer recharge	Amount of water that infiltrates into an aquifer that has a limit above the water table. This is also known as a shallow aquifer. It can contribute to both the main river flow and to the recharge of the watershed
Confined aquifer recharge	Amount of water that infiltrates into an aquifer for which the upper and lower limits are found in geological formations with very low hydraulic conductivities and are almost impermeable. The water that enters the aquifer contributes to recharge or runoff outside of the basin

The real beneficiaries were identified according to data from the agency responsible for water management in Mexico City (SACM). This institution uses an information system based on neighborhoods or "Colonias". However, the agency responsible for generating socioeconomic and population data (INEGI) used "AGEBs" instead. The "Colonias" were used to investigate their sources of water supply and to determine the actual consumption zones of the Magdalena River, and the "AGEBs" were used to determine the population of each neighborhood. Once the beneficiaries were identified, the population number of each colony was estimated. We identified areas that belong to the polygon of influence and those that were outside. We calculated the total population of the polygon and the population that did not belong to but received water from the Magdalena River. Information about the number of inhabitants was obtained from the national population agency (Instituto Nacional de Estadística, Geografía e Informática (INEGI) 2008), and the distribution of water was obtained from the records of the water agency (Dirección General de Construcción y Operación Hidráulica (DGCOH) 2001).

To calculate the actual water availability per capita of the whole polygon (real and potential beneficiaries), the annual baseflow was transformed into daily runoff, differentiating between the rainy season, when rainfall exceeded 60 mm per month (July to November) and the dry season (December to June), divided by the number of people within the polygon of influence. This value was calculated as PWA = DBF/N, where PWA = Water availability in liters/person/day, where DBF = daily amount of water generated by baseflow and N = total number of inhabitants within the polygon of influence.

Results

Water Supply Determination

The calibration model had an acceptable fit between the observed and the simulated annual hydrometric data ($r^2 = 0.878$, Nash–Sutcliffe Coefficient = 0.525), which allowed us to analyze the information. The results show that the watershed provides 18.4 hm^3 of water per year. Baseflow was dominant, with a contribution of 85%, while surface runoff only accounted for 15%. The lateral subsurface flow contributed 98% of the baseflow, and only 2% drained to the unconfined aquifer as groundwater flow.

The forests in this watershed released 440 mm of water per year into the atmosphere by evapotranspiration, which accounted for 40% of the rainfall. According to the model, only 0.43% of the rain water recharged the confined aquifer, which means that almost all of the flow in the basin returns to the river in a short time.

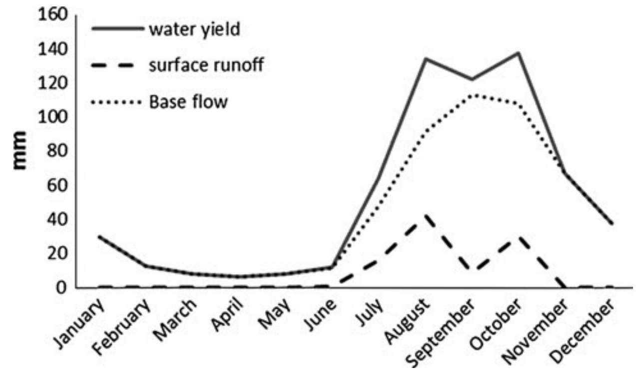


Fig. 3 The Magdalena River Watershed annual baseflow, surface runoff and water yield shown in mm

The monthly data showed that baseflow was greater than surface runoff throughout the year (Fig. 3), with the months of July to November having the greatest water yield. It is important to note that from November to February, there is no surface runoff, so the baseflow provides water to the river in the dry season.

Components of the Hydrologic Cycle and Vegetation Relationships

The SWAT model defined 17 runoff units (or sub-basins) and 13 land cover units. These units included the three types of forests (*Abies religiosa*, *Pinus hartwegii* and *Quercus* and mixed forest) and their associations, including a small portion of the urban area (Fig. 4). The data allowed us to analyze the relationship between vegetation and the components of the hydrological cycle (water yield, surface runoff, baseflow, confined aquifer recharge and evapotranspiration).

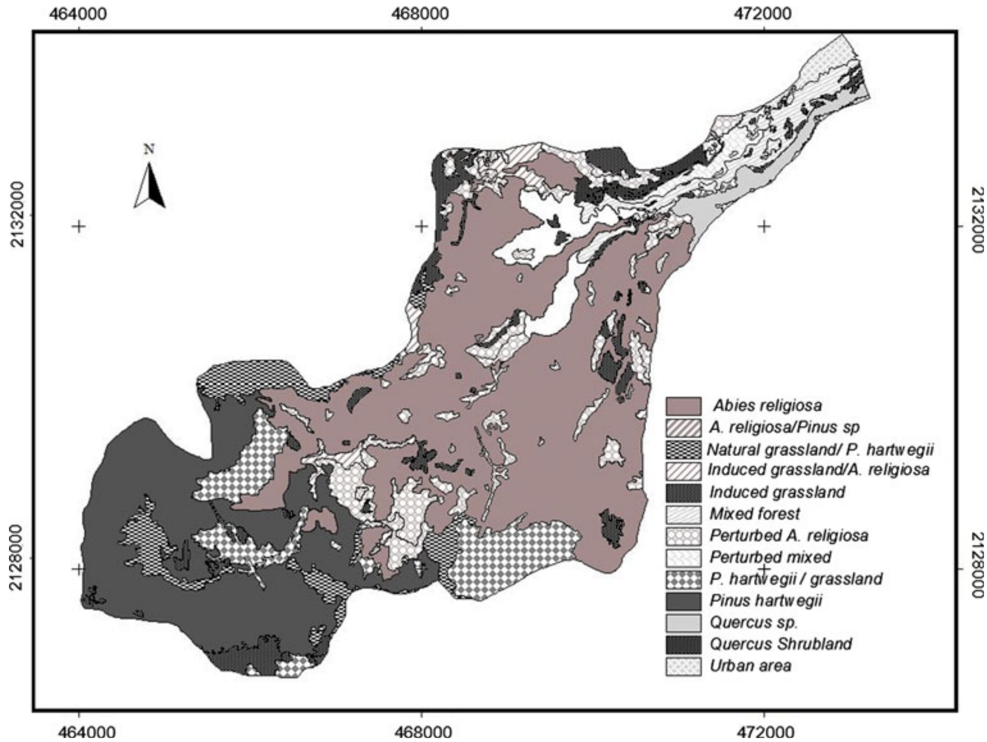
Water Yield

The *Pinus hartwegii* forest, in association with natural grasslands, had the greatest potential to generate water yield, with mean values up to 115 mm per year (Fig. 5a), while the urban land cover generated the lowest value. Due to their size, *Abies religiosa* and *Pinus hartwegii* forests generated the largest annual total runoff volume, 7.4 and 4.5 hm^3, respectively (Fig. 5b).

Surface Runoff

The urban land cover had the greatest susceptibility to generate surface runoff with an annual average of 477 mm. Induced grassland areas were also highly prone to form this type of flow and had values between 257–201 mm. Conversely, the oak-scrub vegetation community was characterized by the lowest tendency to generate surface runoff

Fig. 4 Land cover units in generation zone of Magdalena River Watershed, based on Ávila-Akerberg (2005)



(7 mm) (Fig. 5a). Due to their extension *Abies religiosa* and *Pinus hartwegii* were the main contributors to the total volume of surface runoff. In contrast, *Quercus* sp. produced the lowest volume of surface water runoff, which can be attributed to its flat topography and smaller area compared to *Abies* and *Pinus* forests (Fig. 5b).

Baseflow

The areas with the greatest capacity to generate baseflow were in the upper basin and corresponded to *Pinus hartwegii* forest and natural grassland, with average values between 606 and 579 mm per year. The urban area had an average baseflow of 25 mm, which was considerably lower than that of any vegetation unit (Fig. 5a). Taking into account the total volume, the *Abies religiosa* and *Pinus hartwegii* vegetation units contributed the greatest amount of baseflow to the watershed, with annual volumes of 6.5 and 3.8 hm^3, respectively, while the urban areas provided very small amount of baseflow water (5892 m^3) (Fig. 5b).

Evapotranspiration

The highest evapotranspiration capacity occurred in areas of natural grassland, *Pinus hartwegii* forest and induced grassland, with annual mean values ranging from 431 to 485 mm, while the urban area had the lowest evapotranspiration capacity (348 mm). Due to its area, the *Abies religiosa* forest was the vegetation unit with the highest evapotranspiration value, followed by *Pinus hartwegii* and *P. hartwegii*-grassland. From the 12.7 hm^3 of water lost through evapotranspiration, 42% was lost from the *Abies religiosa* forest, 21% from the *Pinus hartwegii* and 7.8% from the *P. hartweggi*-grassland.

Confined Aquifer Recharge

The *Abies religiosa* and *Pinus hartwegii* forests recharged 61% of the water in the confined aquifer. The *Quercus* shrubland contributed the smallest amount for recharge. It should be noted that the induced grassland-*Abies religiosa* forest, perturbed mixed forest and urban areas were identified by the model as areas with a high potential for recharging the confined aquifer. Figure 6 shows schematically the behavior of water in the watershed according to the types of forests and their associations.

Identification of Beneficiaries

The ecosystem service consumer area, the polygon of influence, covered 32 AGEBs located on either side of the Magdalena River, from the "town of Magdalena" to the "Viveros de Coyoacan". The total population of the polygon was 107301 inhabitants according to the 2005 census

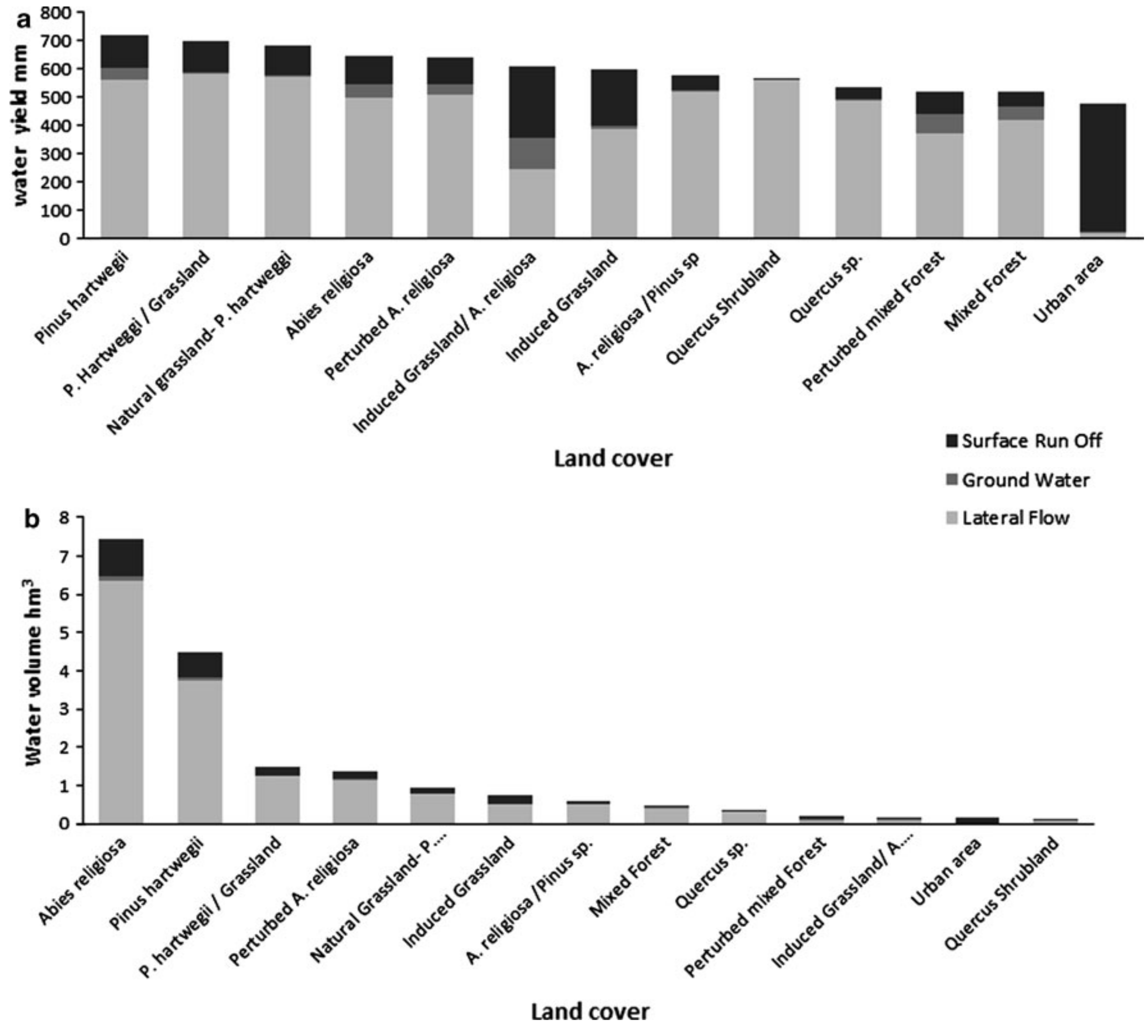


Fig. 5 Amount of water generated by vegetation unit according to flow type (surface runoff and baseflow, divided into subsurface and groundwater) shown in mm (**a**) and in total volume hm^3 (**b**)

data (Instituto Nacional de Estadística, Geografía e Informática (INEGI) 2008). There were 78476 beneficiaries who receive water from the MRW. Forty-one percent belonged to the polygon of influence, and the rest were residents of highland areas that received pumped water (Fig. 7); therefore, only 32,273 inhabitants from the polygon received water from the Magdalena River, and 59% supplied their water needs from external sources, such as wells and the Lerma-Cutzmala Systems. If we take into account the total population of the polygon of influence and the people who actually received water from the Magdalena River, there were 153,203 potential beneficiaries, which is almost twice as many identified real beneficiaries.

Considering the baseflow only, the MRW generated, on average, 0.043 hm^3 of water per day. During the rainy season, the basin generated enough water to supply a total of 526 l to each of the 153,203 potential beneficiaries (Table 3).

Discussion

Water Provision as an Ecosystem Service

Brauman and others (2007) proposed that one of the main points to be addressed for the development of ecosystem service assessment is to understand its biophysical generation in the ecosystem. Our work provides a fundamental tool for understanding how ecosystem processes, in this case the components of the hydrological cycle, determine the provision of one ecosystem service (water supply) and how this benefits the population. The evaluation of baseflow was critical to assess the ecosystem service of the water supply because it gives both spatial and temporal information on service availability and the actual and potential beneficiaries.

Temperate forests located in header watersheds, such as in the MRW, play an important regulatory function in the ecosystem because they affect the quantity, quality and

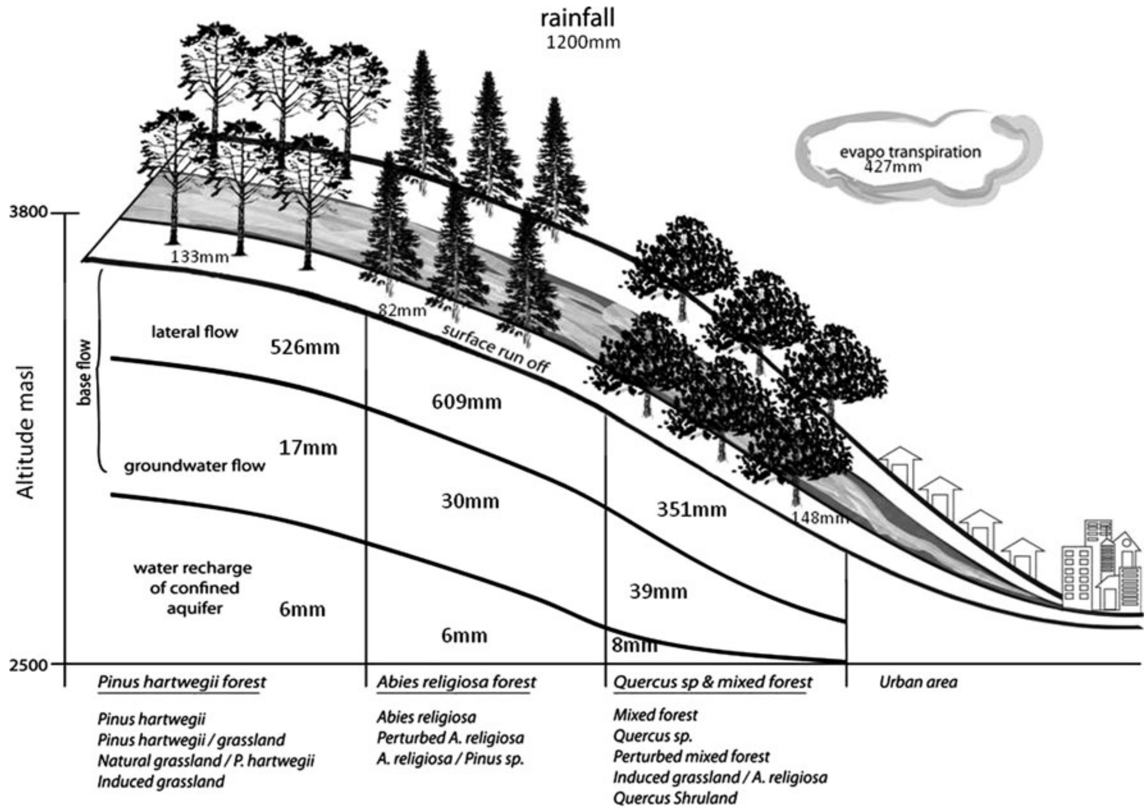


Fig. 6 Schematic representation of water behavior (surface runoff, baseflow, groundwater recharge) in the Magdalena River Watershed according to the types of forests and their associations

timing of water flow; protect the soil from being eroded; and prevent the degradation of rivers throughout the watershed (Cotler 2004). Data concerning the relationship between vegetation and hydrological behavior are essential for management proposals in specific areas. Sixty-six percent of well-preserved forests remain in the study area (Facultad de Ciencias-Universidad Nacional Autónoma de México (UNAM) 2008), producing only 15% of the water flow in a superficial way, while 85% is produced as baseflow, both in the unsaturated soil zone (lateral subsurface runoff) and in the saturated zone (groundwater).

Each vegetation type has different water requirements according to their physiology and environmental conditions (Matsumoto and others 2008; Brümmer and others 2011). For example, Silberstein and others (2002) reported that evapotranspiration in some *Eucalyptus* forests accounts for 90% of the precipitation; while in the study area where 70% of the forests are coniferous, only 40% of the water is released into the atmosphere.

The pattern in the amount of water flowing on the surface and as baseflow in the Magdalena River Watershed is similar to that reported by Robinson and others (2003) for coniferous forests. The areas with the greatest susceptibility to the generation of surface runoff were urban land cover and induced grasslands, and the zones that had the greatest ability to generate baseflow were in the upper basin and corresponded to *Pinus hartwegii* forests. It is important to note that the urban land cover had a lower baseflow than any vegetation unit in the study area. This result is consistent with those values reported by Huber and others (1985); Huber and López (1993) and Bent (2001), who showed that logging causes a significant change in the temporal and spatial distribution of reserves of soil water and evapotranspiration from a watershed, proving the importance of forests for the regulation of the amount of subsurface and underground water. Also, as Bruijnzeel (2004) stated, a good vegetation cover is able to prevent surface erosion and, in cases where the coverage is well-developed, can prevent landslides.

Although much has been published about the effect of forests on regulating the amount of water (Andréassian 2004), basic research with an integral approach is still needed to investigate the relationships between ecosystem processes and how they combine to determine the provision of water. As mentioned above, it is important to not make generalizations about the water-vegetation relationship because each vegetation type behaves differently according to its ecophysiology and the characteristics of the study site. Finally, the scale at which the water-

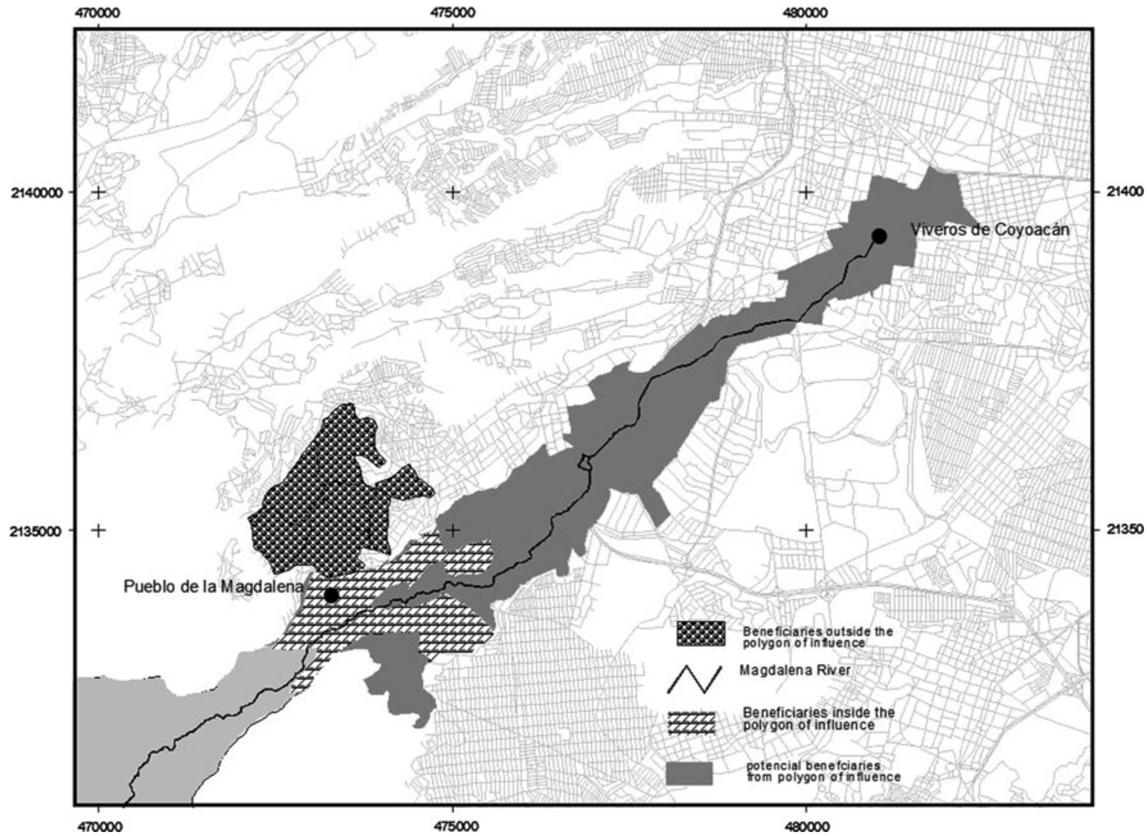


Fig. 7 The polygon of influence, zone of current Magdalena River water consumption, and zone of potential beneficiaries

Table 3 Potential water availability in the rainy and dry seasons. Provision water data are shown annually (hm^3), daily (hm^3) and instant (l/s)

Baseflow	Annual volume (hm^3)	Daily volume (hm^3)	Volume of flow (l/s)	Potential water availability (l/inhabitant/day)
Annual average	15.6	0.043	490	279.4
Rain average (July–November)	12.3	0.080	930	525.9
Dry season average (December–June)	3.3	0.015	180	101.3

vegetation relationship occurs should be taken into account to make more accurate interpretations.

Water Provision Beneficiaries

More than half of the population that receives water from the Magdalena River lives outside the watershed, including those beneficiaries living in areas higher than the river who have to have the water pumped to them. It is important to note that the population is urban, 90% receive less than 5 minimum wages and their main occupation is as laborers or workers (González–Martínez TM 2008).

The data indicate that this watershed could provide water to 153,203 inhabitants. The World Health Organization (WHO/UNICEF Joint Water Supply/Sanitation Monitoring Programe, Water Supply and Sanitation Collaborative Council and UNICEF 2000) recommended that the daily water consumption in cities should be at least 150 l per person. Therefore, in the rainy season, the MRW could supply more than three times the minimum water requirements to the entire population within the influence polygon. However, it would be necessary to develop a resource management strategy for the distinct rainy and dry seasons because the timing of the water supply is a factor that is not taken into account in the water management policies in Mexico City.

It is inconceivable that Mexico City, which is classified as a zone of absolute water scarcity (United Nations Development Programme (UNDP) 2006) with a high degree of pressure on water resources (Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT) 2009), does not take into account the potential of the Magdalena River to supply a greater population. Although this water body does not solve the scarcity problem, it could relieve scarcity in the rainy season.

Model Limitations

This study provides basic information that can be used for a management proposal for an urban river for which there is a lack of information, poor coordination and mismanagement by the authorities. The SWAT is a useful model for analyzing the hydrological behavior of a watershed with the available information. The more field data the model has, the better it will explain reality. Therefore, the modeling conducted for this work is expected to be more robust than that of previous studies (González–Martínez TM 2008; Jujnovsky and others 2010) because the model was fed new information about the vegetation and soil. Despite several years of work in the MRW by different institutions, it is still difficult to obtain information on some parameters, such as meteorological and hydrometric data. Therefore, for future estimates of water supply, it would be essential to have a hydrometric station with updated data for the output of the watershed and meteorological data for the same years. It is also important to conduct a more detailed edaphological study, if possible, for each soil and vegetation unit. It would also be valuable to refine the model to measure the leaf area index and evapotranspiration in the field and to conduct studies on the ecophysiology of plants and the soil water potential.

Conclusions and Perspectives

In conclusion, baseflow allows the Magdalena River to provide water service year round. The vegetation plays a fundamental role because the areas with the greatest baseflow are those with *Pinus hartwegii* and *Abies religiosa*. Therefore, for the Magdalena River to continue providing water year round, it is imperative that the watershed not lose the tree cover.

This study is presented as an effort to measure one ecosystem service by understanding the processes involved, in this case the hydrological cycle, and to provide benefits to the local people. For a full assessment of the ecosystem with the goal of identifying the ecosystem services that could benefit the community, it is necessary to identify the most important processes that determine the provision of service, the benefits, and measures to ensure that this service can actually impact human welfare.

Although this study focuses on a specific case in southwest Mexico City, appropriate water management is a global priority, but solutions must be local. It is important that the agency responsible for water management in Mexico City (SACM) uses appropriate strategies, taking into account the ecosystem that generates the water and the timing for which flow occurs. The management agency should also consider the areas that are suitable for receiving the ecosystem service. The inadequate management of a watershed may result in the loss of a valuable service, such as a water supply. Therefore, collaboration with other institutions is important.

It is intended that this project will serve as a tool to use in decision making for proper and informed water management. Moreover, it is possible to extend these results to the forested areas of the "preservation zone", where the residents of Mexico City could enjoy the ecosystem services in a sustainable way. The sustainability of our natural resources depends on making environmental issues a primary topic on the political agenda, not only in Mexico City but also in the other major cities of the world.

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C A P I T U L O 4

PROPUESTA PARA EVALUAR AL AGUA COMO SERVICIO ECOSISTÉMICO

Considerations to evaluate water from the ecosystem services approach: an alternative for a rural-urban watershed

Abstract

Among all the ecosystem services, water has made a crucial contribution to human development. After nearly 500 years of water mismanagement in Mexico City, we must begin to see its rivers and watersheds as key to the city´s sustainability. Under this paradigm, it is important to develop guidelines for water management that allow this resource to be a benefit for the growing population instead of a threat. It is expected that if water is managed with the ecosystem services approach, it would be easier to convince the authorities to integrate the natural ecosystems into cities. The aim of this paper is to propose basic guidelines for water management in rural-urban watersheds using the Magdalena River Watershed as a model. We conducted a search in Scopus for papers published between 1997 and 2010 related to water as an ecosystem service. From the papers identified, we compared which methods are best to assess water quantity and quality, who the stakeholders are, how decisions should be made related to water management, and what the principal methods for economic valuations of ecosystem service are. We associated the literature review with our results in the Magdalena River and concluded what the best methods are according to the rural-urban watersheds needs. This study serves as a tool in ecosystem management and decision making with characteristics and problems similar to those of Mexico City.

Key words: ecosystem services; water management; Mexico City; water quality; water quantity; economic valuation; environmental perspectives

Introduction

One of the best ways to understand water resource in an integrated manner originated with the inclusion of water in an ecosystem context; considering a watershed as a management unit and using the ecosystem service approach (Maass, 2012). The term "ecosystem services" has been used since 1980, to translate the biophysical functioning of ecosystems and their processes in terms of human welfare. Among the key elements of the ecosystem, water is perhaps the main contribution to the human services (Falkenmark and Folke 2003).

An important aspect of thinking about water from a watershed approach is its ability to connect and splice coastal, terrestrial and freshwater ecosystems, thus providing a broad range of ecosystem services (Postel and Thompson 2005). Watersheds are multidimensional and multifunctional ideal scenarios for the development of new conceptual frameworks to promote transdisciplinary synthetic analysis of biophysical and social processes (Toledo 2006). This integral approach allows understanding, as far as possible, of how ecosystem processes are related to each other in producing ecosystem services. Also, the use of watersheds as a management unit helps in identifying generation and consumer areas for ecosystem services, as well as where the stakeholders and beneficiaries are located.

Despite the advantages of addressing the problem of water from the ecosystem services approach, the leaders in public and private sectors still have not incorporated this concept in their decision making process (Chan et al. 2006). A Scopus literature search between 1997 and 2010 shows that, although there is an increase in water works related to ecosystem services, they are still very low in proportion to total water issue studies (Fig 1).

The main flaws that hinder the sustainable management of ecosystem services include: lack of information, for both decision makers and society in general, market failures, for the impossibility of establishing a formal market for ecosystem services, particularly water being a public good, and institutional failures that can occur when natural areas are protected and do not take into account the rights of ownership or groups living in adjacent areas, leading to social conflicts (Turner and Daily, 2008).

Cities depend on the surrounding ecosystems to meet the needs of its residents and ensure their welfare (Bouland et al. 2009). Mainly, the water, is a basic and limiting factor to the cities development. However, this idea has been little recognized, which has resulted in an inadequate management and bad planning of land use (Niemelä et al. 2010).The relationship between cities and water is crucial, large cities require large amounts of water to supply the people and in turn, their waste, negatively impact freshwater systems (UNESCO, 2010). It is expected that if water management were done from the ecosystem services approach, it would be easier to influence the authorities to integrate natural ecosystems into city management programs (Niemelä et al. 2010). In the quest for sustainability, it is important to see cities as socio-ecosystems, where environmental, social and economic components are integrated. Therefore we propose the assessment of water supply from the ecosystem services approach; analyzing their environmental, social and economic components; using as a model a rural-urban watershed in Mexico City.

The study area: Magdalena river watershed, Mexico City

Mexico City is located within a closed drainage basin where the natural availability of water has been changed by more than four centuries of waterworks. Given the increased demand, the potable water is imported from neighboring basins flows. In turn, most of the rivers in the city have been used as drainage channels which discharge the sewage and landfills. As the urbanization of the Mexico Basin increased, the rivers began to be seen as a security problem because of both sanitary and flood reasons (González-Reynoso et al. 2010).

After nearly 500 years of mishandling water in Mexico City, we must begin to see the rivers and their watersheds as key elements to its sustainability. For this reason we chose a rural-urban watershed inside Mexico City whose characteristics make it an area of vital importance for the water supply of the city. The Magdalena River Watershed (MRW) is located at 19 °15 '00´´N and 99 ° 17' 30"W and natural forest covers 30 km^2 . The reasons for choosing this area as a study model are: Their forests are considered the most important continuous mass of vegetation in Mexico City and one of the most diverse temperate ecosystems of Central Country. Besides that, the Magdalena River is the most important surface water in the city (200L/s), with excellent water quality in the upper watershed (Jujnovsky et al. 2010). Moreover, this area has had a close relationship with the historical and cultural heritage of the city (González-Reynoso et al. 2010).

Methodology for water management

In developing countries such as Mexico, environmental information is very limited, especially at detailed scales. The challenge to achieve ecosystem management is to integrate the scarce and atomized scientific work available with the decision-making process. Researchers commonly take the stance of not giving suggestions because further research is needed; therefore politicians end up making decisions without knowing the dynamics of ecosystems, and minimizing the consequences of mishandling. There may never be enough information to understand all functions and processes of ecosystems but any data generated by researchers could be used as a tool, since environment changes rapidly and the decision makers cannot wait.

Our proposal is based on and adapted from the scheme of Brauman et al. (2007) to understand, evaluate and manage ecosystem services; and the vision of sustainability and transversality for the management of socio-ecosystems (Spangenberg 2011).

As previously stated we believe that the best way to assess an ecosystem service is to take into account the environmental, social and economic aspects of the service. So, we divided the methodological framework in these three components in order to answer the following questions: How can you measure its quantity and quality? Who are the stakeholders? Who benefits from the ecosystem service? Are people aware of the benefit? How should make the decisions? How can you make an economic valuation of the water resource? (Fig2).

Once the framework was designed we conducted a search in Scopus for papers published between 1997 and 2010 related to water as an ecosystem service. We compared the literature review with what we found in the MRW. In order to test whether our proposal would work in an urban-rural watershed within a city that has limitations of information and very strong environmental problems.

I.-Environmental Component: water quantity and quality

Literature review

One of the most important aspects in water management is knowing how much water is provided by the watershed. Estimates can be made either by direct measurements in the field or by using hydrological models. The latter are helpful tools for understanding general water behavior over long periods of time when detailed environmental information is not available. However, in order to know the quantity of water over a short period of time, or compare the hydrological model with reality, monitor with direct measurements is required.

The best ways to monitor the amount of water provided by a watershed is to measure the river flow at its mouth. According to the Food and Agriculture Organization (FAO), the simplest way to measure small flows of a stream is by measuring the time it takes to fill a container of a known volume (Hudson, 1997). In larger streams, the *velocity/area* relationship can be used. Measuring the average velocity of flow and the cross-sectional area of the channel to calculate the flow.

Velocity can be determined simply by discharging a quantity of strongly colored dye into the stream, and measuring the time it takes to flow a known distance downstream. For a more accurate determination of velocity, current meters are used. In addition, to obtain more precise data about the cross-sectional area, one option is to simplify (“modify”) the bottom and the sides of the channel, by building a cement floor and walls on a stream segment (structures called flumes) (Elosegui et al. 2009). If a hydrograph is required, i.e. a plot of the rate of flow against time, then a continuous record of the changes in water level is needed. There are several methods for assessing hydrological ecosystem services using models. There are two types of freshwater-related tools: traditional hydrologic tools and newer ecosystem services tools (Vigerstol and Aukema, 2011). SWAT and VIC are the most prominent examples of traditional hydrological tools that focus on ecosystem services drivers and require post processing for ecosystem services assessments. On the other hand, InVEST and ARIES represent a new breed of ecosystem services specific tools, focusing mainly on end services and visualization of these services across a landscape (Nelson and Daily, 2010). Traditional hydrological tools provide more detail; however, ecosystem services tools tend to be more accessible to non-experts and can provide a good general picture of the ecosystem services (Vigerstol and Aukema, 2011).

Another important aspect in water management is the water quality. All of the studies reviewed have used physic-chemical parameters, metals and nutrients to a lesser extent, with a few studies using biological indicators (from coliform to fish) (Zhou et al. 2006; Alam et al. 2006; Kazi et al. 2009; Zhang et al. 2010; Thomasen & Chow-Fraser 2011).

Most studies on water quality are focused on the risks to human health; however, for a more comprehensive assessment of the ecosystem is advisable to evaluate the “environmental quality”, also called “ecological status”, which is the expression of the quality of the structure and function of aquatic ecosystems (Ruza-Rodríguez 2005). When considering the ecosystem approach, and the fact that communities change their structure and functioning under altered environmental conditions (Lampert and Sommer 2007), it is possible to assess the ecological status of a river by using some of the structural and functional properties of the different levels of biological organization (Segnini 2003).

According to the European Water Framework Directive (DMA 2000), the biological indicators to be used are the composition and abundance of aquatic flora, and the benthic fauna of fish. Macrophytes are useful to detect eutrophication, changes in river dynamics, and the variation of mineralization (conductivity and salinity). Diatoms are used as an indicator of productivity. Macroinvertebrates are the most widely used group of organisms (Fernández et al. 2002; Oscoz et al. 2007) and they are useful to detect organic pollution or acidity. Fish, due to their greater longevity and by their position in the food chain and their mobility, have a particular value as indicators of ecological status. In addition to the above-mentioned biological indicators, the DMA (2000) also proposed using hydromorphological and physical-chemical indicators, including hydrological regime, river continuity, morphology, thermal conditions, oxygenation, salinity, acidification, nutrients, and the presence of specific pollutants (Ruza-Rodriguez and De la Fuente 2006).

The water quantity and quality cannot be measured once and expected that these not change over time; therefore it is necessary the monitoring. Ecosystem monitoring consists of identifying significant long-term changes through quantitative or qualitative measures and periodic data analysis of particular characteristics. Monitoring helps to describe the state of the environment and its trends (Christensen et al. 1996; Abbot and Guijt 1998). Monitoring is essential to conduct an “adaptive management approach” in which the results of ecosystem interventions becomes a learning experience that feed back in to the management cycle (Holling 1978). To carry out this monitoring, it is necessary to integrate multidisciplinary working groups and a large amount of equipment, knowledge, and budget; thus, it requires the support of an institution like a university. One way to reduce labor costs and incorporate an education component into the process is "participatory monitoring". The aim is to have the stakeholders monitoring the ecosystem through simple methods, with the supervision and technical support from a local university, governmental institution or NGO institution. From a participatory point of view, it is essential that the monitoring of data be useful as a tool to generate reflective processes in local communities (Danielsen et al. 2005). Participatory monitoring has great potential in developed countries, where quick decisions can be made to address key threats to natural resources. This can empower local communities to better manage, and to refine sustainable use strategies to improve the lifestyle of the local residents (Danielsen et al. 2009). On the other hand, in developing countries these experiences are rare, and there are very few skilled professionals to oversee these projects (Sheil 2001; Danielsen et al. 2005).

There are international programs that have promoted participatory water monitoring, these programs had success monitoring water systems in several countries around the world (table 1). The parameters and the techniques proposed by these groups may vary, but are focused on physical and chemical analyses. Some of the programs include bacteriological and biological indicators as well. The vast majority of studies on water quality as ecosystem services use the same parameters (Zhou et al. 2006; Alam et al. 2006; Kazi et al. 2009; Zhang et al. 2010; Thomasen and Chow-Fraser 2011).

There are several studies that use macrophytes, diatoms, and macroinvertebrates as indicators of changes in river dynamics (Fernández et al. 2002; Oscoz et al. 2007; DMA 2000; Ruza-Rodriguez and De la Fuente 2006); however, the participatory programs reviewed rarely use them This is probably due to the fact that the identification of some species has to be done in a lab or it is necessary to have an identification guide.

Experience in Magdalena River Watershed

Water quantity was evaluated by Jujnovsky *et al.,* (2010, 2012) applied two different methods: the Thornthwaite method (Dunne and Leopold 1978) and the SWAT 2003 model (Soil and Water Assessment Tool). The Thornthwaite method provides a general idea of water behavior over a long period of time. The advantage is that it does not require a lot of environmental information; it only needs data on vegetation and soil type, as well as monthly rainfall measurements and air temperatures for at least a 10-year period. The disadvantage is that it does not separate run-off in its components (surface, and base flows). In contrast, the SWAT model has greater precision on the types of runoff generated and shows the relationship between the elements of the hydrological cycle and vegetation. The limitation of the SWAT model is that it requires a lot of environmental information and the same amount of years of records of the hydrometric and meteorological data.

Water quality was evaluated by physical-chemical, and biological indicators. There have been several surveys along the Magdalena River since 2003, in well-preserved forested areas, as well as in perturbed and urban areas (Magdalena town). The parameters essential to evaluating the quality of drinking water were: dissolved oxygen and electrical conductivity, measured *in situ*, biochemical oxygen demand, ammonia, nitrogen, nitrate, total suspended solids, total dissolved solids, and fecal coliforms, all measured in the laboratory (PUMA-UNAM 2009).

The results show that water quality presents a general tendency to worsen from the natural area to urban area. The main river pollution was mostly represented by solid, inorganic and organic carbon, and bacteria associated with fecal matter, all from sewage water.

There are some studies on algal and invertebrate diversity that could be integrated into future projects to assessing the ecological status of the river (Ramírez-Rodríguez 2006; Bojorge-García 2006).

Although the parameters suggested by the “System of indicators for the Rescue of the Magdalena River” (PUMA-UNAM 2009) were not raised under a participatory approach these parameters can be used for monitoring participatory in future projects.

Social component: stakeholder’s providers and beneficiaries

Literature review

A stakeholder is anyone who has an interest in the topic at hand and wishes to participate in the decision-making process. Several authors consider the stakeholders as a fundamental part of the socio-ecological system (Gray et al. 2001; Castillo 2005; Maass and Cotler 2006; Díaz et al. 2011); knowing their points of view, needs and desires to change the ecosystem services contributes significantly to the success of a management proposal (Diaz et al. 2011). Also, it is important to define how and who should make the decisions to achieve and execute the proposed actions.

In this study we propose to identify the stakeholders that can potentially alter the generation of the service and those who will benefit from their generation. Recognizing and including all potential stakeholders is virtually impossible (Meffe et al. 2002), but the identification could be more accurate if is done in a participatory way. This means that the people who identify the stakeholders are themselves stakeholders (Montañés 2009).

The generation of the ecosystem service depends largely on the landowners, the people who earn their living from the ecosystem, and the government authorities responsible for ecosystem management. Government authorities are the main stakeholders responsible for the ecosystem services generated, due to their management activities and their regulation. The government authorities also have the financial resources to perform reforestation programs and infrastructure construction; hence, it is important to consider, not only the authorities relating to water, but also the authorities related to the forest.

The academics and NGOs are other groups of stakeholders interested in the ecosystem, and they can make proposals to amend the generation of services (Meffe et al. 2002). The specific role of the academics should be to provide quantitative data on the ecosystem. They are in a good position to anticipate the long-term consequences of stakeholder's actions and identify common patterns, discordance, vacuum areas, and probable tipping points (Díaz et al. 2011). Also, they could play an important role as facilitators in the participatory research processes (Johnson et al. 2001).

One of the main elements in the guidelines for making decisions and implementing policies for environmental management is to know who benefits from the service. Ecosystem services are generated and consumed in different places (Maass et al. 2005), and the stakeholders involved in the generation ecosystem services don't necessarily benefit from it.

Experience in Magdalena River Watershed

The stakeholders identified in the MRW are landowners, traders, inhabitants, government authorities, visitors, and academics. Some stakeholders are more connected to watershed issues while others simply disappear following brief interventions.

The landowners and local authorities are closely related to the service generation." La comunidad Magdalena Atlitic" (La Magdalena) has the property titles, which corresponds to nearly the whole area of the MRW, with a remaining 10.5 km^2 being under legal dispute with neighboring communities. Most people who are part of this community do not earn their living from the watershed, mainly because of the economic transformation of the MRW from the primary sector to the tertiary (Ramos 2008; Aguilar 2008). Like many others communities in developing countries, the Magdalena Atlitic has internal conflicts which hinder the formation and enforcement of clear rules resulting from neither common vision among its members nor internal confidence. As a result, decision making is difficult and this could affect the generation of the ecosystem services.

Government authorities can be divided into local and federal. Among the local institutions include those related to forest management “Comisión de Recursos Naturales” (CORENA) in the upper basin; and those related to the distribution of drinking water in urban areas “Sistema de Aguas de la Ciudad de México” (SACM). The difficulties are that despite the efforts made in recent years of working in a coordinated way, this has not always been possible, and in many cases institutions are still working on a sectored basis, either on river issues or forest, but not comprehensively. The federal authorities, such as the national water commission “Comisión Nacional del Agua” (CONAGUA), to date have not shown interest in the management of the area.

In addition to the landowners and the authorities, the traders are other group of stakeholders that directly modifies the generation of the service. The traders are economically dependent on the influx of visitors to the area, and are mainly engaged in food services. This is a relatively well-organized group formed by both landowners, and by people who are not but have been working in the area long time.

Indirectly, the universities that perform research in the area are a group of stakeholders to be considered due to management proposals made for the watershed. The presence of this group has varied over time; however, the National Autonomous University of Mexico (UNAM) and the Metropolitan Autonomous University (UAM) have been the most consistent.

The ecosystem services of water supply is consumed either within the watershed for recreational activities (by traders and visitors) and outside the watershed once it becomes part of the potable system of water supply (by inhabitants).

We considered that there are actual and potential beneficiaries. The actual beneficiaries are the users who currently receive the drinking water that is generated in the basin. Potential beneficiaries are the people who could benefit from service because of their proximity to the river but they get the water supply from external sources (Lerma and Cutzamala systems). Among all the beneficiaries identified, 40% are located adjacent to the Magdalena River, while more than 50% are located at higher altitude where they must receive the water via a pump system.

Social Component: ecosystems services environmental perspective

Literature review

The relationship between humans and their environment is largely a reflection of environmental perspectives (Díaz et al. 2011). Environmental perspectives research is a first approach to acknowledging the motivation of people with regard to their ecosystems (Durand 2008). Including this type of analysis on a water management proposal allows to understand how communities construct images of reality and how they give meaning to their experiences in relation to the environment (Lazos and Paré 2000). The environment has multiple interpretations, which are socially constructed according to the social and cultural context and the relationships within each social group. These interpretations change according to the interactions with the space and the ways in which individuals appropriate it (Durand 2008).

The methods used to understand environmental perspectives have been made both quantitatively (e.g. Jacobson and Marynowski 1997; Mcfarlane and Boxall 2000; Kearney 2001; Trakolis 2001; Tarrant and Cordell 2002; Slimak and Dietz 2006; Chuenpagdee et al. 2010) and qualitatively (e.g. Kaplowitz 2000; Hull et al. 2001; Davidson-Hunt and Berkes 2003; Olsson et al. 2004; Racevskis and Lupi 2006; López-Medellín 2011). Qualitative approaches are more adequate to analyzing the reality from the point of view of the stakeholders, because allows understanding different aspects of the environment from the perspective of local stakeholders. (Bird, 1987; Evernden, 1992; Greider & Garkovich, 1994; Ponterotto, 2005; Proctor, 1998; Strauss, 1987) .

Experience in Magdalena River Watershed

Ramos and Almeida (in press) described which ecosystem services -incluiding hydrological ones- are recognized by different local stakeholders in Magdalena River Watershed. They used qualitative data collection tools. They found that water quantity was the ecosystem services most mentioned. In addition, stakeholders who have most relation with the MRW mention other hydrological services and recognize the relation between the vegetation cover and water supply. They concluded that ecosystem services approach was relevant for the environment perspectives analysis in MRW

Social component: water management decision making

Literature review

In recent years it has been recognized that the water crisis is a problem of government, not a problem of availability of resources or technology (Bucknall 2006; Pahl-Wostl et al. 2011). The new approaches on water management practices are based on the idea that the system is complex, unpredictable, and characterized by unexpected responses to interventions (Pahl-Wostl et al. 2011). However, despite the fact that the interactions between the people and ecosystems are inherently unpredictable (Gunderson and Light 2006) there is an urgent need for action in its management (Johnson et al. 2001; Pahl-Wostl et al. 2011). Regarding the change in the political discourse of water management, its evolution is based on a shift from the concept of "government" to "governance." The idea is that there should be polycentric governance, where many actors from different institutional environments develop and implement the water management policy; instead of having one government acting as the sole authority for the decision-making process and having state authorities exercise control over civil society groups (Pahl-Wostl et al. 2011).

Some experiences in the implementation of integrated water management derive from the Water Framework Directive, formed by the European Union to maintain the good quality of surface water and groundwater in a European river basin level. This Directive establishes the need for a strong participation of all stakeholders involved in water management. As parallel, the Coordinated European Flood Directive is responsible for risk assessment and management of floods, and also recognizes the right to access public information and to participate in the planning process (Kallis and Butler 2001; Pahl-Wostl et al. 2011). There are some countries, such as England, Spain, Australia, South Africa, the USA, Canada, and Mexico, that have made modifications to their legislation in order to carry out more comprehensive water management (Díaz et al. 2003; Sancho and Parrado 2004; Cotler and Caire 2009; Pahl-Wostl et al. 2011). In all these cases governments have the responsibility to set new relationships among individuals interested and rural development; rather than imposing vertical relationships and strategies that do not take into account local and regional processes (Bonnal 2005).

Mexico has recognized the need to manage water services based on an Integrated Water Resources Management (GIRH) scheme with basin boundaries. The GIRH is supported by the policies, actions, and resources, where the State, the water users, and the civil society control and manage water, regulate its distribution and use, and preserve its quantity and quality (according to the National Water Act in Article 3, Section XXVIII) (Cotler and Caire 2009). To this aim and in accordance with the law, there are watershed spaces for the participation of representatives of water users, federal government agencies, local governments, and civil society organizations (CONAGUA 2007; Cotler and Caire 2009).

Despite all these experience around the world, there is not enough information to assess their performance, thus in practice and in local scales it is not clear how participation should be implemented. In fact, many experts of water management continue to work under a hierarchical scheme and in many cases the local actors are still considered a passive recipient of water services (Bonnal 2005). Users still expect the government to act on their behalf and the government maintains a protective and paternalistic role with users (Sancho and Parrado 2004).

Experiences in Magdalena River Watershed

In the Magdalena river watershed Master Plan (PUEC-UNAM, 2008), water management has emerged from the concept of governance, where the aims of public action should be determined and defined through the consensus among participants. Similarly, the capacity for action and regulation should be done through the shared responsibility of government agencies and social and private organizations. However, to date, the civil society has not been integrated into the decision-making process and the local water agency (SACM) is only able to handle the distribution of the resources without the ability to regulate its own governance.

Economic component: ecosystem service economic valuation

Literature review

Economic valuation can be a difficult and controversial task for trying to put a "price" on ecosystem services; however, institutions in charge of protecting and managing ecosystems must often make difficult spending decisions that involve tradeoffs in allocating resources (Cheen 2004). These types of decisions are economic decisions, and thus are based, either explicitly or implicitly, on society's values (Costanza et al. 1997; De Groot et al. 2010).

Water as an economic good should be valued for its character of being good, useful, and scarce; and must be regulated to ensure the supply and prevent waste (Montecillo and Puchet 2000). In addition, the ecosystem services are often public goods which mean that they are governed by two principles: non-exclusion and non-rivalry. Regarding valuation methods, there are many discussions that focus on the relevance of ecological, economic and social issues (de Groot et al. 2010). The economic valuations are only approximations because ecosystems are complex, are highly interconnected and have non-linear interactions between variables at different time and space scales; these interactions cannot be included in any valuation method (Cheen 2004). In the last 10 years, water as an ecosystem service was valued economically with different methods: market price method (Ward and Michelsen 2002; Pinto et al. 2010; Tang 2010), Hedonic pricing method (Wilson and Carpenter 1999), Damage Cost Avoided, Replacement Cost, and Substitute Cost Methods (Barbier et al. 1997; Wilson and Carpenter 1999; Sundberg 2004; Tang 2010), contingent valuation method (Barbier et al. 1997; Wilson and Carpenter 1999; Loomis et al. 2000; Zhongmin et al. 2003; Hensher et al. 2005; Rolfe and Windle 2005; Atkins and Burdon 2006; Birol et al. 2006), and benefit transfer method (Morrrison and Bennett 2004; Elsin 2010).

In order to make an assessment as close to reality as possible, it is important to choose the ecosystem service (preferably only one) and have a clear ecological identification (if possible biophysical measures); in addition, to choose the most appropriate method for the ecosystem service assessment.

Experiences in Magdalena River Watershed

Caro-Borrero (2012) made an economic valuation of the ecosystem service of water supply, using the replacement cost method. This method is based on determining the cost of replacing a function of an ecological system with a technology system and is used to measure the economic value of the ecosystem function itself (Shabman and Batie 1978). Previous information about water provision (Jujnovsky et al. 2012) was used to give an economic value. Once it gets an economic value, it uses the discount rate to obtain the future value of the resource, to infinity, since the objective is to keep it forever and not just for a couple of years. The technology chosen as a replacement for the ecosystem function was seepage pits. This technology is the most appropriate taking into account the geological, hydrological and hydro-geochemical properties of the basin.

Recommendations

Many of the studies presented here were not developed from the beginning with an overview of ecosystem services, and also they were made with a lot of information limitations.

But we try to adapt the proposed framework with the information that we had in the study area, in order to prove that even with little data is possible to have an ecosystem services approach which could fit as base to assess water from an integral perspective.

Here are some recommendations learned in the study area that could be applied to other basins with similar characteristics.

The water quantity can be calculated using various methods depending on the environmental information available and the skills of those who make the measurements. The Thornthwaite method was used for a general estimation of the amount of water, as it represents 30 years of data, while the SWAT model was useful for separating the runoff and relating it to vegetation types. For future assessments we recommend using ARIES or INVEST for having a ecosystem services approach.

We encourage the use of the concept of environmental quality, instead of water quality, to take into account the complex interrelationships between the structure and function of the river. Then, it can be understood how the hydrological ecosystem services are generated and what measures can be taken for monitoring them.

The identification of stakeholders should be made in conjunction with local communities; recognizing those involved in the generation of the service and those who benefit from it.

In order to know the environmental perspectives we suggest the qualitative method, because it could lead to a more robust understanding of what people recognize about their environment; and it allows the understanding of the different aspects of the environment from the perspective of local actors. The decisions making must be transversal with all the stakeholders to the proposed actions can be carried out.

Ecosystem service valuation should not be conceived as an end in itself, but needs to be directed towards some policy issue. It should be noted that an ecosystem function can never be replaced one hundred percent and replacement does not compensate for the loss. The valuation of ecosystem services is an important issue in the field of environmental protection and sustainable development, as is the fact that many of these services are not incorporated in the market for them to be exploited. Economic assessments cannot be separated from the choices and decisions we have to make every day on the socio-ecosystems. This tool is used to determine differences that cause relatively small changes in the services that ecosystems provide, that affect human well-being.

Conclusions

In this review we show a synthesis of how to evaluate water as an ecosystem service and what the best methods are depending on your needs. We show each component in an integrated manner, in order to used them according with the needs of a particular area.

We present the case of Magdalena River Watershed because it is a good example of a rural-urban watershed that has been studied for several years, but still with a lack of environmental information, and with problems inside the community and with the authorities.

We believe that this review and our experiences in MRW could integrate the basic guidelines to help decision makers towards water management and sustainable actions; despite the lack of data, different scales, and different methods of sampling and analysis.

This review aims to develop guidelines for the evaluation of ecosystem services, as a science in recent formation where there is a lack of knowledge of the subject and there are no established methodologies for evaluation as of yet. In order to propose guidelines that are consistent with the conceptual framework of ecosystem management it is crucial to integrate basic environmental research from a multidisciplinary approach, and attempt to integrate aspects of the landscape, physical, chemical, biological, social and economic, with the needs and perceptions of the community. While dealing with the difficulties that represent access to information and the lack of cooperation between communities and institutions.

Environmental topics should be a primary issue for the agenda of the cities, since it depends on which cities can be sustainable for present and future times. Nevertheless, it is still necessary to generate new information and apply the knowledge acquired for the conservation of ecosystem services, as well as systematic criteria in the sampling and analysis for comparative studies.

Finally, Mexico City must reverse the nearly five centuries of mismanagement of water resources, so this proposal can be seen as a chance to change the course of the water history of one of the world's largest cities.

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Table 1: Parameters used to monitoring water in different participatory programs

	Disolved oxygen*	Turbidity	T°	pH	Conductivity*	Sólids*	Total wáter hardnes	Nutrients*	Bacteria*	Diatoms, macroalgae, mosses and/or microalgae	Macro-invertebrates	Other animals	Water quantity	Others
1.	X	X	X	X				X	X					
2.	X		X	X			X		X		X			X
3.	X		X	X	X				X					
4.	X	X	X	X	X	X				X	X		X	X
5.	X	X						X	X					
6.	X	X						X		X				
7.	X	X	X	X	X			X				X	X	

1. The Watershed Watch of the University of Rhode Island, 2. The Alabama Water Watch of Auburn University, 3. Clean Water Program at the University of Maine, 4. Aquatic Ecology program of the University of Alaska Anchorage, 5. Delaware Sea Grant College Program, 6. Florida Lakewatch, 7. Coastal Georgia Adopt-A-Wetland Program

* Parameters considered as indicators in the indicator system proposed for the Magdalena River Watershed (PUMA-UNAM 2009).

Caption Figures

Figure 1 Scopus search of publications on water issues (black) and water under the focus of ecosystem services (light gray) since 1997 until 2010.

Figure 2 Relevant questions to answer in order to manage water from the ecosystem services approach.

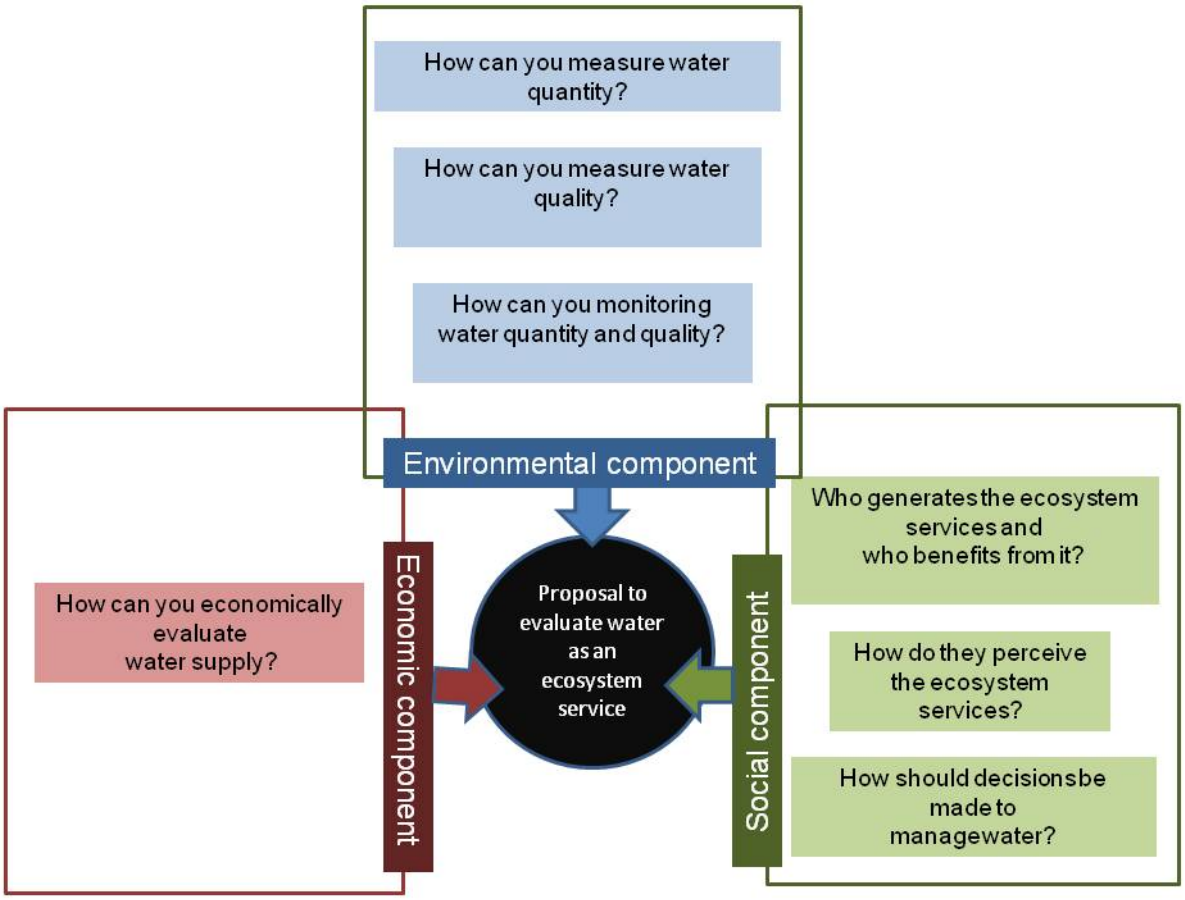
How can you measure water quantity?
How can you measure water quality?
How can you monitoring water quantity and quality?
Environmental component
How can you economically evaluate water supply?
Economic component
Proposal to evaluate water as an ecosystem service
Social component
Who generates the ecosystem services and who benefits from it?
How do they perceive the ecosystem services?
How should decisions be made to manage water?

Figure 1

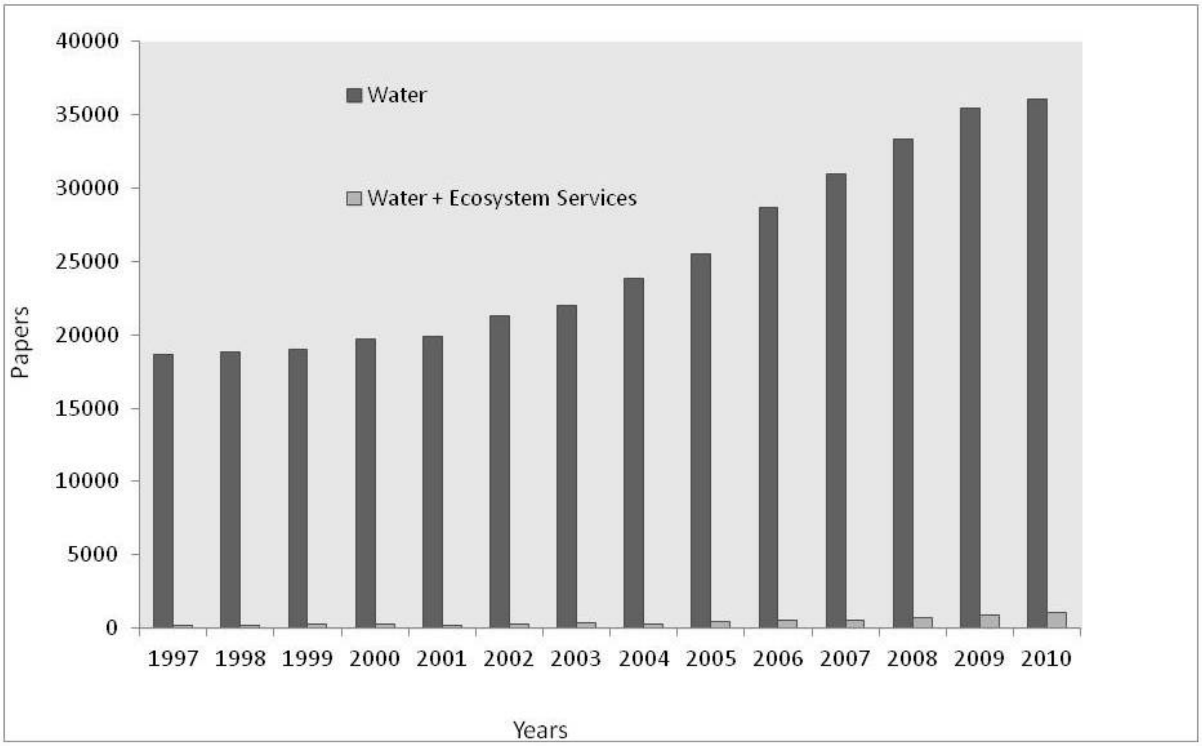
Water
Water + Ecosystem Services
Papers
40000
35000
30000
25000
20000
15000
10000
5000
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Years

Figure 2

C A P I T U L O 5

DISCUSIÓN Y CONCLUSIONES

PROPUESTA DE MANEJO DEL AGUA PARA LA CUENCA DEL RÍO MAGDALENA

Esta propuesta plantea cómo manejar el agua desde la perspectiva de servicios ecosistémicos sintetizando toda la información generada hasta la fecha en la cuenca del río Magdalena D.F., traduciéndola en propuestas concretas para la ejecución de políticas públicas que contribuyan con la conservación de los servicios hidrológicos del área. La metodología para esta propuesta consiste primeramente en la evaluación del servicio ecosistémico de provisión de agua y posteriormente en la construcción de las intervenciones de manejo para que el servicio pueda seguir generándose (Fig 5.1). El marco conceptual está inspirado en los lineamientos para el manejo de ecosistemas de Maass y Cotler (2006). El cual propone a la cuenca hidrográfica como la unidad óptima para manejar el agua, a los servicios ecosistémicos como objetivo primordial de la propuesta, al monitoreo participativo y al concepto de manejo adaptativo para adecuar la propuesta a medida que se avance en la generación del conocimiento y en el fortalecimiento de las relaciones sociales e institucionales. A su vez, dado que se reconoce a la zona de estudio como un socio-ecosistema, se incluyen las intervenciones técnicas y comunicativas propuestas por Castillo *et al.* (2005); y las intervenciones institucionales propuestas por Medardo Tapia (com. Pers.).

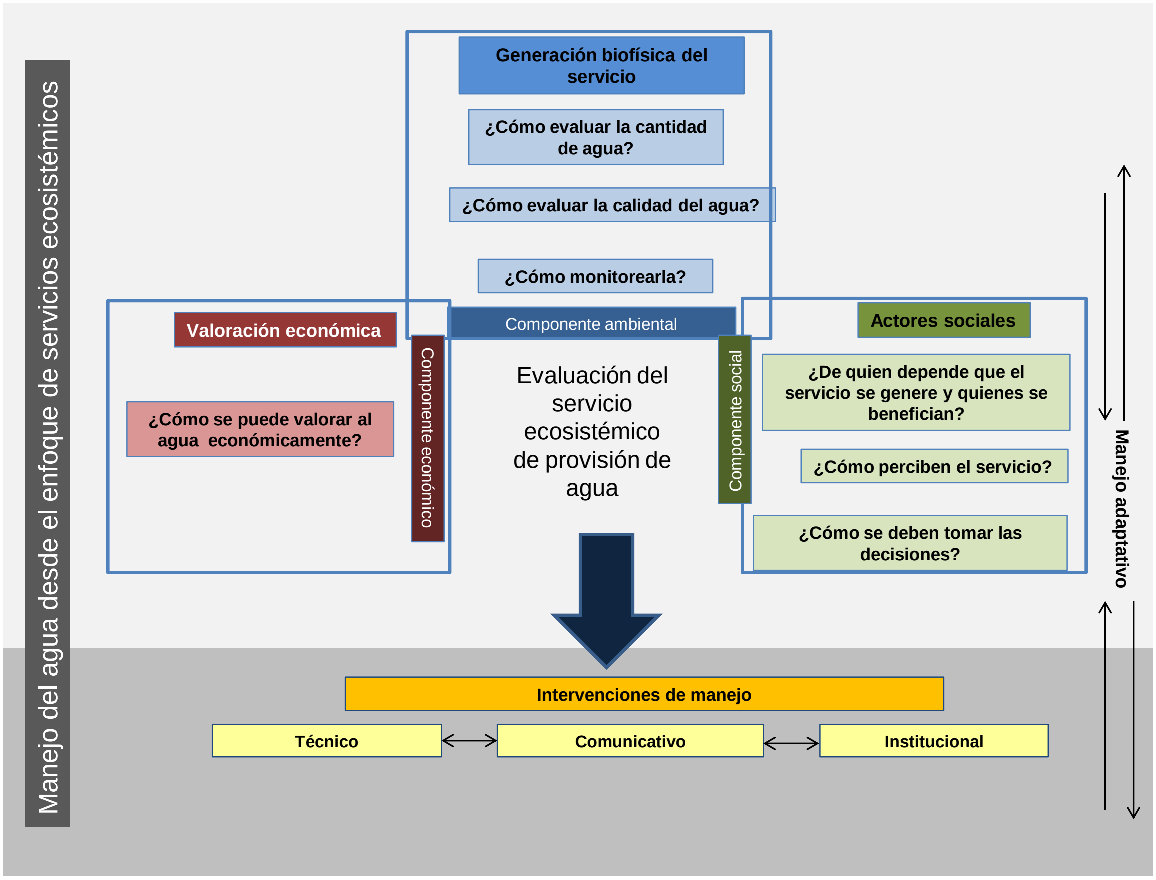

Figura 5.1 Marco conceptual para el manejo del agua desde el enfoque de servicios ecosistémicos, elaboración propia.

Evaluación del servicio ecosistémico

Se propone que para la evaluación del servicio ecosistémico de provisión de agua se deben considerar sus componentes ambientales, sociales y económicos. Con base en el esquema propuesto por Brauman *et al.* (2007) para el entendimiento, evaluación y manejo de servicios ecosistémicos y en las experiencias en la cuenca del río Magdalena se plantearon las preguntas siguientes: ¿Cómo se puede evaluar la cantidad y calidad del agua? ¿Quiénes son los actores sociales involucrados con el manejo? ¿Quién se beneficia de la provisión de servicio ecosistémico? ¿Cómo perciben el servicio? ¿Cómo se toman las decisiones? y ¿cómo se puede evaluar económicamente el servicio?.

A continuación se presenta una síntesis de los aspectos más relevantes de la evaluación. Los datos sobre la estimación de la temporalidad, cantidad y calidad de agua en la CRM se describen en los capítulos 3 y 4; mientras que la revisión detallada de los métodos que se han utilizado para evaluar al agua como servicio ecosistémico desde sus componentes ambiental, social y económico se explican en el capítulo 5.

Con respecto al componente ambiental, el cálculo de cantidad de agua en la CRM se realizó mediante los métodos Thornthwaite y SWAT. Sin embargo no se descarta utilizar los modelos de ARIES o INVEST por tener un enfoque de servicios ecosistémicos y ser ideales para personas no especializadas (Nelson y Daily, 2010).

Con la idea de contar con un proceso continuo de seguimiento del estado del ecosistema, se incluye en la propuesta la medición de los parámetros presentados por el "Sistema de indicadores de los ríos Magdalena y Eslava" (PUMA-UNAM, 2009) donde, para cantidad de agua se propone monitorear el gasto base del río, en relación con el volumen de agua en tiempo de lluvias o estiaje y el gasto unitario de recarga, el cual se refiere al volumen total de recarga anual. Respecto a la calidad del agua, se elaboró un índice que incluye 8 parámetros: Coliformes fecales, conductividad eléctrica, demanda bioquímica de oxígeno (DBO), nitrógeno amoniacal, nitrógeno de nitratos, oxígeno disuelto, sólidos disueltos totales (DST), sólidos suspendidos totales (SST) (PUMA-UNAM, 2009). Por otra parte, los trabajos sobre diversidad y ecología de diversos grupos biológicos (Ramírez-Rodríguez, 2006; Bojorge-García, 2006) se deben de integrar para definir indicadores de calidad ambiental; ya que existen varias especies en la cuenca que son endémicas o en alguna categoría de protección que podrían utilizarse como bandera.

Dentro del componente social es necesario identificar a los actores que potencialmente pueden modificar la generación del servicio y a aquellos que se benefician de este. Si la identificación se hace de manera participativa, la posibilidad de integrar un mayor número de grupos interesados se incrementa (Montañés-Serrano, 2009). Para reconocer las diferentes perspectivas ambientales se recomiendan métodos cualitativos, ya que permite conocer a mayor detalle las percepciones de los actores locales. A su vez, es fundamental saber cómo se toman las decisiones y quienes son las autoridades responsables de llevarlas a cabo.

Dentro del componente económico, se aplicó el método de costo de remplazo para valorar la función ecosistémica de infiltración de agua y la tecnología que se utilizó para remplazarla fueron los pozos de inyección directa (Caro-Borrero, 2012). Se podrían aplicar diversos métodos para hacer valoraciones económicas en la zona, pero deben de escogerse de acuerdo al servicio hidrológico que se quiera evaluar y tomando en cuenta que deben usarse para propósitos de conservación.

Con base en la información generada sobre la generación biofísica, los actores sociales y la valoración económica, se proponen intervenciones de manejo en la CRM para que el servicio de provisión de agua se siga manteniendo.

Intervenciones de manejo de ecosistemas

Intervenciones técnicas.- Consisten en técnicas ecológicas que ayudan al mejoramiento y conservación del capital natural, orientadas a las acciones directas sobre los ecosistemas, Para mantener la provisión de agua en la cuenca del río Magdalena, este tipo de acciones deben estar enfocadas a la conservación de la cantidad, temporalidad y calidad del agua. Para ello es necesario que se cumplan dos premisas básicas: conservar la cobertura forestal y evitar los aportes que contaminan el río. La conservación y/o restauración de la cobertura forestal debe enfocarse principalmente a las comunidades de *Abies religiosa* y *Pinus hartwegii* ya que es donde más escurrimiento base se genera; tomando en cuenta que debe mantenerse la cobertura arbórea en zonas con pendientes pronunciadas, para evitar erosión y arrastre de sólidos al agua. La capacidad de regulación del ecosistema se comprueba con base en la buena calidad del agua

(Jujnovsky *et al.*, 2010; Morales-Luque, 2010). Por lo que es fundamental evitar descargas de aguas residuales y residuos sólidos al río. En zonas contaminadas, se deben colectar las aguas residuales, tratarlas y posteriormente volverlas a verter al río, con la finalidad de conservar un caudal ecológico mínimo para el mantenimiento del río y la vegetación ribereña.

Cabe mencionar que "El Plan Maestro para el Rescate Integral de la cuenca del río Magdalena" (PUEC-UNAM, 2008) ya había propuesto estrategias precisas para conservar el área en buen estado a partir de: la reducción de la erosión y los deslaves, la restauracion por tipo de ecosistema, el manejo forestal sustentable, la prevención de los incendios, la protección de la flora y fauna, y de la educación y comunicación ambiental. Desafortunadamente y a pesar de que el Plan tiene 4 años de haberse entregado al Gobierno del Distrito Federal, hasta el momento no se han visto reflejadas estas recomendaciones en las acciones que ejecutan las instituciones de gobierno encargadas de la zona.

Para que estas intervenciones de tipo técnico se implementen, debe haber conciencia e interés por parte de los tomadores de decisiones y personas involucradas en el proceso de manejo (comuneros, productores, empresarios, autoridades, etc.). Más aún, es indispensable que existan las condiciones de gobernanza y desarrollo institucional adecuadas para conseguir los recursos y administrarlos adecuadamente. Es decir, se requiere lo que Castillo (2003) define como intervenciones comunicativas, y lo que Medardo Tapia y Raúl García Barrios (com. pers.) denominan como intervenciones institucionales (Maass *et al.*, 2007).

Intervenciones comunicativas.- estas medidas están orientadas a transformar el escenario de generación y discusión de la información, discursos y argumentos de los diferentes sectores sociales que participan en el proceso de manejo; generando un proceso de aprendizaje colectivo, ambiental, político y ciudadano que constituya un mecanismo para la articulación del conocimiento y discusión de los sistemas socio-ecológicos. Para que las acciones de manejo en la

CRM sean exitosas y permeen en la comunidad, es fundamental que en la generación de las propuestas participen la mayor parte de los actores sociales involucrados. Para ello, es necesario identificar a los actores de manera participativa, por lo que se recomienda que la identificación se haga de manera conjunta con las comunidades locales. Detrás del fracaso de políticas y programas de manejo está, con frecuencia, precisamente la ausencia de algún actor importante en los procesos de toma de decisiones. Esta ausencia se debe a la falta de un entendimiento claro de cómo funciona y quiénes conforman el socio-ecosistema, pero también, puede ser por un deliberado intento de segregar a un sector en particular (Maass, 2012).

Las intervenciones no se deben hacer en función de la duración de proyectos académicos o gubernamentales. Especialmente los comuneros y los habitantes del lugar deben lograr una relación fuerte y duradera con las dependencias de gobierno y con la academia para que pueda haber un genuino proceso de participación social, que resulte en acciones exitosas para el mantenimiento de los servicios ecosistémicos.

Los actores involucrados tienen diferentes percepciones y necesidades en relación con los servicios ecosistémicos, así como diferentes capacidades y deseos de modificarlos (Díaz et al., 2011); por lo que se recomienda la implementación de talleres con cada grupo de actores para entender sus perspectivas y lograr objetivos conjuntos.

También son fundamentales las campañas de educación y comunicación ambiental para mostrar la relevancia de cuidar los bosques para la generación de agua.

Este es un proceso muy largo que requiere de estrategias y compromisos de muchos grupos de actores a lo largo del tiempo. Una opción es la formación de un comité de cuenca donde haya representantes de diversos grupos, desde comuneros, autoridades, vecinos, comerciantes y académicos que se puedan poner de acuerdo para buscar objetivos comunes. Recientemente, y en acuerdo al artículo 14° de la Ley de Aguas Nacionales, se creó el comité de cuenca del rio

Magdalena, el cual forma parte del consejo de cuenca del Valle de México que administra la Comisión Nacional del Agua. Este comité fue instalado con el consenso de los vecinos y se espera que a partir de esta iniciativa se comience a crear un verdadero proceso participativo en la zona.

Intervenciones institucionales.- Estas juegan un papel central en las acciones de manejo, ya que en la mayoría de los casos son las instituciones las que ejecutan las propuestas. Estas medidas están orientadas a transformar las reglas de interacción social relacionadas con el manejo del ecosistema.

Para que un programa de manejo pueda ser exitoso es indispensable la coordinación de las diferentes dependencias de gobierno, esto con el propósito de que no se lleven a cabo obras contradictorias; y por lo tanto que haya una mejor aplicación de los recursos financieros, así como una mejoría de las condiciones ambientales de la zona.

El manejo del agua bajo el concepto de gobernanza se planeó desde "El Plan Maestro para el Rescate Integral de la cuenca del río Magdalena" (PUEC-UNAM, 2008). Allí se indica que los objetivos deben ser determinados y definidos a través del consenso entre los participantes. La capacidad de acción y regulación debe hacerse a través de la responsabilidad compartida entre las autoridades gubernamentales y las organizaciones sociales y privadas. Sin embargo, hasta la fecha, las comunidades locales no han podido ser integradas en la toma de decisiones.

Las responsabilidades y competencias de las diferentes instituciones de gobierno muchas veces se traslapan y en muchos casos las leyes federales y estatales se contraponen. Por lo tanto, no es sencillo poder ilustrar de manera clara que entidad es la responsable de que acción. Sería necesario hacer un estudio jurídico mucho más profundo a nivel de leyes y reglamentos para poder esclarecer las competencias de cada una de ellas.

La tabla 5.1 muestra las principales instituciones gubernamentales que tienen, o deberían tener, injerencia en la zona de estudio, desde el ámbito federal al local.

Tabla 5.1.-Instituciones gubernamentales con injerencia en el manejo del agua y bosques en la cuenca del río Magdalena, D.F.

Federal	Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT)
	Procuraduría Federal de Protección al Ambiente (PROFEPA)
	Comisión Nacional del Agua (CONAGUA)
	Comisión Nacional Forestal (CONAFOR)
Estatal	Sistema de Aguas de la Ciudad de México (SACM)
	Procuraduría Ambiental de Ordenamiento Territorial (PAOT)
	Secretaria de Medio Ambiente (SMA)
	Comisión de Recursos Naturales (CORENA)
	Secretaría de Desarrollo Urbano y Vivienda (SEDUVI)
	Secretaría de Obras y Servicios
Local	Delegación Magdalena Contreras

Las intervenciones institucionales que involucran la conservación y restauración del bosque deben llevarse a cabo en coordinación con CORENA, la delegación Magdalena Contreras y los comuneros. Estos últimos para que formen brigadas de vigilancia y reforestación. La CONAFOR puede funcionar para otorgar fondos para dichas obras. A su vez, la SEMARNAT es la responsable de otorgar los permisos para las obras de mantenimiento y la PROFEPA de vigilar el cumplimiento de los mismos.

Para evitar que siga avanzando la mancha urbana es necesaria la coordinación entre la PAOT y la SMA, para vigilar el cumplimiento del ordenamiento ecológico del Suelo de Conservación del

D.F. Así mismo, la Secretaría de Obras y Servicios, la SEDUVI y la Delegación, en coordinación, deben evitar que sigan creciendo los asentamientos irregulares.

Para la protección de los márgenes del río Magdalena se necesita la coordinación de la CONAGUA, la SMA y el SACM. Este último para evitar obras que puedan ocasionar la contaminación, desvío o sobreexplotación del río. El SACM en coordinación con la CONAGUA debe implementar una estrategia de suministro de agua potable que sea diferenciada en época de lluvias y estiaje, para no desperdiciar agua que podría utilizarse abasteciendo colonias aledañas a las zonas de generación del servicio ecosistémico.

Para controlar las actividades recreativas y evitar la acumulación de basura es indispensable que las instituciones locales como la asociación de comerciantes o comuneros, en coordinación con la Delegación y la Secretaría de obras organicen la separación, recolección y el traslado de los residuos, para que no acaben en el cauce del rio.

Parte fundamental de las intervenciones es la adecuación y ejecución eficiente de un programa de pago por servicios ambientales. Para ello es necesario realizar valoraciones económicas eligiendo el método más adecuado a los datos que se tengan y al servicio ecosistémico hidrológico que se desee evaluar. El Programa Federal de Pago por Servicios Ambientales hidrológicos (PSAH), ha sido implementado por la CONAFOR desde el año 2003 (Perevochtchikova y Vázquez Beltrán, 2012). Desafortunadamente en la cuenca del río Magdalena hay un desconocimiento de este pago por parte de los comuneros. Esto se debe a la falta de asistencia a las asambleas, problemas de comunicación con la CONAFOR y a que no ha habido una adecuada estrategia de comunicación a través de talleres donde se expliquen los objetivos del programa (Caro-Borrero, 2012). Para que el PSAH pueda ser exitoso es muy importante que esté cimentado con base en propuestas científicas y que este acompañado de intervenciones técnicas y comunicativas congruentes, pues la falta de coordinación entre instituciones hace que los programas se desarrollen en forma contraria a las que fueron concebidos. Caro-Borrero (2012) propone una valoración económica del servicio de infiltración que podría usarse como base para establecer pagos más justos.

La tabla 5.2 ejemplifica las preguntas básicas para la aplicación de las intervenciones.

Finalmente, y a pesar de que la identificación de las técnicas de monitoreo se describen desde la generación biofísica, el monitoreo debe realizarse en todo momento del proceso para corroborar que las intervenciones que se proponen estén funcionando.

Tabla 5.2 Preguntas relevantes para poder ejecutar las intervenciones de manejo en la cuenca del río Magdalena, D.F.

Técnica		**Comunicativa**		**Institucional**		
¿Qué servicios se deben mantener?	**¿Cómo debe estar el ecosistema?**	**¿Quiénes son los responsables de la generación del servicio?**	**¿Quiénes son los usuarios?**	**¿Qué tipo de intervenciones se deben diseñar?**	**¿Cuáles son las instituciones competentes?**	
					Gobierno	**Grupos locales**
Provisión de agua Cantidad de agua Calidad de agua	Bosque bien conservado Río sin contaminación	Directos: Comuneros Autoridades Indirectos: Academia Organismos de la sociedad civil	Directos: Habitantes Indirectos Visitantes	1.-Organización de brigadas de vigilancia contra incendios y tala	SMA CORENA Delegación M.C	Comisariado
				2.-Implementación de programas de reforestación	CONAFOR CORENA	
				3.-Protección de los márgenes del río Magdalena	CONAGUA SACM PAOT SMA	
				4.- Elaboración de estrategia diferenciada por temporadas para el suministro de agua	CONAGUA SACM	
				5.-Cumplimiento del POET del SCDF	PAOT SMA	
				6.-Control de los asentamientos irregulares en barrancas y suelo de conservación	SMA Secretaría de obras PAOT SEDUVI Delegación M.C	
				7.-Control de las zonas recreativas		Comisariado comerciantes
				8.-Recolección de basura y limpieza en los márgenes de los ríos y en la zona boscosa	Secretaría de obras Delegación M.C.	Comerciantes, Vecinos Comuneros
				9.-Adecuación del programa de pago por servicios ambientales hidrológicos.	CONAFOR SACM SMA	

En resumen, la evaluación del servicio ecosistémico de provisión de agua se basa en identificar las mejores técnicas para evaluar y monitorear la cantidad y calidad de agua de la cuenca, identificar a los actores sociales y sus percepciones, así como realizar una valoración económica del servicio a partir de información biofísica. Posteriormente se plantean las intervenciones de manejo tomando como base la información generada en la primera etapa. De tal forma que el monitoreo permitirá verificar que las acciones propuestas se traduzcan en un mejoramiento de la cantidad y calidad de agua; de tal manera que las etapas se puedan ir adaptando o modificando en el tiempo (Figura 5.2).

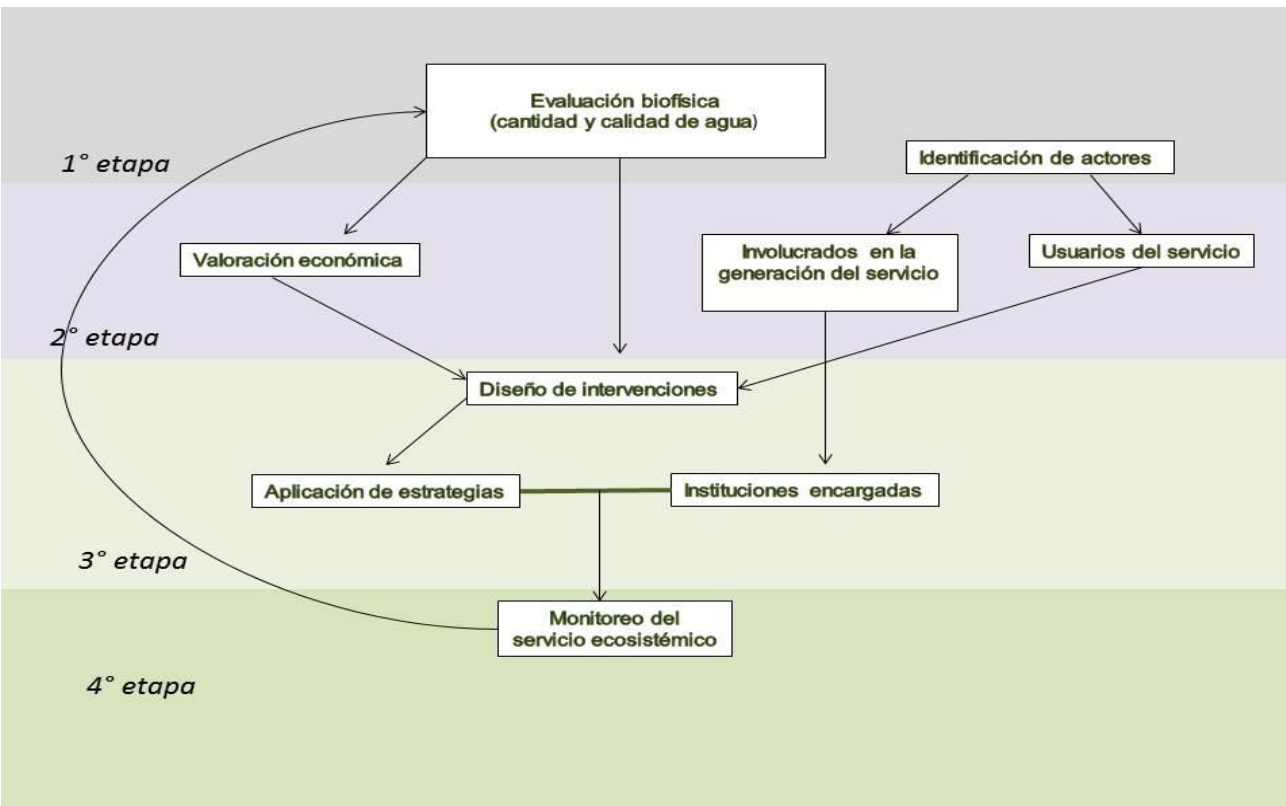

Figura 5.2 Etapas para el mantenimiento del servicio ecosistémico de provisión de agua en la cuenca del río Magdalena, D.F.

En conclusión, para lograr un manejo del agua desde el enfoque ecosistémico, es necesario integrar el trabajo científico con la toma de decisiones. Cuando se pretende manejar los ecosistemas, es necesario reconocer que se trabaja bajo condiciones de incertidumbre y que los datos que se van generando deben de utilizarse como herramienta ya que es muy difícil contar con la información suficiente para entender todas las funciones y los procesos de los ecosistemas, ya que los cambios ambientales y socio-económicos en las ciudades son muy acelerados y requieren respuestas rápidas por parte de los tomadores de decisiones.

La propuesta está planteada a partir de toda la información que se ha generado hasta el momento para la cuenca del río Magdalena, pero teniendo claro que aun no se conocen con detalle los procesos que regulan al ecosistema. Por lo que se espera que se pueda ir adaptando a medida que se avance en la generación del conocimiento y en el fortalecimiento de las relaciones sociales e institucionales.

CONCLUSIONES GENERALES Y PERSPECTIVAS

- El servicio ecosistémico de provisión de agua depende de la regulación de la cantidad, temporalidad y calidad.
- La cantidad de agua en la cuenca del río Magdalena se evaluó tanto con el método de Thornthwaite, como con el modelo SWAT. El primero, muestra de manera general el comportamiento del agua a largo plazo aunque no es posible separar los tipos de escurrimientos y no requiere tener información ambiental muy detalla. Mientras que el modelo SWAT, permitió entender en mayor medida los procesos ecológicos en el bosque y mostró una mayor precisión en los tipos de escurrimientos, aunque se requiere contar con información ambiental precisa y los mismos años de registros para los datos meteorológicos e hidrométricos.
- En la cuenca del río Magdalena el escurrimiento instantáneo promedio es de 0.67 m^3/s y genera anualmente cerca de 20 millones de m^3 de agua. De los cuales se utilizan para la distribución a la población 0.20 m^3/s, lo que significa que solo se aprovecha el 30% de su caudal.
- En la zona natural, el bosque esta regulando la calidad de agua siendo excelente en la parte alta, pero a medida que se desciende en altitud y cuando se adentra en la zona urbana esta disminuye drásticamente.
- La calidad del agua se evaluó solamente con parámetros fisicoquímicos y bacteriológicos, aunque para lograr un enfoque de servicios ecosistémicos es recomendable utilizar indicadores biológicos para poder analizar la calidad ambiental.

- Para que la cuenca el río Magdalena pueda seguir generando provisión de agua todo el año es imperativo que la cuenca no pierda su cubierta vegetal, principalmente en las zonas de bosques de *Pinus hartwegii* y *Abies religiosa*.

- Los beneficiarios que reciben agua del río Magdalena actualmente suman 78,476; sin embargo el flujo que genera el río en época de lluvias podría abastecer hasta 153,203 habitantes

- En lugar de dejar que el agua de buena se combine con agua residuales y se deseche a través del drenaje debería desinfectase y distribuirse.

- Las políticas públicas deberían estar encaminadas hacia estrategias diferenciadas por temporadas y abastecer del suministro a la población más cercana. Esto ayudaría a administrar mejor el servicio en épocas lluvias, evitando inundaciones y no trayendo el agua de lugares lejanos.

- Para evaluar a la provisión de agua de una manera integral, se plantea que no solamente es necesario conocer la cantidad y calidad del agua, también se deben toma en cuenta los componentes sociales y económicos.

- La propuesta de manejo del agua para la CRM incluye la evaluación del servicio ecosistémico y la generación de intervenciones para el mantenimiento del mismo. La evaluación comprende la identificación de las mejores técnicas para evaluar y monitorear la cantidad y calidad de agua de la cuenca, la identificación de los actores sociales y sus percepciones, así como la valoración económica del servicio a partir de información biofísica. Posteriormente se plantean las intervenciones de manejo a partir de la información generada en la primera etapa. Finalmente se plantean las técnicas de monitoreo continuo, de tal manera que las etapas se puedan ir adaptando o modificando en el tiempo.

- Esta propuesta está planteada a partir de toda la información que se ha generado hasta el momento para la zona de estudio, pero teniendo claro que aun no se conocen con detalle los procesos que regulan al ecosistema. Por lo que se espera que se pueda ir adaptando a medida que se avance en la generación del conocimiento y en el fortalecimiento de las relaciones sociales e institucionales, con la idea de que pueda extrapolarse a otras cuencas con características similares.

- Este trabajo contribuye con la generación de conocimiento sobre metodologías para evaluación de servicios ecosistémicos, ya que es un campo de la ciencia que sigue en formación.

- Si se logra incorporar el enfoque de servicios ecosistémicos a las políticas públicas para el manejo del agua será más probable encaminar nuestras acciones hacia la sostenibilidad de la ciudad de México.

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