UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

PROGRAMA DE POSGRADO EN CIENCIAS DE LA TIERRA

GESTIÓN INTEGRADA DEL AGUA URBANA: APLICACIÓN DEL MODELO UVQ AL ÁREA METROPOLITANA DE SAN LUIS POTOSÍ

T E S I S

QUE PARA OBTENER EL GRADO DE:
DOCTOR EN CIENCIA S DE LA TIERRA
(Águas Subterráneas)

P R E S E N T A

SANDRA MARTINEZ

COMITÉ TUTOR
Oscar Escolero Fuentes
Leticia Flores Marquez
Lorenzo Vázquez Selem

JURADO EXAMINADOR
Oscar Escolero Fuentes
Francisco Romero
Eloísa Domínguez Mariani
Maria Perevochtchikova
Leif Wolf

UNAM POSGRADO Ciencias de la Tierra

MÉXICO D.F. 2009

A la memoria de mis padres Hebe y Coco,

a mi hijo Federico

AGRADECIMIENTOS

Un profundo agradecimiento a mi director Dr. Oscar Escolero por impulsarme a esta visión de la gestión del agua y por el apoyo constante a mi formación académica, profesional y personal. Gracias por seguir apoyándome en promover la gestión integrada del agua urbana en San Luis Potosí.

Al Dr. Leif Wolf, coordinador del Proyecto AISUWRS y supervisor de esta investigación, mi especial gratitud por su apoyo en la promoción de este enfoque de gestión con las instituciones de San Luis Potosí, por las facilidades para acceder a todo el material y herramientas de AISUWRS, por sus valiosos comentarios y sugerencias para concluir esta tarea.

Gracias por el tiempo dedicado y los valiosos comentarios a mi comité tutoral, Dres. Leticia Flores y Lorenzo Vazquez, y a mi comité de defensa los Dres. Francisco Romero, Leif Wolf, Eloísa Dominguez y Maria Perevochtchikova.

Agradezco el apoyo económico de la Coordinación de Estudios de Posgrado de la UNAM, Servicio de Intercambio Académico Alemán (DAAD) e Instituto de Geología que me permitieron realizar los estudios de doctorado e intercambios con la Universidad de Karlsruhe, Alemamia.

Deseo reconocer la sincera vocación de apoyo a los estudiantes al Dr. Gustavo Tolson y Dra. Elizabet Solleiro, que hace posible tener los medios y facilidades para hacer nuestra tarea. Gracias a Maria Luisa y Gloria que nos apoyan en los trámites.

Aprecio especialmente el apoyo recibido del Interapas y COTAS de San Luis Potosí para llevar a cabo trabajos de campo, análisis y cartografía. Asimismo, doy las gracias al IMPLAN, Gerencia de Conagua y CEAS de San Luis Potosí por brindarme toda la información disponible y su conocimiento que fueron de gran utilidad para el tratamiento de datos.

Un especial agradecimiento es para el CSIRO (Australia) por el acceso al modelo UVQ y a Grace Mitchell y Claire Diaper por su soporte.

Este trabajo no hubiera sido posible sin las ideas del Dr. Matthias Eiswirth, fallecido en un accidente en 2003, quien fue el iniciador y coordinador del proyecto AISUWRS financiado por la Comisión Europea.

A Elke y familia, muchas gracias por compartirme su casa, su vida en familia, su cultura y hasta la bicicleta durante casi dos meses; fue una experiencia increíble vivir con todos ustedes!. Gracias Julia y Leif por compartirme sus ratos en familia durante mis estancias en Alemania.

Las posadas que me brindaron Rosario y Eloisa en San Luis Potosí me facilitaron hacer el trabajo de campo, muchas gracias!. Gracias Eloisa por apoyarme en el muestreo y análisis, y por estar en SLP cuando ocurría la primera lluvia de la temporada.

A mi familia del cubo: Lener, Rosalva, Miguel, Mario, Cesar, y ahora también Isadora, Rafael y Daniel con quien compartimos el oxigeno, el aire del ventilador, los virus de la computadora, los días malos y buenos, los tips para los tramites, la cafetera, el stress y más. Gracias por la compañía y para los que aún quedan les heredo la silla y el ventilador.

Estos años han sido una agradable experiencia que he tenido la suerte de compartir con Fede, Ami, Antonio, Lila, Gabi, Maria, Ruben, Veronica, Stefanie, Mayeli, Javier, Luis, José Luis, y seguro que alguno se me olvida…

A mis amigos de Argentina, Juan Carlos y Gallego, gracias por estar siempre.

A mi querido hermano Walter, quien me mantuvo conectada a mis raíces y mi familia vía skype.

Antonio compartir contigo fue una increíble experiencia llena de alegría.

Gracias hijo por haberme apoyado y acompañado.

INDICE

RESUMEN

El acelerado crecimiento poblacional que enfrenta la mayor parte de las ciudades de la zona árida Mexicana ha puesto en evidencia las fuertes limitaciones de las instituciones para proveer servicios de agua adecuados a los niveles de desarrollo. La problemática que enfrentan los centros urbanos es compleja y mezcla, desarrollo urbano no planeado, servicios de agua y drenaje ineficientes, disposición no controlada de agua y residuos, degradación de recursos de agua y suelo, envejecimiento de la infraestructura, uso intensivo de recursos de calidad potable, desaprovechamiento de recursos no-convencionales, escasez de agua y conflictos entre usuarios. Los retos actuales hacen evidente la necesidad de tomar decisiones urgentes respecto a la manera en la cual se proporcionan y gestionan los servicios de agua urbana.

El análisis sistémico y el concepto holístico del ciclo de agua urbana son enfoques que se promueven cada vez más para el análisis integrado de los servicios de agua, con el fin de atenuar el estrés hídrico en las grandes aglomeraciones. Sin embargo, el análisis integrado no se aplica con frecuencia debido a la inherente complejidad, las limitaciones en disponibilidad de datos y especialmente, a la carencia de prototipos y herramientas de software apropiadas.

Esta tesis aplica un modelo de balance total de agua urbana llamado UVQ a la Zona Metropolitana de San Luis Potosí, México. UVQ es un modelo hidrológico conceptual, determinístico que describe los flujos de agua y contaminantes en el área urbana desde las fuentes a los puntos de descarga. Incluye todos los tipos de agua tales como agua de lluvia, agua importada, escurrimiento superficial, agua residual y agua subterránea. Los resultados fueron especialmente útiles para el cálculo espacial de la recarga urbana. Un rango de escenarios, incluyendo diferentes estrategias de abastecimiento y el efecto de factores externos como cambio de demanda, fueron simulados y comparados con un escenario base calibrado. El análisis demuestra que especialmente el acuífero urbano somero puede mitigar sustancialmente los problemas de escasez y uso intensivo del acuífero profundo, si se ponen en práctica estrategias de protección de la calidad del agua o un enfoque de uso adaptado a la demanda (fit-for-use). El ejercicio de modelación brinda información relevante para el proceso de toma de decisión e identifica las deficiencias más importantes del sistema actual. Esto representa un paso clave hacia un desarrollo urbano sustentable y sensible al agua incluyendo los acuíferos urbanos someros, los cuales han sido omitidos de las políticas de gestión en la mayor parte de las ciudades de la zona árida Mexicana.

ABSTRACT

The accelerated growth faced by most cities in the Central- and North Mexican arid zone, has revealed the strong limitations in providing water services that meet the current stage of socio-economic development. The set of problems that the urban centers face is complex, and includes unplanned urban growth, inefficient drinking water services and sanitation, uncontrolled disposal of wastewater and solid waste, resulting degradation of soils and water resources, an over-aged infrastructure, intensive use and misuse of good-quality water while disutilizing non-conventional water sources, as well as conflicts between water users. The present challenges imply the urgent need to take decisions with respect to the way in which urban water services are provided and managed.

Systems view thinking and holistic urban water cycle concepts are increasingly called upon for integrated analysis of urban water system to mitigate water stress in large urban agglomerations. However, integrated analysis is frequently not applied due to the inherent complexity, limitations in data availability and especially the lack of guidelines and suitable software tools.

The thesis presents the application of the total urban water balance model UVQ to the Metropolitan Zone of San Luis Potosi. UVQ is a lumped, deterministic, conceptual hydrological Model which describes water and contaminant flows from source to sink in urban areas and includes all water types such as rainwater, imported water, surface runoff, wastewater and groundwater. The results were especially useful for spatially explicit groundwater recharge calculation in urban areas. A range of urban water scenarios, including different supply strategies and the effect of externalities such as demand change, were simulated and compared to a calibrated baseline scenario. The analysis demonstrated that especially the shallow urban groundwater resources can substantially mitigate problems of water scarcity and overexploitation of deep aquifers if appropriate water quality protection or fit-for-use paradigms are put into place. The modeling exercise delivers relevant information for the decision making process and identifies the most relevant shortcomings in current monitoring systems. This represents a key step on the path to water sensitive and sustainable urban development, including the shallow urban aquifers which have been neglected in the management policy of most cities of the Mexican arid zone.

INTRODUCCION

Antecedentes

En las últimas décadas, el acelerado crecimiento de la población urbana en América Latina ha convertido a esta región en la más urbanizada del mundo en desarrollo, con niveles que llegan a superar el 85%. Los patrones de crecimiento urbano, abastecimiento de agua, disposición de agua residual y uso de suelo, si bien varían con el contexto local, relacionan la gestión ineficiente, la falta de planeación, inversión y tecnología. La compleja problemática que enfrentan los centros urbanos de la región mezcla servicios de agua y drenaje ineficientes, disposición no planeada de agua y residuos, degradación de recursos de agua y suelo, envejecimiento de la infraestructura, uso intensivo de recursos de buena calidad, desaprovechamiento de recursos no-convencionales, escasez de agua y conflictos entre usuarios.

En México, esto es especialmente evidente en las regiones centro y norte donde se han registrado los mayores índices de crecimiento de la población urbana y desarrollo económico en recientes décadas (Martinez, 2005). Frente a la creciente demanda, el agua se esta convirtiendo rápidamente en un recurso escaso en estas regiones con sólo 32% de los recursos nacionales de agua disponible y 105 acuíferos declarados como sobre-explotados. Estimaciones indican que la mitad del crecimiento de la población para el año 2030 se concentrará en 31 ciudades de más de 500 000 habitantes, de las cuales 75% se ubican en el centro y norte del país (Conagua, 2006).

En respuesta a la creciente demanda, la gestión del agua en las zonas urbanas de México se ha dado bajo el tradicional enfoque de maximizar el volumen de agua disponible de buena calidad. Las estrategias, impulsadas por la política de desarrollo socio-económico, han promovido la construcción de grandes infraestructuras centralizadas de captación, desalojo y tratamiento, el desarrollo intensivo de acuíferos profundos y la transferencia de agua desde cuencas externas. Las herramientas aplicadas extensamente han sido balances a escala de acuíferos y cuencas que implican una cuantificación de entradas y salidas basadas en cálculos mensuales y anuales (Birkle et al., 1998, Conagua, 2005), así como modelos de simulación y simulación-optimización de acuíferos para evaluar la respuesta del régimen hidrogeológico y espesor saturado a cambios (principalmente incrementos) en la extracción (Conagua 1996; CEASG 1998; Navarro de León 2004; Garfias et al. 2006; Hernández-G y Huizar-A. 2006; Escolero y Torres-O 2007; Aldama et al. 2006). Dado que el principal problema ha sido la competencia por el uso del agua en cuencas y acuíferos, los objetivos se han centrado en estimar los componentes de escurrimiento e infiltración, determinar volumen comprometido para los diferentes usos y volumen disponible para nuevas concesiones. Las metas se orientan a mejorar la distribución entre usuarios a nivel regional y determinar el régimen óptimo de bombeo para maximizar la extracción y reducir el impacto del descenso del nivel del agua, mientras otros solo se limitan a dar una herramienta que avale la disponibilidad o no de agua para futuros usos.

El abastecimiento de agua ha sido identificado por la Conagua como uno de los principales retos que determinará el futuro crecimiento de las ciudades mexicanas. En este sentido, la necesidad de tomar decisiones urgentes respecto a la manera en la cual se proporcionan y gestionan los servicios de agua urbana se hace evidente.

Para reorientar las áreas urbanas hacia la sustentabilidad, los diferentes aspectos de los sistemas de agua (natural y construido) deben ser visualizados en relación al otro, lo cual requiere la adopción de un enfoque integrado para la planeación, provisión y gestión de los sistemas de agua urbana. El origen del paradigma de la gestión integrada de agua urbana (IUWM por sus siglas en ingles) se atribuye en parte a las actividades iniciadas en 1970 por el “Urban Water Resources Research Council of the American Society of Civil Engineers” (Marsalek et al., 2001). Ciertamente, el “Council’s head M. B. McPherson” fue un fuerte promotor de la idea de un balance para los recursos de agua urbana que implicó la necesidad de un enfoque mas holístico y un entendimiento integrado de la manera en que los sistemas de abastecimiento de agua, saneamiento y drenaje son operados. A inicio de los 90, un grupo de expertos de Australia inició un enfoque de IUWM para el diseño y planeación urbana haciendo énfasis en la gestión del lado de la demanda, así como del lado del abastecimiento, la utilización de recursos de agua no-tradicionales y el concepto de “fit-for-purpose” y descentralización (Mitchell, 2006).

Las diferencias del viejo paradigma y del paradigma emergente de gestión de agua urbana se caracterizan abajo. Éstas son simplificaciones y muchos sistemas están en la transición, pero las diferencias de los enfoques son instructivas.

El “viejo” paradigma	**El “nuevo” paradigma**
Los residuos son un problema. Deben ser dispuestos después del tratamiento	Los residuos son un recurso. Deben ser colectados y procesada efectivamente, y usados para abonar suelos y cultivos
La lluvia es un problema. Transportar el agua pluvial lejos de la zona urbana lo más rápido posible.	El agua de lluvia es un recurso. Colectarla para abastecimiento de agua, infiltrarla o conservarla para mantener acuíferos y vegetación
La demanda es una cuestión de cantidad. Cantidad de agua requerida o producida es el único parámetro relevante para las opciones de infraestructura. Tratar toda el agua del lado del abastecimiento para calidad potable, y colectar toda el agua residual para tratamiento.	La demanda es polifacética. La opción de la infraestructura debe equilibrar las diversas características del agua requerida o producida para diversos usuarios finales en términos de cantidad, calidad, nivel de confiabilidad, etc.
Un uso. El agua sigue la trayectoria unidireccional desde la fuente, a un simple uso, al tratamiento y a la disposición en el ambiente.	Recuperación y reutilización. El agua puede ser usada múltiples veces, conectando en cascada desde las necesidades de más alta calidad a la más baja.
Infraestructura gris. La infraestructura es hecha de concreto, metal o plástico.	Infraestructura verde. La infraestructura incluye no sólo las tuberías e instalaciones de tratamiento hechas de concreto, metal, y plástico, sino también suelos y vegetación.
Los sistemas de colección y plantas de tratamiento son mejor grandes y centralizados.	Los sistemas de colección y plantas de tratamiento pequeños y descentralizados son posibles, y a menudo deseables
Limitar la complejidad y emplear soluciones estándar. Un pequeño número de tecnologías de los profesionales del agua urbana definen la infraestructura.	Permitir soluciones diversas. Los responsables son multidisciplinarios. Permitir las nuevas estrategias y tecnologías de gestión.
Integración por accidente. Abastecimiento de agua, saneamiento y aguas pluvial pueden ser manejadas por la misma agencia aunque físicamente los tres sistemas son separados.	Integración física e institucional por diseño. La integración se debe hacer entre el abastecimiento de agua, aguas residuales y precipitación, los cuales requieren una gestión altamente coordinada.
Colaboración = relaciones públicas. Acercamiento a otros organismos y al público cuando se requiere aprobación o solución pre-elegida.	Colaboración = contrato. Acercar otros organismos y público para la búsqueda de soluciones eficaces.

Características del viejo y nuevo paradigma de los sistemas de agua urbana (Fuente: Pinkham, 1999)

La translación del concepto de IUWM dentro de la práctica ha variado internacionalmente. Diferentes enfoques han sido desarrollados para el drenaje urbano en Australia, Alemania, Francia, Japón, Estados Unidos, Dinamarca e Inglaterra (Chocat et al, 2001), mientras en Australia la aplicación se ha orientada a la dimensión técnica de los servicios de abastecimiento de agua urbana, con ensayos de nueva tecnología y métodos para el diseño y la toma de decisión (Mitchell, 2004). En países en desarrollo y especialmente en México, la aplicación de los principios de IUWM ha estado fuertemente limitada por los aspectos institucionales y del conocimiento que perpetúan las prácticas tradicionales y promueven la inercia. En esto, los investigadores tienen el importante rol de asistir a los tomadores de decisión para superar las barreras que hasta ahora han limitado el cambio.

Los principios de la IUWM aplicados en esta tesis se pueden resumir en los siguientes puntos:

1. Considerar todas las partes del ciclo de agua, natural y construido, superficial y sub-superficial, reconociendo a ellos como un sistema integrado.
2. Identificar y manejar los procesos individuales de tal manera que los impactos colectivos sean minimizados y la eficiencia del sistema sea maximizada, tanto como sea posible.
3. Considerar el contexto local, tomando en cuenta las perspectivas ambientales, sociales, culturales y económicas.
4. Incluir a los tomadores de decisión en el proceso de cambio.
5. Buscar la sustentabilidad, apuntando a balancear las necesidades ambientales, sociales y económicas, en el corto, mediano y largo plazo.

Para el primer caso de aplicación de los principios IUWM, se seleccionó la Zona Metropolitana de San Luis Potosí localizada a unos 400 km al noroeste de la Ciudad de México. Este centro urbano yace en la cuenca del Valle de San Luis Potosí a una altitud entre 1850 y 1900 m.s.n.m. y esta flanqueada por la Sierra San Miguelito en el oeste y Cerro San Pedro en el este. El área corresponde a una estructura de graben donde fue depositada una espesa secuencia de rocas volcánicas y posteriormente el relleno formado por material granular, ambos del Terciario. La secuencia granular incluye una lente de arena fina compacta cuyo espesor varía entre 50 y 150 metros. Esta lente se extiende en aproximadamente 300 km^2 bajo la mayor parte de la cuenca, excepto en los bordes, y permite la separación de dos acuíferos en sentido vertical con escasa interacción.

El acuífero somero de tipo libre se localiza en el material aluvial del Cuaternario. El agua es de tipo cálcico-clorurada-bicarbonatada y presenta la influencia de las entradas provenientes del sistema de agua urbana e irrigación en el área agrícola. El acuífero profundo de tipo confinado se localiza en el material granular y rocas volcánicas fracturadas del Terciario, cuya distribución va más allá de los límites de la cuenca superficial. En este acuífero fueron identificados dos tipos químicos de agua (Cardona, 2005): i) tipo sódico-bicarbonatado asociado preferentemente a las rocas volcánicas fracturadas, con altos contenidos de F y Si relacionado con la desvitrificación de la matriz de la roca, y ii) tipo cálcico-bicarbonatado relacionado al material granular del terciario.

El acuífero profundo abastece más del 90% del consumo de agua de la zona metropolitana y fue declarado como sobre-explotado, mientras el acuífero somero fue abandonado para usos urbanos debido a la contaminación. El reto que supone el futuro abastecimiento de agua a este centro urbano, requiere integrar y gestionar de manera adecuada todos los recursos disponibles para contribuir a mitigar los problemas de escasez y cambio climático.

Objetivos y alcances de la investigación

Los *objetivos* de esta investigación son:

- Revisar el estado del conocimiento en gestión de agua con énfasis en zonas urbanas.
- Evaluar los enfoques y herramientas de gestión de agua en el contexto internacional y local, sus impactos y retos actuales.
- Aplicar en la Zona Metropolitana de San Luis Potosí el enfoque de gestión integrada de los recursos de agua basado en el conocimiento del ciclo total de agua urbana.

- Diseñar diferentes estrategias de gestión integrada y evaluar sus impactos.

Mientras el proyecto AISURWRS (Assessing and Improving the Sustainability of Urban Water Resources and Systems) (Wolf et al., 2006) comprendió un enfoque más amplio de la gestión de agua urbana desarrollando y aplicando modelos interconectados, esta tesis se limitó a evaluar el ciclo total de agua urbana usando el modelo principal de esta secuencia (UVQ Model). Las aplicaciones del modelo de balance total de agua urbana UVQ en el marco del proyecto AISURWRS se hicieron en el contexto de ciudades de Europa y Australia; esta tesis presenta la aplicación de esta herramienta y su contribución en la gestión integrada, en el contexto de países en desarrollo con escasa disponibilidad de datos.

La tesis esta conformada por cinco capítulos en formato de artículos que muestran la evolución de la investigación doctoral: Capítulo I, **The water management approaches: towards where we go?** (Martinez et al, 2008); Capítulo II, **The Mexican experience with groundwater management** (Escolero and Martinez, 2006); Capítulo III, **Socio-economic development in arid zones: the influence of water availability in the San Luis Potosí basin, Mexico** (Martinez et al, in print); Capítulo IV, **Water management in San Luis Potosi Metropolitan Area, Mexico** (Martinez et al, artículo en revisión en la revista “Water Resources Development”), Capítulo V, **Quantifying the total urban water cycle as tool to integrated management. Results to the area of San Luis Potosi, Mexico** (Martinez et al, artículo preparado para enviar a la revista “Water Resources Management”)

El *Capítulo I* tuvo como objetivo revisar los enfoques y herramientas de gestión de agua, con especial atención en aplicaciones que incluyen las áreas urbanas, y discutir los alcances en la solución de problemas relacionados al agua. Para esto se llevo a cabo una exhaustiva revisión de publicaciones internacionales que toman en cuenta el agua subterránea, las cuales fueron agrupadas en tres enfoques de gestión: i) del lado de la demanda, ii) del lado del abastecimiento e iii) integrada. Mientras el enfoque y las herramientas orientadas a maximizar la cantidad de agua disponible han prevalecido, formulaciones recientes proponen un entendimiento holístico de los recursos de agua para proveer soluciones más aceptables. Esto conformó la base para discutir el enfoque y las herramientas que han dominado la gestión del agua en México. Los retos que enfrenta México para el futuro abastecimiento de agua son expuestos, así como la necesidad de un cambio de estrategia para que éstos puedan ser superados.

El *Capítulo II* tuvo el objetivo de analizar las políticas de gestión y su relación con el uso y los impactos en el agua subterránea en México. Se discute la implementación, las limitaciones y los efectos de dos principales estrategias de gestión: la apertura del mercado de derechos de agua y la participación de los usuarios en la gestión. Los cambios introducidos en las políticas de gestión no han logrado reducir el uso intensivo del agua subterránea, y los impactos ambientales se manifiestan con intensidad creciente.

El objetivo del *Capítulo III* fue demostrar como la dinámica del desarrollo socio-económico promueve las modalidades de aprovechamiento del recurso y las políticas de gestión del agua. Se revisa la evolución de la cuenca de San Luis Potosí como modelo de cuencas urbanas en la zona árida mexicana, identificando cuatro etapas. En cada etapa, cuando el crecimiento socioeconómico alcanza o excede los límites de los recursos disponibles, las estrategias enfocadas a incrementar la disponibilidad se ponen en práctica. El abastecimiento de agua urbana ha sido identificado como uno de los mayores retos que determinará el futuro crecimiento de las ciudades en la zona árida mexicana. Las limitaciones de las prácticas convencionales de gestión de agua, ponen de manifiesto la necesidad de un cambio de paradigma tendiente a recuperar la sustentabilidad de los sistemas de agua urbana por medio de un enfoque holístico de los recursos.

El *Capítulo IV* tuvo el objetivo de revisar los tópicos y la complejidad de la gestión del agua en la Zona Metropolitana de San Luis Potosí, y discutir problemas emergentes. Por un lado, el aprovechamiento de las fuentes locales ha llegado a su límite y se desarrollan nuevas fuentes externas a la cuenca. Por otro lado, grandes volúmenes de agua se pierden en el sistema y recursos no-convencionales son desaprovechados para demandas de menor calidad. Esto combina las necesidades de una ciudad en rápido desarrollo con falta de planeación, inversión y tecnología, y manejo eficiente. Un conjunto de estrategias desde el enfoque de la gestión integrada son expuestas para responder a los futuros retos en áreas urbanas.

El objetivo del Capítulo V fue aplicar un modelo de balance diario de flujos y contaminantes en el área urbana y desarrollar un rango de escenarios para evaluar el impacto de diferentes estrategias de gestión. El modelo UVQ considera simultáneamente el abastecimiento de agua, el agua residual, de lluvia y agua subterránea en el marco del emergente paradigma de gestión integrada de agua urbana. Los resultados cuantifican el volumen de agua y las cargas contaminantes que fluyen desde las fuentes (precipitación y agua importada) a los puntos de descarga (sistemas de drenaje y acuífero somero), proveyendo un método para estimar la recarga urbana en el lugar. A partir del escenario calibrado, se modelaron y compararon escenarios que incluyen diferentes estrategias de abastecimiento y el efecto de externalidades. Los resultados permitieron evaluar el impacto de opciones de gestión tendientes a un desarrollo urbano sensible al agua.

REFERENCIAS

Aldama, A.; Güitrón, A.; Aparicio, J.; et al. (2006) La Cuenca Lerma Chapala y los modelos de simulación. Rev Cien Desar. CONACYT, Marzo 2006, 36-41.

Birkle P., Torres Rodríguez V., González Partida E. (1998) The water balance for the Basin of the Valley of Mexico and implications for future water consumption, Hydrogeology Journal 6, 500–517.

Cardona A (2005) Hidrogeoquímica de sistemas de flujo regional, intermedio y local resultado del marco geológico en la mesa central: Reacciones, procesos y contaminación. Tesis, doctorado, posgrado en ciencias de la tierra, Univ. Nac. Autónoma de Mexico, Mexico, p 252.

CEASG – Comisión Estatal del Agua y Saneamiento de Guanajuanto (1998) Estudio hidrogeológico y modelo matemático de los acuíferos del estado de Guanajuato. Elaboró Guysa, S.A. de C.V.

Chocat, B., P. Krebs, Marsalek, J., Rauch, W. Schilling, W. (2001) Urban drainage redefined: From stormwater removal to integrated management. Water Science and Technology 43, 61–68.

Conagua – Comisión Nacional del Agua (1996) Estudio de simulación hidrodinámica y diseño óptimo de las redes de observación de los acuíferos de Calera, San Luis Potosí y Toluca, Informe técnico, Contrato No. GAS-012-PRO-96. Elaboró Ariel Consultores SA.

Conagua, Comisión Nacional del Agua (2005) Actualización hidrogeológica de los acuíferos de Ceballos y Oriente Aguanaval Edo. de Dgo, Villa de Arista y San Luis Potosí, Edo. de SLP. Elaboró SABINFOSISTEM S.A. de C.V., contrato No. SGT-GRCCN-05-008-RF-I3.

Conagua - Comisión Nacional del Agua (2006) Water in Mexico, Document printed for 4th World Water Forum.

Escolero, O.; Torres-Onofre, S. (2007) Análisis de la intrusión de agua de mar en el acuífero de La Paz (México). Bol. Geol Min. 118(núm esp), 637-648.

Garfias, J.; Navarro de León, I.; Llanos, H. (2006) Gestión integral de recursos hídricos con arreglos a distintas modalidades de utilización. Paper presentado en VIII Congreso latinoamericano de hidrología subterránea, ALHSUD, Asunción, Paraguay, Septiembre 2006.

Hernández-García, G.; Huizar-Alvarez, R. (2006) Evolución de la extracción de agua subterránea en la región de Zumpango-Pachuca, México central, sus efectos ambientales. Paper presentado en VIII Congreso latinoamericano de hidrología subterránea, ALHSUD, Asunción, Paraguay, Septiembre 2006.

Martinez, S. (2005) Los dilemas de la urbanización en zonas áridas: una visión de San Luis Potosí desde la hidrogeología urbana y la geografía regional, Tesis Maestría, Facultad de Filosofía y Letras, Universidad Nacional Autónoma de México, México, p. 117.

Marsalek, D. J., Rochfort, M. Q., Savic, P. D. (2001) Chapter 2: Urban water as a part of integrated catchment management in Maksimovic, C. and Tejada-Guibert J. A. (eds.), Frontiers in urban water management deadlock hope. IWA Publishing, London, pp. 37–83.

Mitchell, G.V. (2004) Integrated urban water management: A review of the current Australian practice. Australian Water Conservation and Reuse Research Program - Australian Water Association and Urban Water, CSIRO. CMIT-2004-075 April 2004. p.58.

Mitchell, V.G. (2006) Applying integrated urban water management concepts: A review of Australian experience. Environ Manag. 37(5), 589–605.

Navarro de León, I. (2004) Análisis de estrategias de manejo integral del agua subterránea mediante modelación de flujo: Cuenca de la Independencia, Guanajuato, México. Universidad Nacional Autónoma de México, Tesis doctoral.

Pinkham, R. (1999) 21st century water systems: Scenarios, visions and drivers, Available at http://www.rmi.org/images/other/Water/W99-21 21CentWaterSys. pdf.

Wolf L, Morris BL, Burn S, Hötzl H (2006). The AISUWRS approach. In: Wolf L, Morris B, Burn S (eds), Urban Water Resources Toolbox – Integrating Groundwater into Urban Water Management. IWA, London, 296 pp.

CAPÍTULO I. THE WATER MANAGEMENT APPROACHES: TOWARDS WHERE WE GO?

Sandra Martínez, Oscar Escolero, Leif Wolf

En:
Natural Resources: Management, Economic Development and Protection
J. Pauling (Ed)
Nova Science Publishers, New York, pp 295-311. 2008

In: Natural Resources
Editor: Jeanette B. Pauling, pp.
ISBN 978-1-60456-982-7

THE WATER MANAGEMENT APPROACHES: TOWARDS WHERE WE GO?

Sandra Martinez[1,*], *Oscar Escolero*[2,†], *Leif Wolf*[3,‡]
[1]Posgrado en Ciencias de la Tierra, Instituto de Geologia, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Coyoacan 04510, Mexico City, Mexico
[2]Departamento de Geologia Regional, Instituto de Geologia, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Coyoacan 04510, Mexico City, Mexico
[3]Department of Applied Geology, University of Karlsruhe, Kaiserstr.12, 76128 Karlsruhe, Germany

ABSTRACT

This chapter reviews three approaches to water management i) supply-side, ii) demand-side and, iii) integrated. Tools and applications for each approach are reviewed in order to understand their reach in the solution of water-related problems. The paper focuses on management tools which are also applicable on the scale of urban areas.

Recent formulations take into account a holistic understanding of water resources that provides environmentally and socially acceptable solutions. The solutions proposed explore a combination of technologies and strategies, depending on the aims of projects, their local and national context, and the available data. The involvement of decision-makers, stakeholders and other end-users is essential for the specification of relevant issues and the development of useful tools to support decisions.

The challenges that face central and northern Mexico are reviewed. The limitations of conventional practices of water management in Mexico point to the need for a paradigm change, from increasing supply to reducing demand. The change toward more integrated management is a complex and difficult task, given the traditional dominance of centralized and technocratic management. The benefits of holistic management approaches are discussed, as are the obstacles that have limited their adoption so far.

* seddam2002@yahoo.com.mx
† escolero@geologia.unam.mx
‡ wolf@agk.uka.de

1. Introduction

Three major driving forces lay behind the development of water resources in the last century: i) population growth, ii) industrial development and iii) the expansion of irrigation agriculture. In Mexico, these driving forces have been concentrated in the center and north of the country, where arid and semi-arid conditions prevail and groundwater is the main source of water supply. Estimates for the year 2030 indicate that Mexico's population will grow by 84 percent, and that 50 percent of the population will be mainly concentrated in cities located in these regions. As a result, future urban water demand will rise inexorably until it eventually exceeds available sources of supply, so increasing competition for water.

Historically, water management has been driven by the need to maximize the amount of water available to meet growing demand by the construction of physical infrastructure, the development of aquifers and transfers from neighboring basins. This conventional approach is facing increasing environmental constraints and competition for water. In order to meet the current challenges, an integrated approach to water management is proposed so as to increase the range of opportunities available, reduce environmental impacts and achieve more sustainable development.

We review approaches to water management and the usefulness of tools with which to explore solutions to problems currently faced by a great part of Mexican territory. The review concentrates on the management of groundwater and strategies with which it can be integrated. Mexico's management approach is discussed, as are the barriers that so far have limited the adoption of integrated water management (IWM).

2. Approaches to Water Management

Water management has developed in relation to population growth, increasing demand, the degradation of resources, deterioration of water quality, and extensive environmental concerns. For several decades, water managers and policy makers were driven to maximize the volume of water available in order to meet growing demand for direct use (Al Radif, 1999). But in order to overcome the limitations of that approach, demand-driven and integrated strategies were developed, along with new technologies.

Approaches to water management can thus be divided into three categories: i) supply-side, ii) demand-side, and iii) integrated.

2.1. Supply-side Management

Simulation models have been widely used as tools to explore options for groundwater management and will continue to be essential. Traditionally, groundwater system simulation models have been used to test response to water withdrawals, the interaction of groundwater and surface water, and the migration of contaminants. A model is executed repeatedly under different scenarios to achieve a particular objective (Sakiyan and Yazicigil, 2004).

An essential aspect of management modeling is to determine the proper objective function that relates to physical and operational restrictions. This is unlikely to be achieved using simulation techniques alone. Management models that combine simulation and optimization techniques have been developed to consider the behavior of a groundwater system and to determine the best operating policy under the objectives and constraint dictated by the water manager (Gorelick, 1983). The optimization model identifies an optimal management strategy from a set of feasible alternatives while the simulation model ensures that the strategy is physically acceptable.

Two methods are generally used to incorporate the simulation model within a management model: i) embedding and, ii) response matrix. The embedding method directly uses the finite difference or finite element form of the groundwater flow equations as part of the constraint set of an optimization model. Other physical and managerial constraints can be incorporated. The response matrix approach uses an external groundwater simulation model to build unit response, which describes the response of the aquifer system to unit perturbations in the pumpage and/or recharge point in the system. The simulation model is resolved several times, each with a unit stress (pumping/recharge) at a single node (Das and Datta, 2001). The assembled unit responses are used to construct the response matrix, which is included in the optimization model.

These models treat the hydraulic heads, and recharge and pumping rates, as decision variables. They may also include economic considerations. Physical decision variables, such as pumping rates, may be interpreted as surrogate economic variables or even as explicit economic factors. In order to solve optimization-based groundwater management models, use is made of such mathematical programming techniques as: i) lineal programming, ii) non-lineal programming, iii) mixed integer programming, iv) differential dynamic programming, v) stochastic programming, vi) combinatorial optimization, and vii) multiple objective programming. The technique used depends on the particular problem under consideration and the assumptions made in resolving it. The optimizations technique attempts to optimize an objective, such as minimizing the cost of achieving a goal or maximizing well production, and is subject to constraints that limit or define the decision variables, such as drawdown, hydraulic gradient and water demand. Detailed reviews of the use of optimization and simulation in groundwater management have been developed by Gorelick (1983, 1990), Wagner (1995), Das Gupta and Onta (1994) and, Das and Datta (2001).

Simulation and optimization techniques, when used in combination, have been shown to be useful in determining planning and management strategies for the optimal development and operation of groundwater systems. A management model was developed by Finney et al (1992) to identify the pumping and recharge policy that would minimize saltwater intrusion in the Jakarta Basin, Indonesia. The trade-offs between water demand and saltwater volume were evaluated to demonstrate that increased water demands would lead to a significant degradation of the basin if historical policies continued to be pursued. An optimized policy was suggested that redistributes pumping and introduces artificial recharge to significantly reduce the saltwater volume.

Varljen and Shafer (1993) determined pumping rates for a well field in Pekin, Illinois, in order to minimize the risk of withdrawing contaminated water. A simulation model was used to determine the pumping of each well as a function of well-field pumping policy. The groundwater management model evaluated the impact of variations in pumping policy on capture zones and identified a pumping strategy to meet water demand while reducing the risk of contamination by 50 percent.

An operational groundwater management model with an economic objective, incorporating both pumpage and recharge, was developed by Das Gupta et al (1996). The model was formulated for a situation in which the available surface water was inadequate to meet demand and the deficit would be equivalent to the minimum groundwater supply requirement. Maximum groundwater withdrawal was limited to avoid adverse environmental consequences. The objective was to obtain an optimal pumping and recharge policy by maximizing relative net benefit or minimizing operational cost, subject to a specified allowable drawdown, a minimum pumping requirement and a maximum allowable recharge. Analysis of optimum pumping distributions satisfied certain defined minimum potentiometric heads as well as economic criteria.

McPhee and Yeh (2004) have developed a multi-objective management model for groundwater resources on a basin-wide scale. The model was formulates for to estimate the tradeoff between the exploitation of groundwater and the conservation of ecosystems that depend on interaction between groundwater and surface water. The basin has seen significant population growth, which has increased the demand for groundwater that constitutes the San Pedro River base-flow. Intensive abstraction has become intermittent along several reaches of the river. Three management objectives were considered in the formulation: minimizing the net present value of mitigation costs, maximizing aquifer yield, and minimizing drawdown al selected locations. The management model defined a set of best policies for groundwater pumping rate and recharge. Decision makers face the task of selecting among them the one that best reflects their preference.

Magnouni and Treichel (1994), Mueller and Male (1993), Feyen and Gorelick (2004), Barlow et al (1996), Reinelt (2005) have demonstrated the use of simulation models combined with optimization techniques in mathematical programming to study a variety of aquifer management problems. Groundwater management models are capable of determining optimal pumping/recharge rate and optimal well locations, subject to restrictions on drawdowns, gradients and water demands. It must be noted that a number of the studies identified strategies for the operation of reservoir systems that were superior to those currently in operation. However, most of the groundwater management models developed have been applied to ideal and hypothetical conditions. There is an absence of published reports describing the implementation of groundwater management strategies derived from the combination of simulation and optimization models. These applications would provide research into elements concerning the practical limitations and the improvements that are needed in groundwater management techniques.

2.2. Demand-side Management

Water-related challenges are attributable to i) increasing demand as a result of population growth and economic development, ii) lower real availability due to pollution, iii) inefficient use, iv) competition among agricultural, urban and environmental demand. In order to face these challenges, a change of the water resources management paradigm has been promoted. Instead of aiming to increase supply, the new paradigm – which is widely considered to be more economically efficient (Gleick, 2000) – strives to curtail demand. From both technological and economic perspectives, water authorities and utilities are beginning to explore improvements in efficiency, options for managing demand, reuse, and reallocation of water among users (Hanemann, 1998).

The complexity of selecting efficient water management options from a set of feasible alternatives suggest that a more integrated approach is needed in order to complement existing simulation-based planning (Jenkins et al, 2004). Optimization techniques are used to identify optimal management strategy to resolve complex problems of water allocation that involve economic objectives. These management models are referred to as policy evaluation and allocation models.

A set of publications describes the application of optimization techniques to design management strategies on a regional scale (Bredehoeft et al, 1995). Lall and Lin (1991) developed a groundwater management model for Salt Lake Valley, Utah. The model was formulated from the perspective of a water authority seeking to meet the demands of competing supply agencies. The objective was to minimize the annual cost of municipal and industrial groundwater supply, subject to drawdown, water rights and water quality restrictions. The model was applied to a variety of groundwater demand scenarios. The results suggested that the redistribution of pumping within the boundaries of the agency supply areas could reduce basin-wide pumping costs by more than 50 percent. In addition there were potential advantages to transferring water between agencies, but the capital cost of the new infrastructure was not evaluated in the analysis.

Watkins and McKinney (1999) evaluated a number of structural and institutional alternatives to meet environmental and economic goals under a range of hydrologic conditions. The model evaluated a combination of demand-side and supply-side strategies. The supply-side alternatives included new water supplies i) construction of surface-water reservoirs, ii) water transfer from a neighboring basin, iii) enhancement of aquifer recharge, and iv) development of the neighboring aquifer. The demand-side alternatives included i) conservation of irrigation and urban water, ii) wastewater re-use, and iii) direct regulation of pumping during the dry season. The urban water conservation program emphasized plumbing retrofits and conservation landscaping that was aimed at reducing municipal water demands, while the use of more efficient irrigation technologies could lower demand for irrigation without sacrificing crop yields. Options were identified for the use of reclaimed wastewater for irrigation or aquifer recharge, thus effectively reducing net withdrawals from the aquifer. Water market was studied as a means of mitigating the economic effects of pumping limits and as a dry-year option. Groundwater and surface water simulation models were incorporated as constraint. The objective function of the model included municipal and agricultural water supplies, riparian habitat, endangered species, commercial fisheries, recreation, and others. These management objectives were expressed in environmental and economic terms using multi-objective programming. The model allowed evaluation tradeoffs, identified alternatives for further study and eliminated inferior alternatives without finding an optimal solution. The combination of water conservation, reuse, and dry-year options appears to be a good solution to the problem of water resources. However, any water management plan requires acceptance by stakeholders.

An economic-engineering optimization model that integrates surface water, groundwater and water demands in California's supply system was presented by Jenkins et al (2004). The results show the value of optimization modeling in order to integrate information needed to manage a complex water system. The model identified significant improvements in performance through water transfers and exchanges, conjunctive use, and various operational changes to increase flexibility. These changes also greatly reduced the costs to agricultural and urban users of meeting environmental requirements. Model results also suggested benefits for the expansion of selected conveyance and storage facilities.

An integrated hydrologic-agronomic-economic model for irrigation-dominated river basins was presented by Cai et al (2003). This model includes multiple-source nodes (reservoirs, aquifers, river reaches, etc) and multiple demand sites. The model's main advantage is its ability to reflect the interrelationships among essential hydrologic, agronomic, and economic components while exploring the economic and environmental consequences of various policy choices. The model's components included the integration of elements that ranged from the crop root zone to the river system. The model was applied to problems of water management in the Syr Darya River basin of Central Asia, providing environmental and economic information regarding reservoir operations, infrastructure improvement, economic incentives, and economic evaluation of irrigation water use. The model was mainly used for short-term analysis; the issue of groundwater quality degradation could not, therefore, be dealt with.

Optimization techniques applied to the development of regional systems with varied water quality, have been dealt with by Brimberg el at (1993). The model's purpose was to determine the optimal distribution of a limited high-quality water supply and plan the optimal development of marginal sources, such as wastewater, runoff and saline groundwater. The objective was to minimize operational and capital cost of the development of marginal sources while simultaneously allocating a conventional regional supply among a set of local sites. Constraint of water quality at each demand site was imposed. In this way an optimal investment strategy for marginal water source development and use was obtained while satisfying quality requirements at the individual sites. An important conclusion is the feasibility and economic viability of saline groundwater production over a wide range of energy prices and required quality levels. Use of this water source could be increased considerably by immediate investments in new capacity.

Management models using optimization techniques for policy evaluation and allocation have been widely developed by academic researchers, but only a few models are currently applied in real-life water management due to the complexity of the issues involved. These models provide means by which to understand the interaction of hydrological, political, and socio-economic factors with the allocation of water resources. They permit the evaluation of the environmental, economic and social benefits of demand management options such as prices, taxes, economic incentives, market-based regulation, infrastructure improvement, and the development of marginal sources, among others. In terms of water supply, the models offer an alternative for the joint management of complex systems of interrelated water supplies and demands, using a wide variety of options over a wide range of hydrologic conditions.

Water demand forecasting models are useful tools for policy-markers who consider demand-side solutions. A computer model based on scenarios of future water use has been designed in order to assess the impact of global change and management measures on water use on a regional scale (Döll and Hauschild, 2002). This model combined two methods, a water use model NoWUM, and the development of scenarios. The NoWUM model was applied to compute two reference scenarios of municipality-specific water uses by various sectors (irrigation, livestock, household, industry and tourism), summarize the story lines of the two reference scenarios and show the assumed developments to the main driving forces of water use. This approach was applied in order to support regional planning in two semi-arid Brazilian states suffering from water scarcity. The results show the impact of certain interventions, such as appropriate water pricing, in controlling the increase in domestic and industrial water use.

The IWR-MAIN water demand analysis program is a tool for estimating future water demand and evaluating demand management measures in urban areas. IWR-MAIN includes a cost-benefit module for evaluating water demand management measures and an advanced user-interface that facilitates the handling of data files and the processing of forecast results. This model requires the user to select and specify a water forecasting methodology (Davis, 2003), dependent on the specific objective and available data. The model is designed for i) translating demographic, housing, and business statistics into estimates of existing water demands, and ii) using projections of population, housing and employment to derive baseline forecasts of water use (Opitz et al 1997). The total urban water consumption may be disaggregated in spatial, temporal and sectoral components, so obtaining projections of water demand by sector, area y time period. Several possible scenarios for water use, supply and management are estimated by specifying the factors that affect demand: i) population density, ii) population distribution, iii) per capita income, iv) commercial activity and mix, v) industrial activity and mix, vi) naturally occurring conservation, vii) urban water use efficiency resulting from the implementation of best management practices (BMPs), and viii) climate change (Davis, 2003). This tool has been widely used in water demand and conservation studies for water utilities and authorities in the United States.

Water demand management allows for the exploration of measures of conservation, efficiency improvements and reallocation among users, in order to reduce potential gaps between water supply and demand. Additionally, tools applied in this approach can be useful for i) assessing the extent and cost of additional water supply infrastructure, ii) showing where conflicts might occur over use and, iii) assessing the problem of scarcity by comparing use with availability.

2.3. Integrated Water Management

IWM seeks to find join solutions to a wide range of management objectives and interests, including supply, quality, flood control, the conservation of aquatic ecosystems, user conflicts, recreation and fisheries (GWP, 2004; Heinz et al, 2007). These include the establishment of multi-disciplinary teams at various levels (local, regional, and national) to discuss different perspectives on water resources and build consensus. The stakeholders, such as farmers, industries, municipalities, households, authorities and NGOs, are incorporated in order to ensure that their experiences and views form part of the development and management plans. The tools employed within IWM include a combination of physical and social technology and strategies (Desa, 2006) that permit a multiplicity of situations to be tackled.

The IWM approach-based water cycle includes the development of alternative resources (stormwater, wastewater, and saline groundwater) in order to increase the range of opportunities available, reduce environmental impacts and achieve more sustainable development (Pinkham, 1999; Niemczynowicz, 1999; Mitchell and Diaper, 2004; Thomas and Durham, 2003). The water sensitive urban design concept in the framework of integrated urban water management (IUWM) to link land development, water-cycle management and the protection of aquatic ecosystems as part of the same management challenge (Lloyd, 2004). Within this concept, a wide range of tool sets are explored and evaluated as management solutions. Case studies in Australia demonstrate practical management applications (Mitchell, 2006). Sites such as Figtree Place and Heritage Mews use rainwater tanks, infiltration trenches and a central basin where treated stormwater enters the unconfined aquifer for retention and retrieval (Coombes et al, 1999; Boubli, 2002). These devices assist in the control of both the quantity and the quality of runoff, potable supply substitution and rainwater harvesting.

IWM can also be addressed from a concept of cleaner production. Cleaner production interventions have been extremely successful in the industrial sector and could be translated to the water sector in order to minimize freshwater consumption and wastewater generation (Nhapi and Hoko, 2004). Nhapi and Gijzen (2005), proposed three intervention steps, focusing on sewage management, but also considering water supply, nutrient use and other material flows associated with the urban water cycle. The first step is to minimize wastewater generation by drastically reducing water consumption and waste generation. The second step is the treatment and optimal reuse of nutrients and water at the lowest possible level. Afterwards, the remaining waste flows may be safely discharged into the environment. The third step involves enhancing the self-purification capacity of receiving water bodies.

The paradigm of IUWM promotes the concept of the total urban water cycle for a more holistic and integrated evaluation (Hardy et al, 2005). Typical representations of the urban water cycle either consider the man-made and natural systems as separate entities or the modeling approach only concentrates on one of the two aspects (Mitchell et al, 2003). One of the recent advances in modeling is the proposed urban volume and quality (UVQ) model. This is a conceptual hydrological model that simulates an integrated urban system at a daily time step (Mitchell and Diaper, 2004). It estimates the volume of water flowing throughout the system and the associated contaminant loads, from source to discharge point. UVQ represents i) a variety of types of land use, such as residential, industrial, commercial, parks and rural open space, ii) different water infrastructure, such as combined sewers, septic tanks, separate stormwater systems, and groundwater wells, and iii) a variety of local climatic conditions. The evaluated area is represented in three spatial scales: land block, neighbourhood and study area. Data requirements for UVQ are demanding. Parameters such as indoor and outdoor water demands, infiltration and exfiltration of pipes, as well as information on occupancy, lot size, gardens, roofs, paving, roads and public open areas, are required for each spatial scale. The model allows estimates to be made of the impact of alternative scenarios that include the performance of a wide range of non-conventional demand- and supply-side management techniques for water collection, infiltration, treatment and reuse on a scale based on the land block, neighbourhood and study area.

IWM has posed challenges to traditional methods based on models that simulate physical systems and on technocratic and centralized decisions. IWM is multidisciplinary and requires the participation of users, planners and policy makers at all levels. Given the increasing complexity and disciplinary breadth of water management problems, decision support systems (DSSs) have become necessary to make models more useful. The enormous advances in computing and information technologies allow individual computer models to be linked with data sets created for different individual problems in a DSS. A DSS for IWM is an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision-makers in solving relatively large, unstructured water resource management problems (McKinney, 2004). The use of technology such as databases and graphic user interfaces permits the creation of inputs and results that are readily understandable to analysts and decision-makers. Three main subsystems must be integrated in an interactive manner in a DSS: i) a user-interface for dialog generation and management of the interface between the user and the system, ii) a model management subsystem, and iii) an information management subsystem. A review of water resources DSSs has been developed by McKinney, (2004). Simulation and optimization models are the most used in water resources DSSs; these include Aquatool, CALSIM and DELFT-TOOLS, among others.

Research models funded by the European Union have been integrated into an interactive DSS addressing physical, economic and social aspects of land degradation on a regional scale (Oxley et al, 2004). MODULUS was built to enable end-users to understand the processes that cause, and are caused by, land degradation, and to provide appropriate tools for the design and evaluation of policy options. MODULUS integrates ten models through a graphic user interface. These include: climate and weather, hill-slope hydrology, plant growth, natural vegetation, groundwater, surface water, crop choice, irrigation, and land-use models. The models operate on very different spatial and temporal scales and utilize different modeling techniques and implementation languages. The system and its models were applied and tested in the Argolida (Greece) and Marina Baixa (Spain) regions in collaboration with local decision- makers and researchers with experience in these regions.

Burn et al (2006) present a DSS for IUWM that integrates a number of complex models with data transfer and handling via a GIS development platform in which stormwater, wastewater, water supply, groundwater and contaminants are simultaneously considered. The principal model is the above-mentioned UVQ. Information on the pipe network is fed into the network exfiltration and infiltration model (NEIMO) that estimates the amounts of exfiltration from, or groundwater infiltration into, sewers. The output is then forwarded to unsaturated zone models calculating water flows and travel times to the water table and the combined effects of absorption and the decay of contaminants. All upstream water and contaminant flows are then gathered to feed numerical groundwater flow and transport models such as MODFLOW® or FEFLOW®, which, based on the selected scenario of water use, will allow for the prediction of impacts to the urban aquifer, such as variations in the level or volume of groundwater with quality deterioration. The DSS supports the selection and comparison of predefined scenarios, allowing the end-user to choose preferences for a best-practice response decision e.g. groundwater treatment, or system improvements that prevent contamination. These scenarios are then used in a separate socio-economic model to assess the socio-economic implications of the different methodologies. The DSS has been applied to four case-study cities located on different aquifers (Klinger et al, 2006). In all case studies, the scenarios were specified by local stakeholders.

A great deal of knowledge, as well as new tools, has been generated by research carried out worldwide. However, only a small amount has been made available to support practical decisions. The involvement of decision-makers, stakeholders and other end-users is essential for the specification of relevant issues and the development of useful interactive support tools. Limitations to the development and application of DSSs to water resources management include, among others, i) lack of effective communication between scientists and end-users of the DSS, ii) the multidisciplinary nature of DSSs and their theoretical underpinnings, iii) lack of available methods to measure the effectiveness of DSSs, iv) lack of case studies in which the performance of DSSs has been evaluated in appropriate institutional settings.

3. Water-related Problems in Mexico

There have been three mayor driving forces for the expansion of water use in central and northern Mexico, where arid and semi-arid conditions prevail: i) population growth, ii) industrial development, and iii) the expansion of irrigation agriculture. These forces have been associated with speedy processes of urbanization, industrialization and economic transformation, modifying forms of land and water use. The problems that have accompanied this development are:

i. An increase in the extraction of groundwater as a secure source of supply in quantity and quality. Some 70 percent of the volume of water supplied to cities comes from groundwater that supply about 75 million inhabitants (PNH, 2002). The aquifers situated near or below urban areas are subject to intensive extraction, often exceeding the natural recharge rate by more than 40 percent. Significant social, economic and environmental impacts can be observed (Escolero, 1993[a]; Carrillo-Rivera et al, 2007). These include i) the disappearance of springs, lakes and wetlands, ii) a reduction in groundwater discharge, iii) loss of ecosystems, iv) a decline of the water-table and increasing pumping costs, v) land subsidence and surface fracturing, vi) undesirable water quality due to pumping.

ii. Contamination of water sources by wastewater discharge and waste disposal. Seventy-three percent of surface water and some 40 aquifers suffer varying degrees of contamination as a result of anthropogenic activity (PNH, 2002). As a result, indices of diarrheic illnesses are very high, with children the most vulnerable group. Chemical changes in abstracted groundwater due to uncontrolled withdrawal are also an important issue. Most of the wells located in the arid and semi-arid zone of Mexico capture water with fluoride concentrations higher than 1 mg/l, and it is estimated that about 5 million people are affected by fluoride in groundwater (Ortiz et al, 2006).

iii. Increasing competition among different users and uses as a result of scarcity and legislation that has prohibited new groundwater extractions since 1960-1980 in over-exploited aquifers. The 1992 opening of the water market promoted the transfer of water rights, mainly from the farm to the urban and industrial sectors. Irrigation with raw wastewater constitutes a common practice around urban areas as a consequence of the competition for water resources.

iv. Change in the natural drainage pattern. Runoffs are disrupted as ground is sealed during urbanization, by highway construction, and as watercourses are diverted or paved. This has increased flooding and generated a negative environmental and economic impact in urban areas and their surroundings.

v. Lack of economic resources for the construction and maintenance of supply, drainage and sanitation infrastructure have led to deficiencies in services. Even though the coverage of water supply systems in major urban centers is high (more than 95 percent), physical and economic efficiency are low (about 60 and 35 percent, respectively). Municipal water utilities have gained much more independence within the last decade, but pricing is still a political issue. Thus, capital is lacking for investment in obsolete infrastructure, and most utilities barely cover their operational costs.

These problems affect the sustainability of development in central and northern Mexico, where 77 percent of the population lives and the most important industrial infrastructure, irrigation land and principal cities are to be found. Almost 85 percent of the nation's gross domestic product is generated in central and northern Mexico, but it accounts for just a third of the country's water resources (Conagua, 2006).

Urban water supply has been identified as one of the main challenges that will determine the future growth of Mexican cities. Estimates for 2030 indicate that the nation's population will grow by 84 percent compared with its present level of some 110 million inhabitants, and that 50 percent will be concentrated in 31 cities of more than 500 000 inhabitants (Conagua, 2006). To make matters worse, nearly 75 percent of these cities lie in central and northern Mexico, where natural water availability is 32 percent and 104 aquifers that supply 60 percent of the groundwater employed for all uses are over-exploited.

4. Management in Mexico

The technocratic and centralized approach to water management in Mexico promoted policies and technical tools that aimed to maximize the volume of water available in order to meet growing demand. Solutions were focused on the supply side, and the management of water resources was synonymous of optimization of reservoir operations. Simulation models have been widely applied to reservoir management with intensive extraction. Conagua (1996), CEASG (1998), Navarro de León (2004), Garfias et al (2006), Hernández-G and Huizar-A (2006) Escolero and Torres-Onofre (2007) evaluate the historical and future effects of groundwater extraction on the hydrogeologic regime and productive thickness by means of simulation models. Future demand is analyzed in accordance with different climatic scenarios, and trends in population growth and economic development. The results suggest the need for urgent action to reduce the intensive extraction. A review of the use of optimization and simulation in groundwater management in Mexico was developed by Escolero (1993[b]). The models reviewed were applied to determine optimal pumping rate and well locations, subject to specified drawdown, maximum pumping capacity and water demand. More recently, Aldama et al (2006) presented a simulation and optimization model for the Lerma-Chapala basin. A basin simulation model integrating the components – river, aquifers, reservoirs, irrigated areas, urban centers and industrial zones – was linked with optimization. The objective was to achieve maximum well production for irrigation while minimizing the deficit, subject to constraint of allowable drawdown in order to avoid damage to the environment. This model allowed for a consensus to be built around the policy for optimal operation of the basin's water resources.

Policies have favored the construction of new physical infrastructure (dams, wells, channels), the development of aquifers and water transfers from neighboring basins to meet ever-increasing water demand. But the traditional means of supply augmentation are facing increasing environmental constraints and competition for water. The international literature contains examples of adverse economic and environmental impacts associated with this approach. Imbalances between demand and supply, resource degradation, and competition among sectors call for sustainable management of water resources using new methods and innovative approaches. As an indication of progress toward a new vision, a paradigm change from increasing supply to reducing demand was proposed in Mexico by the National Water Commission as a central element of policy (Conagua, 2006).

It is now well established that traditional supply-side water management has reached a limit. However, the inertia built up by ingrained forms of technocratic institutional power and expertise, values and leadership, perpetuates traditional practices and impedes change to integrated management. Until now, technical engineering has been the dominant source of knowledge, decisions and power within the local and national water institutions. These institutions have been responsible for providing water supply and flood protection, but have lacked a vision of a sustainable water future. The political focus is still on drinking water provision; non-traditional resources, including shallow aquifers and stormwater, are not a priority. The change of paradigm clearly requires the reorientation of authorities so that they work to improve cooperation with utilities, planning agencies and water users, and also to promote understanding of the totality of resources involved in management.

Researchers have an important role in assisting planners and policy-makers to lower the barriers that so far have impeded IWM. Researchers can spread knowledge and awareness of the tools that are available. They can generate models and promote debate with decision-makers about the practical limitations of management techniques and the ways in which these can be overcome.

In Mexico, the water market is restricted to the aquifer's administrative limits and bound by the regulations that local authorities dictate. Simulation and optimization models may be useful technical instruments in the promotion of more rational regulations. These models provide scenarios of water allocation, transfers and exchanges that allow decision-makers to explore their economic and environmental consequences, and to consider other economic instruments as complementary measures. This will be particularly useful in aquifers where social and economic forces have failed to interact widely with the allocation of water resources. However, before they can be adopted as instruments of management policy, optimal water allocations must agree with the perspectives of users as well as planners and policy-makers. This often requires that models be calibrated not only with respect to the physical parameters of the system, but also to its decision-making processes. This aspect is often overlooked in the development and design of models, and leads to poor acceptance in practice.

Urban stormwater and wastewater may be used for irrigation and/or recharge of aquifers. Stormwater may be harvested and stored or treated for less demanding uses. Shallow urban aquifers have been neglected because they are commonly considered to be polluted and unusable for drinking water purposes. Tools and methods that can assess the use, and ascertain the demand for, alternative water resources may be applied in the framework of a common urban system. For such applications, the collection and availability of data is critical. Before any calculations are made, it is important to assess and analyze the available data. The selection of the tools to be applied is driven in part by data can be made available through collection. Time and money will be needed in order to identify and compile existing data that may support a first application, and additional costs will be incurred in order to generate new information for future applications.

5. CONCLUSION

This paper makes reference to the IWRM concept as outlined in GWP (2004) but focused on urban areas as a subset problem.

The development of the management of water resources has been linked with increased demand, the degradation of resources, the deterioration of water quality, and extensive social and environmental concerns. Until recently, water resources management was driven by the need to maximize the volume of water available in order to meet growing demand. The current challenges, however, require the promotion of a paradigm change in water resources management along with the development and application of new technologies.

The Integrated Water Management (IWM) approach includes i) water resource management (including alternative sources and protection), ii) water supply management, iii) water demand management and allocation, and iv) wastewater system and sanitation management. The solutions proposed explore a combination of technologies and strategies in order to assure economic and environmental sustainability as well as social acceptance. However, the development and implementation of IWM is a complex and difficult task. In Mexico, where a centralized and technocratic management has been dominant, IWM still requires wider institutional acceptance of the need to decentralize decision-making by involving the views of farmers, industries, municipalities, households, authorities and NGOs in plans for development and management.

A broad range of tools is available for IWM. These tools include optimal water allocation; optimal development and operation of systems; water-sensitive design, including urban layout and landscaping; utilization of non-conventional sources, including stormwater, wastewater, shallow and saline groundwater; stormwater and wastewater source control and pollution prevention; stormwater flow and quality management; the use of mixtures of soft (ecological) and hard (infrastructure) technologies; and nonstructural tools such as education, pricing incentives, regulations, and restriction regimes. Given the increasing complexity of water management problems, the solutions require a mix of these tools, depending on the aims of projects, their local and national context, and the availability of data. Researchers may assist in the selection and application of the appropriate tools for each particular case.

The challenges that face central and northern Mexico require i) a clear understanding of the regional water cycle and its relation with the urban water cycle, ii) an improvement in public awareness of the main issues that relate to water management and of the risks of unplanned development, iii) an understanding of the interdependency of urban water systems (supply and drainage) and urban groundwater resources as a part of the same cycle, so requiring assessment within a common framework. Alternative sources may complement – or even replace – traditional supply sources, so reducing the volume of drinking water that cities need to import, as well as of the stormwater and wastewater that they export to surrounding areas.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the UNAM's General Direction of Postgraduate Studies for their support.

REFERENCES

Aldama, A.; Güitrón, A.; Aparicio, J.; et al. La Cuenca Lerma Chapala y los modelos de simulación. *Rev Cien Desar.* CONACYT, México, Marzo 2006, pp.36-41.

Al Radif, A. Integrated water resources management (IWRM): an approach to face the challenges of the next century and to avert future crises. *Desalination.* 1999, 124, 145–153

Barlow, P.M.; Wagner, B.J.; Belitz, K. Pumping strategies for management of shallow water table: the value of the simulation-optimization approach. *Ground Water.* 1996, 34(2), 305-317.

Boubli, D. (2002) Heritage Mews, *Castle Hill: a case study in delivering water sensitive urban design.* http://www.wsud.org/downloads/Info%20Exchange%20&%20Lit/Heritage % 20Mews% 20Castle%20hill.pdf Cited April 2007.

Bredehoeft, J.D.; Reichard, E.G.; Gorelick, S.M. If it works, don't fix it: benefits from regional ground water management. In *Groundwater models for resource analysis and management;* El-Kadi, A.; Ed.; CRC Press/Lewis Publishing Co., 1995, pp 101-121.

Brimberg, J.; Oron, G.; Mehrez, A. A model for the development of marginal water sources in arid zones: The case of the Negev Desert. Israel. *Water Resour Res.* 1993, 29(9), 3059-3067.

Burn, S.; De Silva, D.; Ambrose, M.; et al. A decision support system for urban groundwater resource sustainability. *Water Practice & Technology. 2006,* 1(1), http://www.iwaponline.com/wpt /001/0010/0010010.pdf doi: 10.2166/WPT.2006010.

Cai, X.; McKinney, D.C.; Lasdon, L.S. Integrated hydrologic-agronomic-economic model for river basin management. *J Water Resour Plan Manag.* 2003, 129(1), 4-17, doi: 10.1061/(ASCE)0733-9496(2003)129:1(4).

Carrillo-Rivera, A.; Cardona, A.; Huizar-Alvarez, R. et al. Response of the interaction between groundwater and other components of the environment in Mexico. *Environ Geol.* 2007. doi 10.1007/s00254-007-1005-2.

CEASG – Comisión Estatal del Agua y Saneamiento de Guanajuanto. *Estudio hidrogeológico y modelo matemático de los acuíferos del estado de Guanajuato.* Elaboró Guysa, S.A. de C.V., 1998.

Conagua – Comisión Nacional del Agua. Estudio de simulación hidrodinámica y diseño óptimo de las redes de observación de los acuíferos de Calera, San Luis Potosí y Toluca, *Informe técnico,* Contrato No. GAS-012-PRO-96. Elaboró Ariel Consultores SA., 1996.

Conagua - *Comisión Nacional del Agua. Water in Mexico,* Document printed for 4th World Water Forum. 2006.

Coombes, P.J.; Argue, J.R.; Kuczera, G. (1999) *Figtree Place: a case study in water sensitive urban development.* http://www.wsud.org/downloads/Info%20Exchange%20&%20Lit/FIGTREE%20LAST21.pdf. Cited April 2007.

Das Gupta, A.; Onta, P.R. Ground-water management models for Asian developing countries. *Water Resour Devl.* 1994, 10(4), 457-474.

Das Gupta, A.; Nobi, N.; Paudyal, G.N. Groundwater management model for an extensive multi-aquifer system and an application. *Ground Water.* 1996, 34 (2), 349-357.

Das, A.; Datta, B. Application of optimization techniques in groundwater quantity and quality management. *Sadhana.* 2001, 26(4), 293–316.

Davis, Y.W. (2003) Water demand forecast methodology for California water planning areas. Work plan and model review. *Report submitted to: California Bay-Delta Authority.* http://www.waterplan.water.ca.gov/docs/technical/Water_DemandForecast_Methodology .pdf . Cited May 2007.

Desa, M.N. (2006) Integrated urban water management and modeling approach: an overview. Paper presented at the national conference, water for sustainable development towards a developed nation by 2020. *Nigeria Sembilan,* 13-14 July 2006, http://jps.selangor. gov.my/NC/Integrated%20Urban%20Water%20Management.pdf. Cited June 2007.

Döll, P.; Hauschild, M. Model-based scenarios of water use in two semi-arid Brazilian states. *Reg Environ Change.* 2002, 2, 150–162.

Escolero, O. Panorama del agua subterránea en México. In El agua, recurso vital. *Universidad Tecnológica de la Mixteca,* Mexico, 1993[a], pp:37-52.

Escolero, O. Manejo óptimo de un acuífero. Tesis Maestria, Facultad de Ingeniería, Univ Nac Aut México, México, 1993[b], p 68.

Escolero, O.; Torres-Onofre, S. Análisis de la intrusión de agua de mar en el acuífero de La Paz (México). *Bol. Geol Min.* 2007, 118(núm esp), 637-648.

Feyen, L.; Gorelick, S.M. Reliable groundwater management in hidroecologically sensitive areas. *Water Resour Res.* 2004, 40 W07408, doi:10.1029/2003WR003003.

Finney, B.; Samsuhadi, A.; Willis, R. Quasi three-dimensional optimization model of Jakarta basin. *J Water Resour Plan Manag.* 1992, 118(1), 18-31.

Garfias, J.; Navarro de León, I.; Llanos, H. Gestión integral de recursos hídricos con arreglos a distintas modalidades de utilización. *Paper presented in VIII Congreso latinoamericano de hidrología subterránea,* ALHSUD, Asunción, Paraguay, Septiembre 2006.

Global Water Partnership – GWP. Catalyzing Change: A handbook for developing integrated water resources management (IWRM) and water efficiency strategies. 2004. http://www.gwpforum.org/gwp/library/handbook.pdf Cited June 2007.

Gorelik, S.M. A review of distributed parameter groundwater management modeling methods. *Water Resour Res.* 1983, 19(2), 305-319.

Gorelick, S.M. Large scale nonlinear deterministic and stochastic optimization: Formulations involving simulation of subsurface contamination. *Mathematical Program.* 1990, 48, 19-39.

Gleick, P.H. The changing water paradigm: a look at twenty-first century water resources development. *Water International.* 2000, 25(1), 127–138.

Hanemann, W.M. Determinants of urban water use. In *Urban water demand management and planning;* Baumann, D.D.; Boland, J.J.; Hanemann, W.M. Eds.; McGraw-Hill Professional, 1998, pp: 31-76.

Hardy, M.J.; Kuczera, G.; Coombes, P.J. Integrated urban water cycle management: the urban cycle model. *Water Science & Technology.* 2005, 52(9), 1–9.

Heinz, I.; Pulido-Velazquez, M.; Lund, J.R.; et al. Hydro-economic modeling in river basin management: Implications and applications for the European water framework directive. *Water Resour Manage.* 2007, 21, 1103–1125, doi 10.1007/s11269-006-9101-8.

Hernández-Garcia, G.; Huizar-Alvarez, R. Evolución de la extracción de agua subterránea en la región de Zumpango-Pachuca, México central, sus efectos ambientales. *Paper presented in VIII Congreso latinoamericano de hidrologia subterránea,* ALHSUD, Asunción, Paraguay, Septiembre 2006.

Jenkins, M.W.; Lund, J.R.; Howitt, R.E.; et al. Optimization of California's water supply system: Results and insights. *J Water Resour Plan Manag.* 2004, 130(4), 271-280, doi 10.1061/(ASCE)0733-9496(2004)130:4(271).

Klinger, J.; Morris, B.; Souvents, P.; et al. Application to real world problems. In *Urban water resources toolbox: integrating groundwater into urban water management,* Wolf, L.; Morris, B.; Burn, S., Eds; IWA Publishing, London UK, 2006, pp 100-250.

Lall, U.; Lin, Y.W.H. A groundwater management model for Salt Lake County, Utah with some water rights and water quality considerations. *J. Hydrol.* 1991, 123, 367-393.

Lloyd, S.D. (2004) *Quantifying environmental benefits, economic outcomes and community support for water sensitive urban designs.* http://www.wsud.org/downloads/Info Exchange & Lit/Lloyd 2004 _final paper.pdf. Cited April 2007).

Magnouni, S.E.; Treichel, W. A multi-criterion approach to groundwater management. *Water Resour Res.* 1994, 30(6), 1881-1895.

McKinney, D.C. International survey of decision support systems for integrated water management. *Technical report.* Support to enhance privatization, investment, and competitiveness in the water sector of the romanian economy. IRG Project No 1673-000. 2004. p 65.

McPhee, J.; Yeh, W.W.G. Multiobjective optimization for sustainable groundwater management in semiarid regions. *J Water Resour Plan Manag.* 2004, 130(6), 490-497.

Mitchell, V.G.; Diaper, C.; Gray, S.R. et al. UVQ: modelling the movement of water and contaminants through the total urban water cycle. Paper presented at the 28th international hydrology and water resources symposium, Wollongong 2003.

Mitchell, V.G.; Diaper, C. (2004) UVQ: a tool for assessing the water and contaminant balance impacts of urban water development scenarios. *Paper presented at the IWA world water forum.* http://www.urbanwater.de/results/publications/mitchell-diaper-uvq-iwa-2004.pdf. Cited June 2007.

Mitchell, V.G. Applying integrated urban water management concepts: A review of Australian experience. *Environ Manag.* 2006, 37(5), 589–605.

Mueller, F.A.; Male, J.W. A management model for specification of groundwater withdrawal permits. *Water Resour Res.* 1993, 29(5), 1359-1368.

Navarro de León, I. *Análisis de estrategias de manejo integral del agua subterránea mediante modelación de flujo: Cuenca de la Independencia,* Guanajuato, México. Universidad Nacional Autónoma de México, Tesis doctoral, 2004.

Nhapi, I.; Hoko, Z. A cleaner production approach to urban water management: Potential for application in Harare, Zimbabwe. *Phys Chemy Earth.* 2004, 29(15-18, SPEC.ISS.), 1281-1289.

Nhapi, I.; Gijzen, H.J. *A 3-step strategic approach to sustainable wastewater management.* Water SA. 2005, 31(1), 133-140.

Niemczynowicz, J. Urban hydrology and water management: present and future challenges. *Urban Water.* 1999, 1, 1–14.

Opitz, E.M.; Langowski, J.F.; Dziegielewski, B., et al. Forecasting urban water use: models and application. In *Urban water demand management and planning;* Baumann, D.D.; Boland, J.J.; Hanemann, W.M.; Eds.; McGraw-Hill Professional, 1997, pp: 95-136.

Ortiz, P.M.; Bocanegra, S.M.; Landín, R.L. Evaluación de la contaminación por flúor y arsénico en el agua de pozo para consumo humano de las zonas centro, altiplano y media del estado de San Luis Potosí. Universidad Autónoma de San Luis Potosí. 2006.

Oxley, T.; McIntosh, B.S.; Winder, N. et al. *Integrated modelling and decision-support tools: a Mediterranean example, Environ Model & Software*. 2004, 19, 999–1010, doi: 10.1016/j.envsoft.2003.11.003.

Pinkham, R. (1999) *21st century water systems: scenarios, visions and drivers.* https:// www.rmi.org/images/PDFs/Water/W99-21_21CentWaterSys.pdf. Cited April 2007.

PNH - Plan Nacional Hidráulico 2002 -2006, *Comisión Nacional del Agua,* México. 2002.

Reinelt, P. Seawater intrusion policy analysis with a numerical spatially heterogeneous dynamic optimization model. *Water Resour Res.* 2005, 41 W05006, doi 10.1029/2004WR003111.

Sakiyan, I.; Yazicigil, H. Sustainable development and management of an aquifer system in western Turkey. *Hydrogeol J.* 2004, 12, 66-80, doi 10.1007/s10040-003-0315-z.

Thomas, J.S.; Durham, B. Integrated Water Resource Management: looking at the whole picture. *Desalination. 2003,* 156, 21-28.

Varljen, M.D.; Shafer, J.M. Coupled simulation-optimization modeling for municipal ground-water supply protection. *Ground Water.* 1993, 31(3), 401-409.

Wagner, B.J. Recent advances in simulation-optimization groundwater management modeling. *Rev Geophys.* 1995, 33 (Suppl American Geophysical Union). http:// www.agu.org/revgeophys /wagner01 /node2.html

Watkins, D.W.; McKinney, D.C. Screening water supply options for the Edwards Aquifer Region in Central Texas. *J Water Resour Plan Manag.* 1999, 125(1), 14-24.

CAPÍTULO II. THE MEXICAN EXPERIENCE WITH GROUNDWATER MANAGEMENT

Oscar A. Escolero y Sandra E. Martínez

En:
The Global Importance of Groundwater in the 21st Century:
Proceedings of the International Symposium on Groundwater Sustainability
G. Bergkamp and J McKay (Eds)
NGWA Press. pp. 97-103. 2006

The Mexican Experience with Groundwater Management

by Oscar A. Escolero[1] and Sandra E. Martínez[2]

Abstract

The management of groundwater in Mexico is a process that has evolved through time, from a technocratic and centralized approach to a decentralized approach that includes social participation. This paper analyzes the changes that have taken place to improve groundwater management in Mexico, from structural aspects such as improvement of irrigation to nonstructural aspects such as user participation, the regulatory framework that influences water availability and water rights markets. It describes groundwater conditions in Mexico, their use and exploitation, and the management issues that affect groundwater.

Introduction

Groundwater in Mexico plays a critical role for water supply, industry and irrigation. Since the 1950s exploitation of groundwater resources has accelerated as a result of the country's general development. In 1975, 32 aquifers were subject to intensive use. This number grew to 36 in 1981, 80 in 1985 and 130 in the year 2000. The intensive use of groundwater is considered to be present when the natural conditions of the hydrogeologic system are substantially modified by the extraction of large volumes of water relative to that which is stored in the aquifer and also when groundwater extraction impacts the natural water discharge regime, degrades groundwater quality and destabilizes the subsoil (Custodio and Llamas 2003).

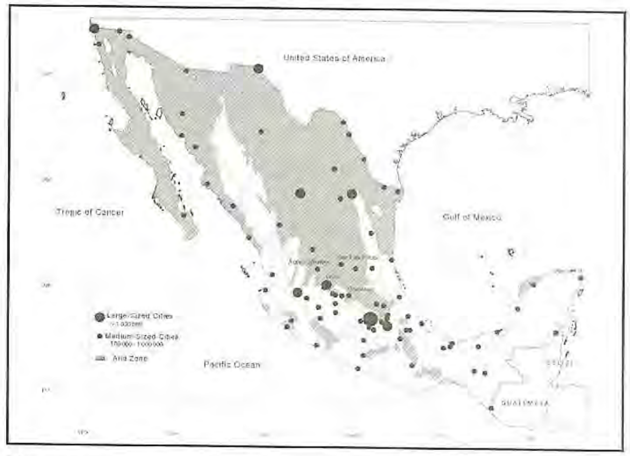

Figure 1.

The 1917 Mexican Constitution (paragraph 5, Article 27) enables landowners to extract the underlying water through artificial means. However, the federal government may intervene when public interests or third parties are affected. The forms of intervention were established in the 1926 Federal Water Law and include pumping prohibitions, regulations and reserves. Between 1958 and 1980, 85 decrees of prohibition were issued, in which the authorization for new wells was restricted in more than 50% of the national territory, and regulations for the operation and the use of water in the irrigation districts were issued.

In 1986 the modifications of the Federal Law of Rights established water use fees. It divided the country into zones according to the degree of water availability and set differentiated tariffs that reflect-

[1] Department of Regional Geology, Geology Institute, Universidad Nacional Autónoma de México, Mexico; escolero@geologia.unam.mx

[2] Department of Regional Geology, Geology Institute, Universidad Nacional Autónoma de México, Mexico

ed the degree of water scarcity in each zone. Technical standards were later issued to regulate maximum permissible limits in wastewater discharges and for the construction of drinking water wells. However, the application of these measures did not succeed in controlling or reducing groundwater pollution or intensive use. Some of the reasons for this failure were:

- Rules for the application of these legal measures were never issued.
- Limits coincided with political boundaries and interests instead of coinciding with the aquifers' natural limits.
- The legal measures were established without understanding either the operation of the aquifer system or the availability of water.
- Unjustified and unrealistic restrictions were imposed.
- There was no previous consultation and agreement with the groundwater users.

The 1992 National Water Law attempted to address these deficiencies. It established those cases requiring the federal government's intervention:

- Prevention of aquifer overuse
- Protection and recovery of ecosystems
- Protection of drinking water supplies
- Preservation and control of water quality
- Shortage or extraordinary drought.

The 1992 law authorizes the federal government to issue water use concession titles for water extraction or permits for wastewater discharge into water bodies of national property (lakes, rivers, aquifers). Concession titles can be granted for one to 50 years. The National Water Commission (*Comisión Nacional del Agua* or CONAGUA) can authorize the extension of water rights and the transmissions of these rights between users. The rights must be recorded in the Public Registry of Water Rights. The concession titles authorize the user to extract a certain annual volume of water from a specific aquifer. These rights can be transmitted between users and it is necessary to register the change in ownership of the concession title. Water rights are independent of the property of the land.

The Water Markets in Mexico

Previous to the passing of the 1992 Water Law, it was estimated that there were 300,000 water users, whereas only 2000 concession titles had been issued. An important program for the regularization of water users was launched in 1995. In 2003, 330,000 concession titles had been issued, of which 47% corresponded to agricultural users, while 36% to domestic water supply (Cantu and Garduño 2004). At the same time, a vigorous water rights market arose as a result of the regularization process and the enforcement of sanctions established in the water legislation. By 1996, 440 water rights transfers were registered, 64% of them within the agricultural sector (Plata-Olvera 1996).

The water market works in a variety of ways in Mexico: leasing of water rights; direct sale of water; leasing the land together with the water; temporary or permanent and total or partial cession of rights; and production by contract. It is significant that this process of water rights reassignment started in the regions where the aquifers had been subject to intensive use for many years. This is the case of the Comarca Lagunera region, the Lerma-Balsas basin and the Valley of Mexico. Today, it is estimated that more than 40% of the groundwater rights in those areas has been transferred to other users.

Most water transfers take place when small farmers, often farmers in communal use lands, sell their water rights to agroindustrial companies or urban areas. This is possible as water rights may be transmitted without selling the land, allowing farmers to continue to cultivate the land with rainwater or sell it to others. This pattern of water transfers has substantially modified cultivation patterns, the areas where water extractions concentrate, the sale price of water rights, as well as the profitability obtained from the use of the water. The Aguascalientes region is an example where the extraction of water for agricultural use was reduced by 16% between 1987 and 1998, while the extraction of drinking water increased by 46% during the same period. In the Querétaro region, the extraction of water for agricultural use was reduced by 50% between 1980 and 1989, while groundwater use for domestic water supply grew by 216% in the same period of time.

The process of water rights transfers has resulted in a concentration of water rights in the hands of fewer users and an increase in the profits obtained through irrigation water. Water rights are being purchased by industries that produce fruits and vegetables for export and alfalfa for the dairy industry. It is estimated that more than 60% of the cultivated areas where basic grains are grown today in intensively used aquifers will stop being profitable probably within the next ten years. Therefore, in a very near future, basic grains in these areas will either be substituted by more profitable crops or the land will be driven out of production entirely. This may have unintended consequences as these regions currently generate 40% of the agricultural employment as well as 50% of water consumption.

The water markets are therefore driving a process of transmission of water rights to more profitable agricultural uses with more efficient yields and overall a better economy at a larger scale. Products remaining profitable include fruits, vegetables and alfalfa.

Agriculture and Groundwater Use

Recent trade agreements have opened Mexican agriculture to the world market. The agricultural sector is therefore in transition from a system of subsidized agricultural production and price guarantees toward a competitive model ruled by free market forces. The signature of the North American Free Trade Agreement (NAFTA or TLCAN in Spanish) and the Agreements of the Ronda of Uruguay have resulted in a reduction in the international prices of grains and the disappearance of the "price guarantee" practice[3]. As a result, the agroindustrial sector found it more profitable to acquire raw materials in the United States than in Mexico.

Given the importance of agriculture in Mexico, both for the generation of rural employment and for food security, and in order to offset the effects of the liberalization of the economy and minimize the impacts of increased pumping costs, the government established a series of programs through which subsidies were given to producers and their base organizations. Many of these initiatives were developed under a program known as the "Alliance for farm work" (*Alianza para el campo* or PROCAMPO), established in 1993 for a 15-year period to support the commercialization of agricultural products, mainly targeted to basic grains. The program covered the following areas:

- Support for agriculture
- Promotion of cattle breeding
- Rural development and farming sanitation
- Research and technological transfer
- Promotion of exports.

The program aimed to replace the "price guarantee" system with a system of direct subsidies to agricultural production. Payments were made for each hectare cultivated with basic grains. In 1995, in response to the low revenues obtained with the cultivation of basic grains, the program was reformed to include a wider variety of more profitable crops. Overall, the federal government subsidies under PROCAMPO covered between 30% and 50% of total production costs. In many cases an additional 10% was contributed by state governments.

The increased profits from the higher priced agricultural products like fruits, vegetables and flowers are being offset by increased pumping costs as a result of lowering groundwater levels in areas with intensive groundwater use. For instance, while analyzing the variations of harvest values in Mexico, Palacios-Velez (2004) observed that these values grew at an annual rate of 1.4% between 1980 and 1999, while the irrigated surface diminished at an annual rate of 0.15% during the same period of time. Electrical energy consumption by wells used for irrigation grew by 20% between 1995 and 1999, while the amount of users grew by 13.6% during the same period of time.

[3] Under the price guarantee system, the federal government established a state company (CONASUPO) for the purchase and distribution of basic grains. Every year, the government established a guaranteed price for each basic grain, which in theory represented the minimum price that was paid for that product.

In 1984 the government established "Tarifa 09," a subsidy program addressing electricity rates. It allows farmers to pay for only one third of what regular users pay for energy consumption. In the case of the Querétaro aquifer, it is expected that the costs for water pumping will increase by 133% when subsidies are eliminated, making agriculture of most products in these lands unprofitable.

Agricultural protection and subsidy programs have contributed to maintain levels of production which allow small producers to continue cultivating basic grains, while big producers keep obtaining great economic benefits thanks to larger subsidies. To some extent these subsidies contribute to maintain the intensive levels of groundwater use, while generating a series of external consequences which will have to be absorbed by society.

Environmental Impacts of Intensive Groundwater Use

Parts of the country's main aquifers are under intensive use. Excessive groundwater use has modified the aquifers' geometry and resulted in land subsidence, changed original flow patterns and degraded water quality. As a consequence, many natural and social processes have been affected. A larger analysis of this topic is presented by Escolero (1993) who describes the direct and indirect impacts of intensive groundwater use.

Environmental degradation is an impact of intensive groundwater use. The costs of environmental degradation can be understood as a decrease in a nation's well-being. Some of the results of environmental degradation are (Sarraf et al. 2004) the loss of a healthy life and a reduction in the population's well-being; economic loss due to a reduction in productivity and the value of natural resources; loss of natural resources for recreation or conservation uses; and reduction in the sustainability of social development in a region. The environmental costs can be divided into two large groups (USEPA 1995): those having a direct impact on the user and called private costs, and those costs transmitted to other individuals, society or the environment which are called social or external costs.

For the particular case of intensive groundwater use, the environmental costs have two main causes. The first one is the reduction of the saturated thickness of the aquifer and the resulting reduction in the production rate of wells. The second one is the increase in the depth of the static level in certain zones of the aquifer, resulting in the migration of poor quality water to zones of good quality water. Some environmental costs of intensive groundwater use are:

- The loss of farmlands due to the presence of excessive salt in the soils
- Aquifer pollution caused by seawater intrusion
- Terrain collapsing and cracking
- Degradation in the quality of groundwater due to migration of mineralized water located at great depths
- Increase in costs and accessibility due to the exhaustion of resources
- Increase in electrical energy consumption.

The Comarca Lagunera region in northern Mexico provides an example of how intensive groundwater use has caused an increase in electrical energy consumption resulting from the need to pump water from greater depths. In 1986, 195 wells were measured. Their pumping level was 85 meters, producing an average of 33.4 liters per second (L/s), as well as an electromechanical efficiency of 44.6%, requiring a consumption of 0.68 kWh/m^3. Five years later in 1991, 502 wells were measured. Their pumping level depth was an average of 95.6 meters, producing 30.6 L/s flow with an electromechanical efficiency of 43% and consumption of 0.74 kWh to extract one cubic meter of water. Further, the costs of pumping groundwater were increased by 54% between 1959 and 1996 in Santo Domingo, Guaymas and Aguascalientes aquifers, where a drawdown of one meter per year in the groundwater level had been observed.

A study of the environmental costs resulting from the intensive use of the aquifer of Querétaro revealed a clear increase in pumping costs during the period of 1970 to 1996 (CONAGUA 1997). This is a result of lower piezometric levels resulting in a $6 million (USD) increase in electrical energy costs for that period; the further deterioration of groundwater quality, where damage costs run in the order of $26 million (USD) in the same period; and the damage to the urban infrastructure appraised at over $4 million USD for the same period (CONAGUA 1997). The first $6 million are related to private costs while the other $30 million are attached to causes known as external costs and are presently being absorbed by the inhabitants of the Querétaro region. Today it is estimated that the total of these costs runs in the order of $4 million USD per year. If the aquifer damage is to continue at this rate, these costs will be increased to $5.3 million USD per year in the next five years.

User Participation in Groundwater Management

In 1987 the Mexican government launched a strategy for the participation of organized groundwater users in water management as an institutional response to the problems derived from intensive groundwater use. Through the organization of groundwater user groups, the goal was to obtain a consensus for the approval of "Aquifer Regulations" that would enforce a reduction in groundwater extraction. The first water user association, called "Water Group," was formed in August 1990 in the Comarca Lagunera region, leading to the approval of the "Regulation Decree for the Aquifer of the Comarca Lagunera." Following this same scheme, another water group was constituted in 1991 in the Valley of Santo Domingo, preceding the approval of the "Regulations Decree" for this aquifer. Other user groups were also organized in the north and central parts of the country, although their decrees never were approved.

The legal scope of these user groups was not established at the time of consolidation. Therefore it remained unclear how their activities would be financed or what the legal framework validating their functions and/or actions would be. This generated the opposition of many federal government officials who ruled against the functioning of these groups.

Following a stagnation period between 1993 and 1995 due to changes in the federal government, the formation of new user groups started again at the end of 1995. These new groups, known as Technical Committees for Groundwater (*Comités Técnicos de Aguas Subterráneas* or COTAS), were first launched in the Querétaro Valley aquifer. These committees were then established in various aquifers in the center and north of the country. Two years later, in the state of Guanajuato, local authorities took the initiative of promoting the creation of such committees in all of the state's aquifers by supporting them financially through a trusteeship established for this purpose.

After reviewing the results obtained under the aquifer Regulation Decrees approved in the Comarca Lagunera region and the Valley of Santo Domingo, the conclusion is that they were never really applied. According to some of the parties involved, this is either due to a lack of political will to do so or to corruption. In the opinion of others, the state subordinated its protection of the aquifers to the needs of agricultural growth with the intention of controlling and preserving the country's political stability (Marañon-Pimentel and Wester 2000). These results point to the need to review the role and participation of users in groundwater management. Some of the deficiencies that were observed include:

- Absence of a framework that guarantees that of all users are represented
- Users' representatives not elected through a democratic process
- Legal framework for the operation of the COTAS not well defined
- No legal power by the COTAS for the application of their agreements
- Opposition of lower level officials to the users' participation in management
- Absence of financial mechanisms to guarantee the continuity of the COTAS activities
- Absence of a master plan to direct the efforts to reduce extractions
- Absence of a relation between the proposals submitted by the aquifer regulations and the socioeconomic reality of each region
- Lack of awareness of the benefits of the reductions in water extraction by the users
- Absence of mechanisms to enforce the application of the regulations established in the decrees
- Lack of authority of COTAS, who have a mere advisory role so the authorities don't necessarily take their activities into consideration.

In order to address some of these deficiencies, a governmental initiative has taken place to reframe the function of the COTAS. Among other issues, the changes include:

- Making the selection process of the users' representatives more democratic
- Including other stakeholders
- Elaborating an Aquifer Management Plan as a prerequisite to the proposal of the aquifer regulations
- Identifying the external costs derived from intensive use and advocating their inclusion in production costs
- Advocating for the reorientation of subsidies
- Aiming toward technical and financial autonomy for the COTAS
- Promoting self-management and collective actions as a mechanism to create a "Partnership for the Management of Water."

Ostrom's work (1990), considered by federal agencies as a departure point, discusses the evolution of institutions collectively handling the resources of common use such as groundwater. In this work, the factors identified as characteristic of successful collective management are:

- Clear definition of the boundaries and availability of the resource
- Congruence between appropriation and provision of the rights of use of the resource
- Rules of operation agreed between the parties and authorities involved
- Supervision on the part of the users regarding the behavior and use of the resource
- Gradual sanctions depending on the gravity and context of the infraction
- Mechanisms for conflict resolution between the users and the authorities
- Legal recognition of the users' organizations
- Entities inlaid in multiple levels of these organizations.

As part of this approach, administrative limits of the main country's aquifers have been published in official decrees. Technical Norms have been developed for the calculation of water availability in the country's main aquifers, and the resulting amounts have been published in official decrees. Aquifer Management Plans are also being developed. Subsidy programs that affect the economic output of water have also been analyzed and efforts are being made to reconvert and modernize the agricultural sector into an engineered agriculture of high yield and low water consumption.

In a parallel effort, the federal government has purchased water rights in order to promote the creation of a strategic reserve of groundwater which will enable a long-term development of both the urban and industrial sectors.

Conclusions

Groundwater management in Mexico has evolved through time from a technocratic and centralized approach to a decentralized approach with social participation. This evolution has been associated with the changes in the country's political system, the transformation of the legal instruments and the forms of participation of society, allowing more transparency in the performance of the federal authority.

The subsidies that were established to maintain political and social stability and to sustain agricultural production and rural employment have resulted in the intensive use of aquifers. A Public Registry of Water Rights was established and water markets were created in order to achieve greater economic efficiency in the use of the water. The establishment of the water rights market has transferred water rights to the larger agroindustrial companies and to urban areas.

The environmental costs that resulted from the intensive groundwater use continue to increase as the static water levels are lowered. This has resulted in a continued decrease in the sustainability of agriculture and is a major reason why an urgent intervention is needed to modernize this sector of the economy.

One of the relevant aspects in the change in groundwater management is the recognition of the importance of the participation of the water users as effective partners in the decision making process.

Although an enormous effort has been done to improve groundwater management, it is necessary to integrate all these efforts in a new national policy that allows the development of Aquifer Management Plans with an adaptive and collaborative approach.

Acknowledgements

The authors want to thank the reviewers whose commentaries allowed us to substantially improve this paper.

References

Cantú M, To, and Garduño, H.V. 2004. Administration of water rights. From regularization to axis of management of the hydric resources. In: The water in Mexico from the academic point of view (in Spanish). Jiménez B. and Marín L. Editors. Mexican academy of Sciences. Mexico. p. 271-288.

CONAGUA (National Water Commission). 1997. Study of the Environmental Economic Costs for the overexploitation of the groundwater in the valley of Querétaro (in Spanish). Hidrosistemas Universales, S.A. of C.V., under Contract N° GAS-013-PRO97.

CONAGUA (National Water Commission). 2006. Water in México. México, D. F. 36 pp. www.cna.gob.mx.

Custodio, E. and Llamas, M.R. 2003. Intensive use of groundwater: introductory considerations. In: Intensive Use of Groundwater: Challenges and Opportunities. Balkema Publishers, a member of Swets & Zeitlinger Publishers. Lisse, The Netherlands. p 3 – 12.

Escolero, O. 1993. Panoramic of the groundwater in Mexico. In: The Water: Vital resource (in Spanish). Technological University of the Mixteca. Acatlima, Huajuapan of Leon, Oaxaca, Mexico. p 37-52.

Marañon-Pimentel, B. and Wester, P. 2000. Institutional answers for the management of the aquifers in the Lerma-Chapala River basin, Mexico (in Spanish). IWMI, Latin American Series N° 17, Mexico. International Water Management Institute. 53 pp.

Palacios-Velez, E. 2004. The use of the water in the agricultural sector. In: The management of the water in Mexico: The challenges for the sustainable development (in Spanish). Jacobo-Villa M.A. and Saborío E. Editors. Autonomous Metropolitan University, Iztapalapa Unit. Mexico. p. 139-157.

Plata-Olvera, F. 1996. Market of the water in Mexico. In: Water: challenges and opportunities for XXI century. Memories of the International Seminary on the Efficient Management of the Water (in Spanish). Government of the State of Aguascalientes. Mexico. p. 321-331.

Ostrom, E., 1990. The Evolution of Institutions of Collective Action. Edición en español: Fondo de Cultura Económica, México. 395 pp.

Sarraf, M., Larsen B. and Owaygen, M. 2004. Costs of Environmental Degradation: The case of Lebanon and Tunisia. Environmental Economic Series, Paper N° 97. The World Bank Environment Department. 106 pp.

USEPA. 1995. An Introduction to Environmental Accounting As A Business Management Tool: Key Concepts and Terms. U. S. Environmental Protection Agency, EPA/742/R-95/001. 39 pp.

CAPÍTULO III SOCIOECONOMIC DEVELOPMENT IN ARID ZONES: THE INFLUENCE OF WATER AVAILABILITY IN THE SAN LUIS POTOSÍ BASIN, MEXICO

Sandra Martínez, Javier Delgado, Oscar Escolero, Eloisa Domínguez y Manuel Suárez

En:
Arid Environments
A. Fernandez-Bernal and M. A. De La Rosa (Eds)
Nova Science Publishers, New York (en impresión). 2009

In: Arid Environments
Editors: Antonio Fernandez-Bernal et al., pp. -
ISBN: 978-1-60692-411-2

SOCIO-ECONOMIC DEVELOPMENT IN ARID ZONES: THE INFLUENCE OF WATER AVAILABILITY IN THE SAN LUIS POTOSÍ BASIN, MEXICO

Sandra Martinez*[*1], *Javier Delgado*[*2], *Oscar Escolero*[*3], *Eloisa Domínguez*[*4] and *Manuel Suárez*[*2]

[1] Posgrado en Ciencias de la Tierra, Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), México D. F. 04510, México

[2]Instituto de Geografía, Geografía Social, Universidad Nacional Autónoma de México (UNAM), México D. F. 04510, México

[3] Instituto de Geología, Geología Regional, Universidad Nacional Autónoma de México (UNAM), México D. F. 04510, México

[4] Instituto Potosino de Investigación Científica y Tecnológica A.C, Camino a la Presa San José 2055, San Luis Potosí. 78216. México

ABSTRACT

Where rapid urbanization occurs in arid zones, the socio-economic system places severe stress on water resources that, in turn, form a constraint on socio-economic development. A review of the San Luis Potosí Basin identified the dynamic of the socio-economic process that drives the development of water resources. At each stage, when utilization of water resources approached or exceeded its threshold, engineering efforts

* seddam2002@yahoo.com.mx
* jdelgado@igiris.igeograf.unam.mx
* escolero@geologia.unam.mx
* edominguez@ipicyt.edu.mx
* jdelgado@igiris.igeograf.unam.mx

were put into practice to increase the volume available. The case study indicates that the foundations and main driving forces of socio-economic development in San Luis Potosí are generally similar to those of other urban basins in Mexico's arid zone.

Growth rates of economic activity and population in Mexico's arid zone are among the nation's highest. However, development is often severely limited by high stress on water resources. In order to face that challenge, a paradigm change has iniciated in which integrated water resources management plays the central policy element. In this chapter, some initiatives will be presented that put in practice this approach, and measures necessary to reach a balance between socio-economic and water related goals are discussed.

1. INTRODUCTION

Water scarcity is without any doubt one of the most challenging current and future issues concerning natural resources, especially in arid and semi-arid regions (Knapp 1995). The challenge is heightened by the rapid urbanization of such regions in developing countries, primarily because of their continued high dependence on agricultural activities. In addition, the water infrastructure that is needed to support development fails to keep pace with the rapid growth of the cities.

Mexico's arid zone, which comprise close to 53 percent of the nation's territory (figure 1), has registered the highest growth rates of urban population. Between 1940 and 1990 the urban population rose from 1.3 million to 16.6 million inhabitants – approximately one third of the nation's total (Gutiérrez and Valdez 1997). At the same time, there have been changes in the spatial organization of the economy, such as industrial relocation, the development of the services sector, and the diversification of regional economies and employment. These were coupled with the development of large-scale urban infrastructure, the urbanization of cheap land, and changes in the way water is used (Delgado 2003).

Social and economic development is strongly linked to water availability (Biswas 2006). Estimates for the year 2030 indicate that Mexico's population will grow by 84 percent compared with a current level of some 110 million inhabitants, and that half of them will be concentrated in 31 cities with more than 500 000 inhabitants (Conagua 2006). Nearly 50 percent of these cities are located in the arid zone, where water stress reaches values of between 20 and 86 percent and 104 aquifers that supply 60 percent of groundwater employed for all uses are over-exploited. The reduced availability of water can present a severe constraint to socio-economic development, while increasing the potential for conflict among users.

We reviewed the historical and current interactions between the socio-economic dynamic and water resources in San Luis Potosí Basin. We analyzed the extent to which the management of water resources was resolving conflicts of interest among the forces driving socio-economic development. The San Luis Potosí analysis is valid for other urban basins in the Mexican arid zone that exhibit similar physical and socio-economic conditions, such as population, economic scale and investment, industrial structures, geographical location, historical culture, national policy and water sources.

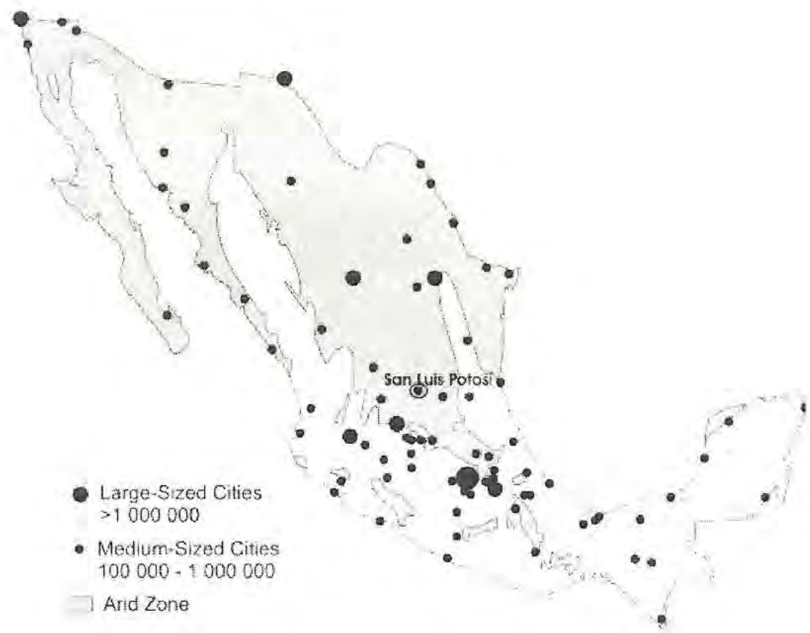

Figure 1. Mexico's arid zone.

2. Interaction between Socio-Economic Dynamic and Water Resources

The scarcity of water in a given geographic context is a relative situation that is determined by the demand of a population at a given level of economic development, and by the quantity and quality of water resources available to meet that demand. These are not fixed values. While the demand for water depends on socio-economic growth, its availability grows with the knowledge, technology and financial capacity that permit access to more.

Socio-economic growth generates demand for water. Thus, when demand is strong and water resources are in short supply, the socio-economic system is unable to achieve its expected growth rate over time. In general, when the growth of population, the economy and urbanization approach or exceed the available water resources, or the utilization of water resources approaches or exceeds their natural threshold, they will be severely stressed by the socio-economic system and act as a powerful and direct constraint on socio-economic development (Fang et al. 2007).

The availability of water resources in any one area cannot sustain exponential growth. In a context of rapid socio-economic development, authorities seek to adjust water demand and supply, but without changing the socio-economic structure. However, this is very difficult to achieve in a sustainable way. Additional water supplies to support socio-economic growth have traditionally been obtained by intensive ground- and surface-water abstraction or by imports from external sources. The adverse economic and environmental impacts that are then manifested include decline of the water-table, increased pumping costs and modifications to natural ecosystems.

Effective management of water resources plays an important role in i) alleviating negative impacts on the social and environmental systems, ii) increasing the range of opportunities available to develop more sustainable supply systems, iii) decreasing economic loss. This must include specific control measures, such as strengthening the planning and management of water resources, adjusting the traditional means of water exploitation and utilization, and rationalizing the pattern of socio-economic development.

3. The San Luis Potosi Basin

The San Luis Potosí Basin (figure 2) is located in the west of the state with the same name. It covers an area of 1980 km^2 and the elevation of the basin floor is between 1850 and 1900 m above datum (mean sea level). The climate is semi-arid with an mean annual temperature of 17.4 °C and mean annual precipitation of 356 mm, for the period of 1989-2006.

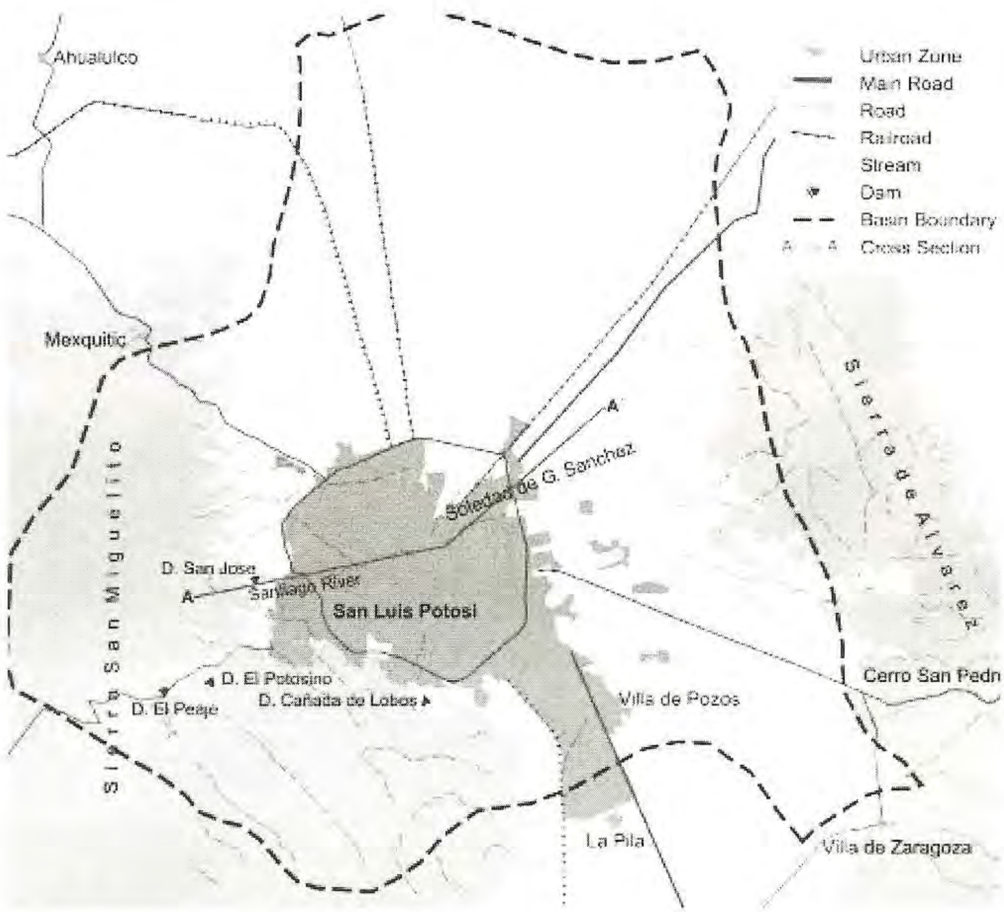

Figure 2. San Luis Potosí Basin.

This is a closed drainage basin lacking any perennial runoff. The runoffs originating in Sierra San Miguelito are captured by means of four dams: San José, El Peaje, El Potosino and

Cañada del Lobo. The San José and El Peaje dams regulate the Santiago River and contribute to urban water supply. The El Potosino and Cañada del Lobo dams were built for flood control.

The San Luis Potosí Basin resembles other basins of northeastern Mexico. It is formed by a graben structure developed during the Oligocene, where a thick sequence of Tertiary volcanic rocks was deposited. A Tertiary granular sequence was deposited on top of the volcanic units as basin fill material. The granular sequence includes a fully 50 to 150 m -thick bed of fine-grained, compact sand. This layer is found under most of the flat part of the basin except at the edges and permits the separation of two aquifers in a vertical direction (figure 3): i) a shallow aquifer in alluvial material, and ii) a deep aquifer in the granular material and fractured volcanic rocks (Cardona 1990; Carrillo-Rivera 1992). The shallow aquifer is recharged by rainwater, the infiltration of wastewater from agricultural irrigation, and leakage from sewers and water-supply pipelines. The recharge area of the deep aquifer is in the Sierra San Miguelito, far beyond the basin's western limit.

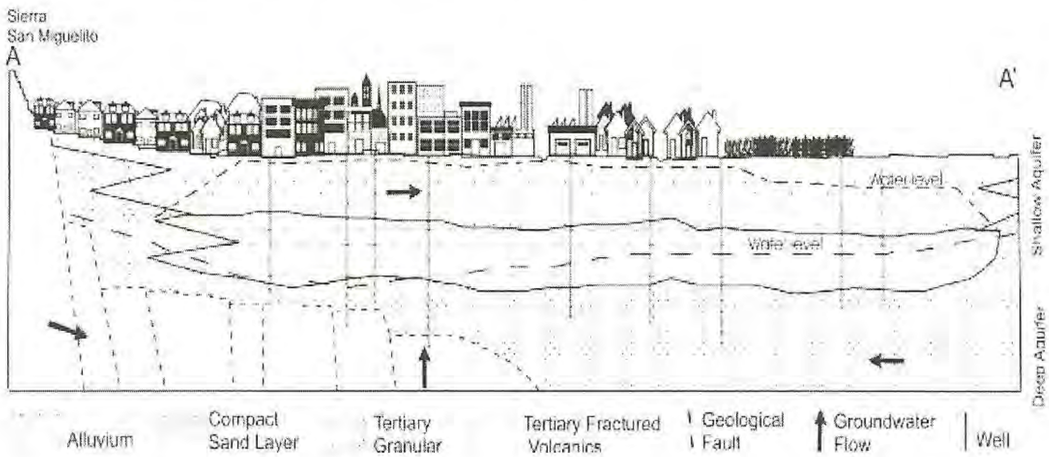

Figure 3. Hydrogeology framework of San Luis Potosí Basin (Modified by Carrillo-Rivera 1992).

The basin encompasses almost the totality of the municipalities of San Luis Potosí and Soledad de G. Sánchez, as well as a small fraction of the rural municipalities of Mexquitic de Carmona, Cerro San Pedro and Villa de Zaragoza. In the Mexican arid zone, water scarcity contributed to a pattern of population distribution characterized by large urban centers surrounded by extensive, sparsely populated areas. This pattern was reinforced over time. Currently, 95 percent of the populations of San Luis Potosí and Soledad de G. Sánchez – an estimated 1 130 000 inhabitants – is concentrated in the metropolitan area, giving it the characteristics of an urban basin. The metropolitan area accounts for 35 percent of the state's total population.

The San Luis Potosí metropolitan area is one of the key urban centers of the Mexican arid region, where socio-economic development has been remarkable in recent decades. Utilization of water resources has reached 122.7 hm^3/year; some 95 percent of the supplies come from the deep aquifer, while the San José Dam provides the remainder. Groundwater abstraction was estimated by Conagua (2005) at 116.1 hm^3/year, of which urban use accounts for 78.2 percent, followed by 11.4 percent for industry, 7.4 percent for agricultural purposes, and 3 percent for other uses.

The physical and socio-economic conditions of the San Luis Potosí Basin are similar to those of other urban basins in Mexico's arid zone. Population, economic development and investment are on similar scales in all of them, as are industrial structures, geographical location, historical culture, national policy, water sources, etc.

4. STAGES IN SOCIO-ECONOMICS AND WATER SUPPLY MANAGEMENT

A historical review of San Luis Potosí identified the dynamic of the socio-economic process that drove the development of water resources (figure 4). Three socio-economic stages and their management modalities of water supply were identified during the evolution of the city (figure 5): the first, from the end of the 16^{th} century to the end of the 19^{th}; the second, from the close of the 19^{th} century to the middle of the 20^{th}, and the third, from mid 20^{th} century to the beginning of the present century. The stages were defined in relation to dominant characteristics, though characteristics of a previous stage sometimes prevail.

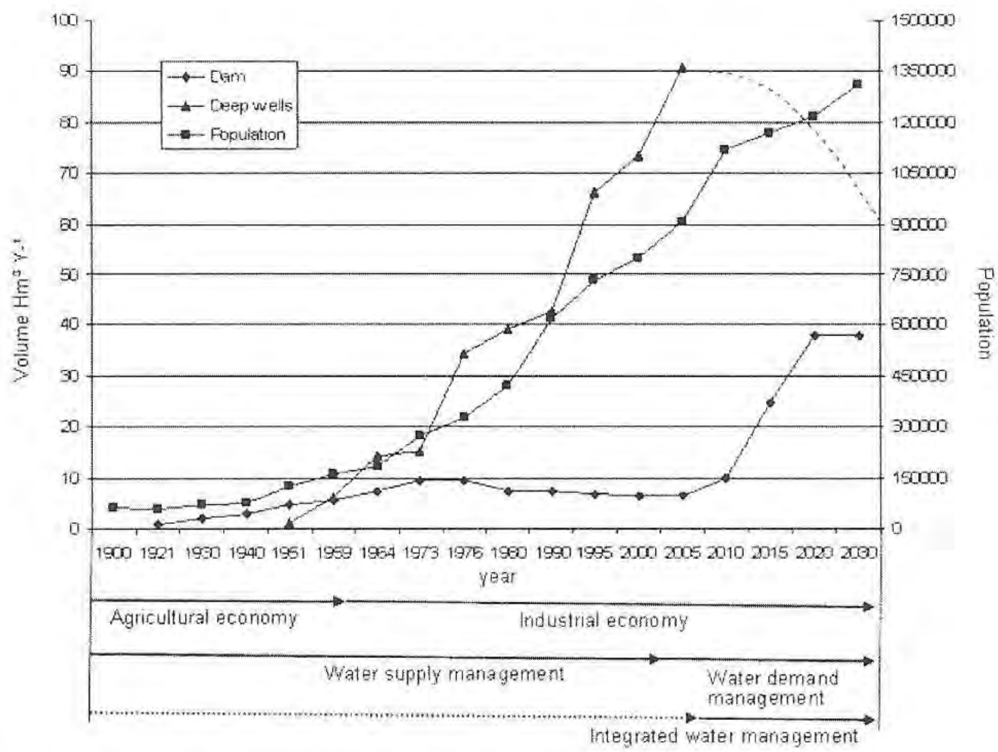

Figure 4. Socio-economic dynamics and development of water resources.

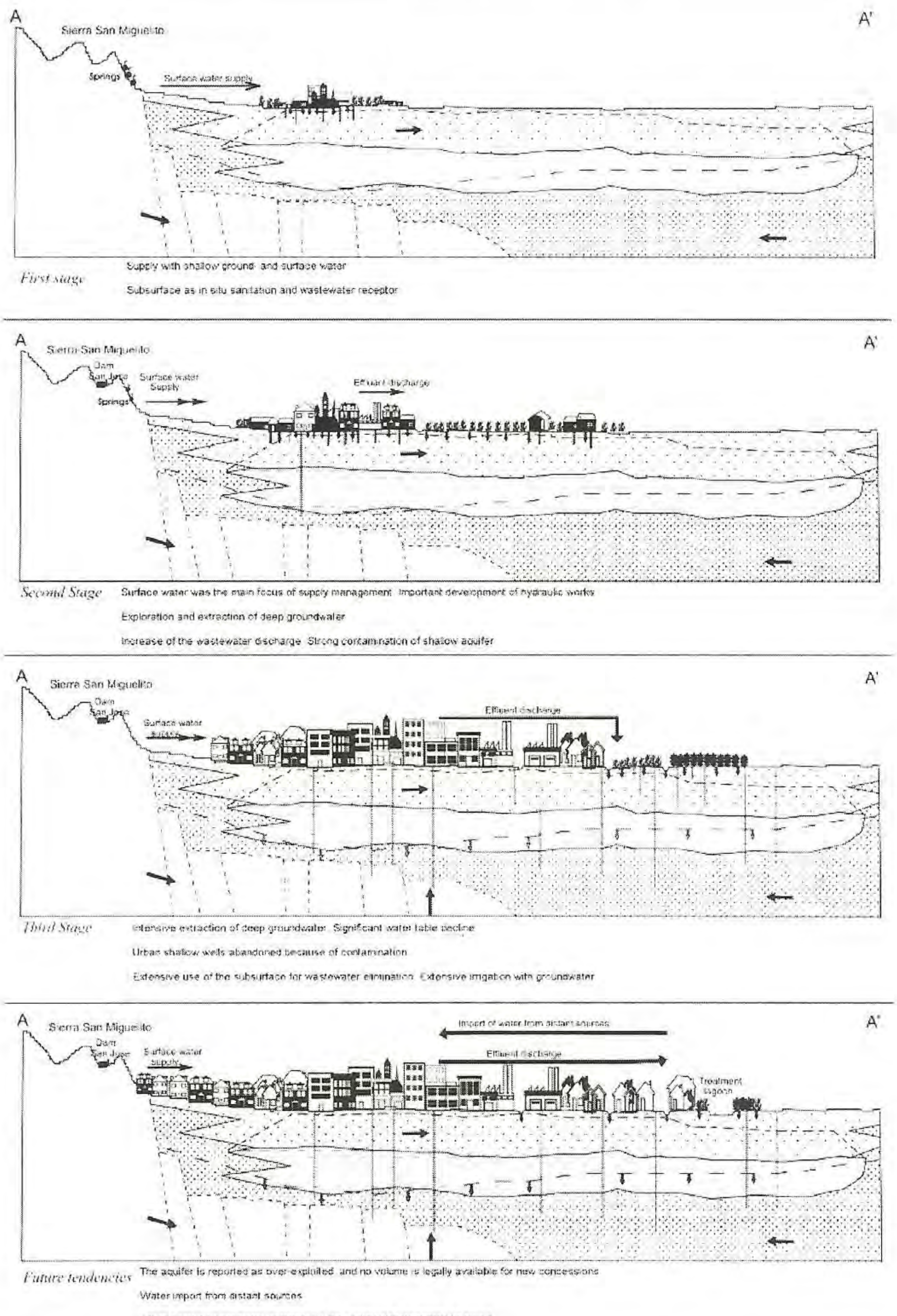

Figure 5. Management modalities of water supply during the evolution of the city (Modified by Morris et al. 1997).

First Stage

Colonization for mining established the framework for the first stage. The city, which was founded due to the presence of rich deposits of silver and abundant water resources, became the economic and mining center of the region.

In the early stages of socio-economic development, there was no shortage of water. The runoffs of the Sierra San Miguelito, particularly the Santiago River that crosses the city, were the main sources of water supply for several decades. Sources more distant from downtown, such as springs in the foothills of Sierra San Miguelito, were made available by projects for the capture, transport and storage of water.

The gradual development of the socio-economic system led to a correspondingly slow increase in the amount of water use. However, water was relatively abundant compared with demand. The characteristics of the subsurface allowed obtaining the extra water resources required, thus shallow wells were drilled and dug. At the same time, the subsurface was used as an *in situ* sanitation and wastewater receptor. These functions – those of aquifers and receptor – are in conflict, yet are linked strongly (Morris et al. 1997). The benefits of use of the subsurface were evident from the outset, while the long-term costs involved were not always appreciated.

Second Stage

The second stage ran from the end of the 19th century to the middle of the 20th. Agriculture became the mainstay of the state's economy, in response to the agro-exporter model favored by the Mexican Revolution (1910-1927), the construction of the railroad, and the opening up to foreign investment.

Agriculture came to employ 83 percent of the working population in the state (Márquez 1986) and, despite major foreign investment in metals and mining, farm output was worth twice as much as what the mines produced (Monroy and Calvillo 1997). The railroad played a key role in socio-economic development. It boosted economic production by increasing the mobility of goods and people among productive zones and main cities, while developing trade with the United States. San Luis Potosí strengthened its role as a regional center of commerce; as a result, the urban population grew from 70 000 to 100 000 inhabitants between 1921 and 1930. By the end of the 1950s, some 160 000 inhabitants were distributed over 1250 hectares (Villa de Mebius 1988).

Despite the rapid growth, water resources represented only a moderate constraint to socio-economic development. Surface water was the main focus of supply management. Dams, irrigation channels, watering troughs and aqueducts were built in order to obtain more water. These projects included such outstanding examples as the San José and El Peaje dams that regulated the Santiago River, so ensuring water supply for the urban population as well as the agricultural enterprises that had been set up on the outskirts of the city. Additionally, abstraction from the shallow aquifer continued to meet part of the demand.

But the degree of economic and social development achieved by San Luis Potosi demanded new sources of water supply. The answer came in the form of oil-industry technology that was used to explore for deeper groundwater and extract it. The wells reached depths of 150 m, with water-levels at 80-100 m, producing discharges of 30-40 l/s (Carrillo-Rivera 1992).

The wastewater, discharged mainly in the municipality of Soledad de G. Sánchez by canals and natural streams, was partly used to irrigate 1500 hectares of orchards and alfalfa (IIZD 1961).

Third Stage

The third stage runs from the middle of the 20th century to the beginning of the 21st. Water-scarce regions adjusted their socio-economic structures in order to redirect water to cities and industries. Industry produces an economic return on water that is some 20 to 70 times what is achieved by agriculture (Ohlsson 2000). The means to change the socio-economic structure were provided by the creation of fiscal and credit incentives, as well as direct investment in urban and industrial infrastructure. National strategic planning for urban development promoted medium-sized cities for the relocation of economic activity and population, long heavily concentrated in Mexico City. San Luis Potosí was amply provided with investment in infrastructure, as well as credit for the stimulation and promotion of industry. This strategy encouraged the development of the metal-mechanical, chemical, food, textile, footwear, furniture and construction industries (PDUSLP 2000; Aguilar et al. 1996). Communications were further improved by the construction of Federal Highway 57, which linked two giants: Mexico City in the south and the US market in the north. San Luis Potosí's location on this north-south axis enhanced its strategic role in commerce and as a transfer point for manufactured goods and raw materials – especially after the 1994 implementation of the North American Free Trade Agreement (Nafta).

The changes from an agricultural economy to one based on industry and services formed the basis for urban growth from the 1950s onward. At the beginning of 1970s, Soledad de G. Sánchez was absorbed as part of the conurbation of San Luis Potosi City. The growth dynamic stimulated demand for land for infrastructure, services and housing. Proximity to the industrial area and low land prices promoted the location of the lower-middle and lower income sectors in the east and southeast of the city. These areas showed growth rates of close to 6 percent and a population density of up to 82 inhabitants per km^2 (PDUSLP 2000). On the contrary, high-income sectors were located to the west, in the aquifer's recharge area, applying pressure on areas with environmental value. In 2000, the metropolitan area accounted for 35 percent of the state's total population and half its gross domestic project.

Economic changes and improvements in living standards increased the demand for water. The solution was found in abstraction of deep groundwater that rose from 25.4 hm^3/year in 1960 to 116.1 hm^3/year in 2005. Speculators – helped by official complacency, corruption and a lack of controls – began to buy up agricultural water rights in advance of the 1992 opening of the water market. The new rules permitted the transfer among users of titles of concessions or allocations that establish the right to withdraw and use an annual volume of water from a specific aquifer. The water rights market made possible re-allocation among users in aquifers subject to intensive use (Escolero and Martinez 2007). Most water transfers took place when small farmers sold their water rights to industry or construction companies. This pattern of water transfer has substantially modified cultivation patterns, the areas where water abstractions are most heavily concentrated, the price of water rights, and the profits that can be obtained from the use of water.

The level of urbanization can represent socio-economic development, to a certain extent (Fang et al. 2007). Figure 6 shows urbanization and urban water utilization in the basin's principal municipalities from 1950 to 2005. Between 1950 and 1990, urbanization grew along with the increase of urban water utilization. Later, however, urbanization slowed down while urban water use increased considerably. This may have been in response to two factors. On the one hand, the socio-economic growth had been fast and required a stage of reorganization; the great investments fell. On the other hand, the increase in urban water use was driven by a major development of the services sector that is connected to the mains water supply, and by a rise in per capita water consumption. From 2000, both, urbanization level and urban water use have been increasing in response to new investment and employment generated; the residential area grew considerably.

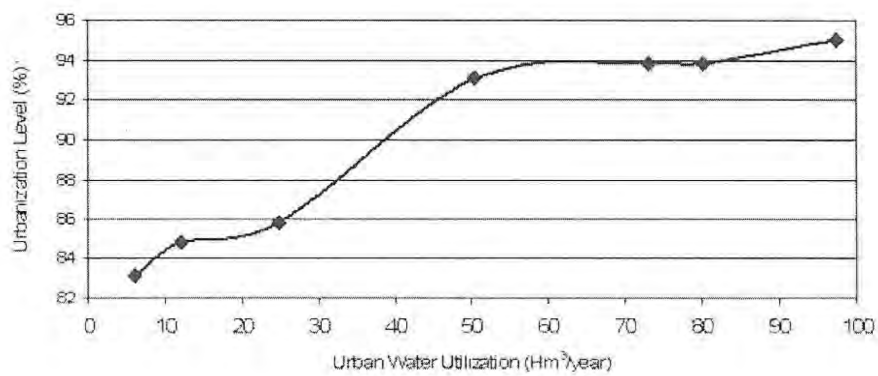

Figure 6. Process of urbanization and urban water utilization.

An indicator of economic transformation based on working population by sector is show in table 1. In the 1960-2000 period in the municipality of San Luis Potosi, almost 19 percent of the employed population abandoned agriculture in order to work in services. In the municipality of Soledad de G. Sánchez, the economic transformation was much more remarkable as a result of conurbation. There, the working population in the agricultural sector fell by more than 58 percent, of which 20 percent went to work in industry and almost 40 percent in services. In both municipalities, the abandonment of agriculture by workers peaked between 1960 and 1970, when the conurbation process began.

As shown in table 2, displacement of agriculture as main economic activity was accompanied by a moderate decrease in its water use. It is important to mention here the trends of increases in cultivation of high water consumption cropos like alfalfa (4880 has) and the reuse of wastewater for irrigation. Of the wastewater discharge, estimated at 69.8 hm^3/year, about 44 hm^3/year is used to irrigate 2652 hectares of crops. Industry is currently the most profitable sector in San Luis Potosí, where it produces 80.5 percent of the municipal gross product (PDUSLP 2000). And industry has improved efficiency in water use as a way gaining access to international markets and in order to reduce costs.

Extensive use of the subsurface for wastewater elimination entails long-term environmental costs that are related to the contamination of sources of water supply. In San Luis Potosí, shallow wells for human consumption were abandoned from the mid-20th century onward because of contamination. In 1995, the National Water Commission (Conagua) registered 282 shallow wells, mainly located in Soledad de G. Sánchez that were still functioning for restricted use in livestock and agriculture.

Table 1. Municipal working population by economic sector

Year	Working Population (%)					
	Agriculture		Industry		Services	
	SLP	SGS	SLP	SGS	SLP	SGS
1960	20.7	63.2	33.0	17.1	46.3	19.7
1970	9.9	35.0	35.1	30.5	55.0	34.5
1990	5.9	8.6	34.7	37.6	59.4	53.8
2000	1.6	3.8	33.0	36.7	65.4	59.5

Table 2. Evolution of water uses by sector

Year	Urban Population	Uses	Contribution of dam (hm^3/year)	Extracted Groundwater (hm^3/year)
1960	175 000	Urban	5.7	6.8
		Agriculture		12
		Industry		6.6
2005	907 876	Urban	6.6	90.8
		Agriculture		8.5
		Industry		13.2

5. Socio-Economic Forces that Drive Future Water Stress

The driving forces generated by socio-economic development occur on both regional and local scales The regional driving forces derive from national policies and have a long-term impact on the urban area, where they stimulate the growth. In turn, urban growth promotes driving forces in the urban periphery that affect land and water resources. In response, the urban periphery creates driving forces that strengthen growth and concentration in the urban area. Figure 7 shows the driving forces that act on San Luis Potosí and other urban areas located in Mexico's arid zones. These forces stimulate the urban growth and increase water demands, causing competition among water users.

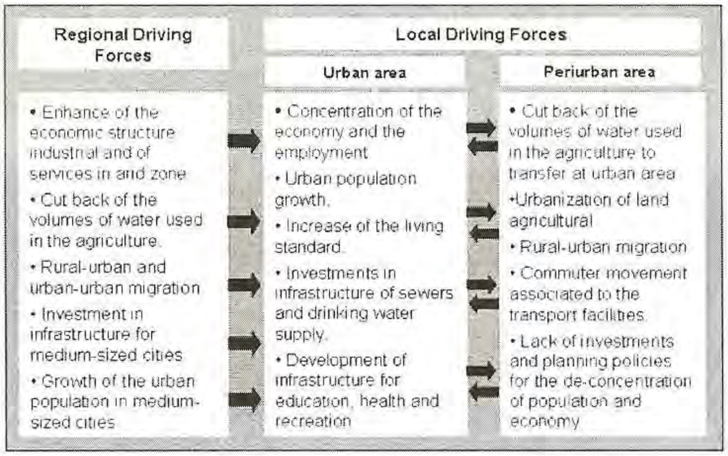

Figure 7. Socio-economic driving forces on the water resources.

Urban water supply has been identified as one of the most critical factors that will determine the future growth of Mexican cities. Estimates for the year 2030 indicate that Mexico's population will grow by 84 percent compared with a current level of some 110 million inhabitants, and that half of them will be concentrated in 31 cities with more than 500 000 inhabitants (Conagua 2006). San Luis Potosí metropolitan area is one of the urban centers where this concentration is expected. The state government's planning policies are weak, and a lack of direct investment in infrastructure makes attempts to reduce concentration of the population and economy unfeasible, at least for the next few years.

In recent decades, growing water demand for domestic and industrial purposes has been met by increasingly intensive extraction from deep aquifer. Intensive groundwater use has resulted in negative impacts that may be measured in terms of i) average drawdown of 1 m/year in the water level, ii) increases in pumping costs, iii) induced changes in groundwater quality, visible in the increase in deep wells producing high-fluoride water (> 1.5 mg/l) from 33 percent in 1983 to approximately 65 percent in 2005. Other factors in the degradation of urban water resources are the discharge of untreated wastewater of domestic and industrial origin and sewerage leakage; both have led to contamination of the shallow aquifer, thereby limiting its use.

The utilization of deep groundwater resources has exceeded its threshold. Water availability in the basin, calculated in accordance with Conagua's technical norms, is represented by the formula:

Mean annual availability = total annual mean recharge – natural discharge – volume granted in concessions

Calculations of the availability of the deep aquifer realized by Conagua (2005) indicate:

Mean annual availability = 80.8 hm^3/year – 0 hm^3/year – 136.7 hm^3/year

Mean annual availability = - 55.9 hm^3/year

This shows that concessions have been granted for a volume that exceeds by 55.9 hm^3/year the annual estimated recharge. It has to be explained that the volume granted in concessions (136.7 hm^3/year) is larger than the volume abstracted from aquifers, estimated in 2005 at 116.1 hm^3/year. As a result, Conagua reported the aquifer as over-exploited, and no volume is legally available for new concessions.

The current socio-economic system increases demand, and water scarcity is perceived as a problem. Water stress in the basin reaches a value of 40.9 percent, putting it into what the United Nations regards as a high-stress category that is a factor limiting development. Worse still, beyond the northern limits of the basin lies a large region subject to stress values of 55 percent whose crops and industries – high-volume water consumers – are likely to move toward San Luis Potosí under pressure from the water resources constraint force. With this scenario as the background, a fourth stage in water supply management was identified (figure 5).

6. Water Resources Management in Response to Water Stress

Whether local water resources will allow future development of San Luis Potosí is the main question to be answered by water resources management policy. The traditional top-down, supply led, technically based and sectoral approaches to water management are imposing unsustainably high economic, social and ecological costs on societies and on the environment. If these tendencies persist, water scarcity and deteriorating water quality will become critical factors limiting future economic development and the provision of basic services. Effective long lasting solutions to water problems require a paradigm change in order to remediate the mistakes of the past and recover sustainability in the use of local resources. Such a new paradigm is summarized in the integrated water resources management (IWRM) concept, which has been defined as process that promotes the coordinated development and management of water, land and related resources in order to maximise welfare (GWP, 2004).

It is important to keep in mind that IWRM is a process of change; a process that may start with small steps. The current water supply challenge provides a framework of opportunity to encourage the reform process. In this context, the National Water Commission has begun a gradual change from the merely supply-side approach towards integrated management.

A lot of attention is currently being paid to the use of greenhouse agriculture as a replacement for traditional methods. Greenhouse agriculture produces more and better products with a minimal quantity of water. Private initiatives in the urban periphery of San Luis Potosí show the financial and technical feasibility of such projects. Greenhouse agriculture represents a big opportunity for Mexican arid zones, as long as it can be accompanied by the necessary changes to financial, administrative and technical habits without which no further development can be expected.

Self-supplied industries represent only 11.4 percent of water consumption because they are obliged to invest in technologies that restrict water use. However, the most important role that industries play in water resources management relates to the pollution control program.

Urban sanitation programs, which are undertaken by the local government, concentrate on wastewater treatment for reuse as a replacement for good-quality water in industry and agricultural irrigation. By 2006, treatment capacity in the San Luis Potosí metropolitan area had grown to 85 percent, but weak control over wastewater discharges constitutes a risk for operation of the treatment plants. Industrial efforts to control water intakes and wastewater discharges should facilitate the best and cheapest solutions for municipalities.

Industry and agriculture represent only 11.4 and 7.4 percent respectively of total groundwater abstraction. Water rationalization in these sectors would not radically change water resources management, but it could be an important influence on the future development of San Luis Potosí. A reduction in consumption for irrigation in neighbour aquifers, for example, would allow the release of volumes of water that would be available for transfer to the metropolitan zone.

When socio-economic development reaches a high level, water-scarce regions have the economic ability to transfer water from distant regions (Fang et al. 2007). El Realito Dam, in the Santa Maria River in the boundary with the neighboring state of Guanajuato, will supply 31.5 hm^3/year. This volume ensures that expected demand should be met in the coming year. It will also allow, during some years at least, for a halt in the use of wells that produce high-fluoride water. Estimates made by Conagua (2004) suggest an investment of 15 million dollars and an annual operational cost of 7 million dollars for the removal of fluoride contained in 59 wells that provided 1490 l/s.

There are evident difficulties in implementing an integrated urban water management scheme that includes sanitation, leakage repairs and flood control when municipal, state or federal taxes – or a combination of all three – are insufficient to meet the costs. Water pricing is the keystone of any urban water policy. San Luis Potosí's current situation is not economically viable; water is so cheap that no incentive could exist to protect its quantity and quality (Conagua, 2004). The cost of repairing leakages is far higher than that of letting the water be wasted and lost. The impact of the bad water quality on public health, and on the value of some industrial and farm products in not taken into consideration, yet it restricts socio-economic growth. A change in water policy must include modifications to the tariff structure, with the aim of bring it closer to the principles of "polluter pays" and "user pays". Economic and social development must be accompanied by an increase in the price of water because the improvements will require higher water standards. Local government has to pay attention to this linkage. If socio-economic and water goals are properly linked, overall progress will be sufficient to meet the cost of water programs.

7. Conclusion

Water has become the scarcest resource where urbanization is rapid in arid zones. The foregoing has provided an outline of the various driving forces of demand for water resources during different stages of socio-economic development. The case study in the San Luis Potosí basin indicates that the foundations and main driving forces of socio-economic development are generally similar to those of other urban basins in Mexico's arid zone.

For centuries, management of water resources has been dominated by a supply-side approach. At each stage, when the utilization of water resources approached or exceeded its threshold, engineering efforts were employed to increase the volume available. This policy has led to problems that involve the increasingly serious over-exploitation of basins and aquifers. In addition, untreated wastewater discharge of both municipal and industrial origin to surface- and groundwater bodies has led to pollution that limits their direct use.

Water-related challenges in the Mexican arid zone are attributable to i) increasing demand that derives from population growth and greater economic development, ii) less availability, and iii) inefficient use. It is a zone where water availability is low but, paradoxically, growth rates of economic activity and population are high. Water stress reaches values of more than 40 percent, making it a factor that limits development.

In view of the current challenges, Conagua, local governments and users' associations are working toward an integrated management rather than continuing with the approach geared to increasing supply. This change of paradigm involves measures to rationalize water use with a view to remedying the errors of the past and recovering sustainable use of local resources. However, the investment required to achieve the proposed goals is more than the federal and local governments can afford. A change in water policy must include finding a balance between socio-economic progress and the price of water. If both objectives are properly linked, overall progress will be sufficient to meet the costs of water programs.

ACKNOWLEDGEMENTS

The authors appreciate support received from the UNAM's General Direction of Postgraduate Studies and the "Rural-urban interface in the Alta de Lerma Basin, towards a methodology of integration of natural and social sciences" project, financed by CONACYT 1430. Thanks also to Gerardo Zenteno for support in the editing of graphics.

REFERENCES

Aguilar, A.; Graizbord, B.; Sánchez-C, A. Las ciudades intermedias y el desarrollo regional en México; *El Colegio de México A.C.;* (Ed); México. 1996, p 403.

Biswas, A.K. Water management in the 21st century for the developing world. Lecture at Phnom Penh, Cambodia. http://www.thirdworldcentre.org/publi.html Cited April 2008.

Cardona, A. Caracterización físico-química y origen de los sólidos disueltos en el agua subterránea del Valle de San Luís Potosí: Su relación con el sistema de flujo. *Tesis Maestría, Universidad de Nuevo León, México.* 1990, p 97.

Carrillo-Rivera, J.J. The hydrogeology of the San Luis Potosí area, Mexico. *Ph D Thesis, London University, UK.* 1992, p 196.

Conagua. Manejo integrado y sostenible del agua en la Región Centro de San Luis Potosí. Informe OMM/PROMMA N° 190. Realizó: *Organización Meteorológica Mundial.* 2004.

Conagua. Actualización hidrogeológica de los acuíferos de Ceballos y Oriente Aguanaval, Edo de Dgo, Villa de Arista y San Luis Potosí, Edo de SLP. *Informe técnico. Elaboró: Sabinfosistem SA de CV.* 2005.

Conagua. Water in Mexico, *Document printed for 4th World Water Forum.* 2006.

Delgado, J. La urbanización difusa, arquetipo territorial de la ciudad-región. In Nuevos enfoques de la relación campo-ciudad; *Rev Sociológica,* Universidad Autónoma Metropolitana, México. 2003, 51, 16-48.

Escolero, O.; Martinez, S. The Mexican experience with groundwater management. In The global importance of groundwater in the 21st century; Bergkamp, G.; McKay, J.; (Eds); Proceedings of the international symposium on groundwater sustainability, Alicante, Spain, January 2006. *NGWA Press*. 2007, 97-103.

Fang, C-l.; Bao, C.; Huang, J-c. Management implications to water resources constraint force on socio-economic system in rapid urbanization: A case study of the Hexi Corridor, *NW China. Water Resour Manage.* 2007, 21, 1613–1633. DOI 10.1007/s11269-006-9117-0.

Global Water Partnership – GWP. Catalyzing Change: A handbook for developing integrated water resources management (IWRM) and water efficiency strategies. 2004. http://www.gwpforum.org/gwp/library/handbook.pdf Cited June 2007.

Gutierrez-MG, M.T.;Valdez-Q, R. Zonas áridas de México: Cambios en el crecimiento de la población urbana y su distribución de 1900 a 1990. Rev Geografía y Desarrollo, *Colegio Mexicano de Geografía A.C.* 1997, 15, 67-79.

IIZD-Instituto de Investigaciones de Zonas Desérticas. Estudios geohidrológico y físico-químico de los suelos en el Municipio de Soledad Diez Gutiérrez, SLP. *Univ Autónoma de San Luis Potosí.* 1961, p 39.

Knapp, J. Water use in arid and semi-arid regions: in the hands of local and watershed-level managers. *J. Soil Water Conserv.* 1995, 50, 412–423.

Márquez, E. San Luis Potosí, Textos de su historia; Instituto de Investigaciones Dr. José María Luis Mora; Ed; México. 1986, p 548.

Monroy-C, M.I.; Calvillo-U, T. Breve historia de San Luis Potosí. Fideicomiso Historia para las Américas, *El Colegio de México y Fondo de Cultura Económica;* (Eds); México. 1997, p 335.

Morris, B.L.; Lawrence, A.R.; Foster, S. Sustainable groundwater management for fast-growing cities: mission achievable or mission impossible?. *In Groundwater in the urban environment: problem, processes and management;* Chilton et. al.; Eds; Balkema, Rotterdam. 1997, 55-66.

Ohlsson L. Water conflicts and social resource scarcity. *Phys Chem Earth.* 2000, B 25(3), 213–220.

PDUSLP- Plan Estatal de Desarrollo Urbano del Estado de San Luis Potosí 2001-2020. Elaboró: Gobierno del Estado de San Luis Potosí, Universidad Autónoma de San Luis Potosí. 2000.

Villa de Mebius, R.H. San Luis Potosí, una historia compartida; Instituto de Investigaciones Dr. José María Luis Mora; Ed; México. 1988, p.583.

CAPÍTULO IV. WATER MANAGEMENT IN SAN LUIS POTOSÍ METROPOLITAN AREA, MEXICO

Sandra Martínez, Oscar Escolero, Stefanie Kralisch

Artículo en revisión “Water Resources Development”

...

Water Management in San Luis Potosi Metropolitan Area, México

Sandra Martinez[1], Oscar Escolero[2], Stefanie Kralisch[2]

[1]Posgrado en Ciencias de la Tierra, Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), México D. F. 04510, México. e-mail: seddam2002@yahoo.com.mx
[2]Departamento Geología Regional, Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), México D. F. 04510, México. e-mail: escolero@geologia.unam.mx

Abstract.
The San Luis Potosí Metropolitan Zone, one of the key urban centres of Mexico's semi-arid central region has experienced remarkable socio-economic development in recent decades, but it confronts inadequate water services in a context of scarcity, inefficient management, and lack of planning, investment and technology. Strategies currently being undertaken include efforts to improve the efficiency of wells, reduce leakage, sanitise the area, and develop alternative water supplies from neighbouring catchments. The challenge today is to move from considerations that focus mainly on supply management, to an approach based on integrated management of water resources. This represents an immense task, but innovative water technologies, management systems and institutional arrangements are necessary in order to meet the multiple objectives of equity, environmental integrity and economic efficiency.

INTRODUCTION

The development of water resources had three main driving forces: i) population growth, ii) industrial development, and iii) the expansion of irrigated agriculture. These factors have been especially evident in developing countries where social and economic growth has been strongly linked to water availability and the development of water infrastructure (Biswas, 2006).
As a consequence of rising demand, water is rapidly becoming a scarce resource in most of the developing world's arid and semi-arid regions. Central and northern Mexico, where arid and semi-arid conditions prevail, have registered the nation's highest growth rates of urban population in recent decades, generating increased competition for water among sectors (Martinez*, et al*., in press). The priorities for the allocation of water have shifted due to high economic output from the industrial and urban sectors. The central

and northern regions have only 32 percent of the nation's available water resources, but house 77 percent of the population and generate 85 percent of gross domestic product.

Urban water supply has been identified as one of the most critical factors in determining the future growth of Mexican cities (Conagua, 2006). Estimates for the year 2030 indicate that Mexico's population will grow by 84 percent from a current level of some 110 million inhabitants, and that half of the total will be concentrated in 31 cities of more than 500 000 inhabitants. The challenge is made greater because nearly 75 percent of these 31 cities are located in central and northern Mexico, where 105 aquifers that supply 60 percent of groundwater, employed for all uses, are over-exploited (Conagua, 2008).

Many of Mexico's urban centres suffer inadequate water services in a context of scarcity (Tortajada, 2006; Sandoval, 2004; Rodriguez, 2003). Patterns of urban growth, water supply, wastewater disposal, and land use relate to inefficient management and lack of planning, investment and technology; they also vary from city to city. The problems are complex not only due to technical and economic factors, but also because of the policy and institutional framework, human resources development, and for socio-cultural reasons.

The aim of this paper is to present the variety of topics that relate to water management in the San Luis Potosí Metropolitan Zone (ZMSLP, by its initials in Spanish) and their complexity. The paper proceeds by reviewing problems that are emerging in water resources management, and suggests strategies that are important in order to respond to these challenges.

DEVELOPMENT SETTING OF SAN LUIS POTOSÍ METROPOLITAN AREA

The metropolitan area is located approximately 400 kilometres northwest of Mexico City. It lies in the San Luis Potosí valley in the west-centre of the state of the same name at an altitude of between 1850 and 1900 meters above sea level. The area is flanked by the hills of Sierra San Miguelito to the west and Cerro San Pedro to the east; the hills have an altitude of more than 2300 meters. The urban area's orography is hilly in the southeast and more or less flat in the north and northeast, with a dominant southwestnortheast incline of 0.33 percent. The climate is semi-arid with an average rainfall of 356 mm between 1989 and 2006, an average annual temperature of 17.6 ºC, and average annual potential evaporation of approximately 2000 mm.

The ZMSLP is one of the key urban centres of central Mexico, and its socio-economic development has been remarkable in recent decades. In 1960, the city of San Luis Potosí had about 175 000 inhabitants in an area of 4000 hectares. In the 1970s, the growth of San Luis Potosi and its proximity to Soledad de G. Sánchez led to the development of a conurbation. The process reinforced the urban centre’s supremacy over the rest of the state while polarising economic and population growth. The population grew from 273 000 inhabitants in 1973 to about 1 135 800 in 2004. The ZMSLP accounts for 43 percent of the state’s total population, 60 percent of its urban inhabitants and 47 percent of the economically active population. In economic terms, the metropolitan zone generates 71.5 percent of the state’s GDP and 79.4 percent of the gross value of its production (INEGI, 1999).

The urbanized area covers approximately 14 800 has. Simplified land uses from an original town planning classification (HASLP, 2003) show the dominant forms in the urban area. Figure 1 shows a predominance of high-density residential areas inhabited mainly by the lower and lower-middle social levels. These areas grew rapidly in the south, east and north between 1970 and 1990 (Martinez, 2005). The rapid development of these sectors, associated to the demand for labour by industry and commerce, has represented a challenge – principally in terms of management and investment – for the institutions that provide basic services.

Medium-density residential areas are heavily concentrated to the west, in the foothills of the Sierra San Miguelito. This area was developed over the last decade by upper-middle and upper-class social sectors attracted by the proximity of services and recreational areas, the scenic and environmental quality, and by its remoteness from the sewage-disposal works to the east of the city. Growth of housing and recreational infrastructure in this area is effectively uncontrolled, forcing changes in land use in response to the needs of high-income sectors to the detriment of environmental buffer zones and the recharge of aquifers.

The ZMSLP was amply provided with investment in urban infrastructure. Construction of a ring road led to a re-articulation of the various urban sectors while connecting regional highways that converge in the metropolitan zone. The ring road constitutes a major element in delimitation of the urban area; it also encourages its expansion into farmland, woodland and areas where aquifers are recharged (Martinez, 2005).

Industry is concentrated in two industrial parks in the southeast on route 57. Some 326 companies were registered in the parks in 2004, and the main industries represented were food and drink processing, automobiles, chemicals, textiles, paper, steel and metalwork. The most dynamic and developed sectors export to the United States and Canada taking advantage of economical transport links between Mexico City and the north-eastern US. The stability of this sector promoted the development of commerce and services that are now highly consolidated (PDUSLP, 2000).

The ZMSLP forms part of a group of Mexican cities that has led population growth over the last 20 years. Estimates for the year 2033 indicate that the ZMSLP will have approximately 2 070 000 inhabitants (Interapas, 2005) encouraged by investments in industry and services (for example, General Motors is expected to build a plant that will provide 1800 to 2300 jobs). The growing challenges in terms of urban water management require new strategies to meet both demand and supply.

SOURCES OF WATER FOR THE METROPOLITAN AREA

The ZMSLP depends on local groundwater sources for more than 90 percent of its supply; the rest is provided by surface water (Figure 2). Water is captured from 120 sources, of which 119 are deep wells, and a surface source that consists of the El Peaje and El Potosino dams that supply the San José reservoir. In 2004, supplies totalled 95.38 hm^3, of which 88.3 hm^3 was extracted from groundwater sources and 7.08 hm^3 from the San José reservoir.

System for the collection of surface water

Surface water for the metropolitan zone is collected by a system that consists of the El Peaje and El Potosino dams, which supply water to the San José reservoir (Table 1). Taken together, the dams have an average flow of 300 l/s and a maximum of 489 l/s, though the maximum level is only rarely achieved (Interapas, 2005). The system includes the Los Filtros potabilisation plant, which receives the water from the San José reservoir by means of a 4.7 kilometre open channel. The potabilisation plant was designed and constructed 70 years ago to treat an average of 260 l/s, and it is currently estimated to be processing nearly 240 l/s. Another plant, Lomas IV, receives 30 l/s from a San José reservoir branch channel. The water utility delivers the water to a private consortium that operates the system.

Surface sources provide an average of 6.5 hm^3/year to the ZMSLP supply system, with a minimum of 0.9 hm^3 in 2001 and a maximum of 9.5 hm^3 in 1976. Water quality is reported to be good due to the absence of sources of pollution such as human settlements, farming and forestry (Conagua, 2004).

The system for the use of surface water suffers from severe restrictions that relate to the capacity and state of the infrastructure, as well the absence of investment in rehabilitation and maintenance. Storage capacity of the main dam, San José – designed and built more than a century ago – has fallen by about 50 percent, while that of El Peaje has been reduced by 17 percent. In addition, because of the limited capacity of the Los Filtros potabilisation plant, overflow from the dams has to be discharged into the Santiago riverbed, now transformed into an avenue that crosses the city from west to northeast. The overflows have reached volumes as high as 14 hm^3/year, paradoxically twice the volume used for supply. The discharges, into what is now known as the Rio Santiago Boulevard, flood the urban area and its surroundings, damage infrastructure and cause traffic problems. They also spark outrage among people who still lack potable water or who receive it only sparingly.

Because of the limited availability of surface water, for decades solutions were based on the development of local groundwater sources. As shortages increased, the local government and the water utility devised strategies to improve the supply system and make greater use of local surface sources. With that as the background, a project was launched to extend and update the Los Filtros potabilization plant. The project includes installation of a pipeline to replace the open channel that brings water from the dam to the plant. Treatment capacity is being increased to 480 l/s, and the potabilisation system is being refurbished. The project will provide economic, social and environmental benefits for 200 000 inhabitants who will have access to water supplies that are adequate in terms both of quality and quantity. It will also put an end to the problems caused by the discharge of overflows.

Plans to increase the use of local surface sources also include the renovation of the San José and San Antonio dams, as well as the San Antonio reservoir's feeder channel. These improvements should add 150 l/s to the supply (Conagua, 2004). The San Antonio dam is located in the southeast of the ZMSLP, upstream from the industrial area. It was built for flood control and its current use is restricted to small-scale irrigation of farmland.

San Luis Potosi Valley Aquifer

The San Luis Potosí aquifer system underlies much of the surface endoreic basin. It consists of a shallow aquifer and a deep one, separated by a lens of fine material that permits very little interaction. The shallow aquifer is recharged by rainfall in the valley and the Sierra San Miguelito foothills, as well as by leaks from the urban water system. The deep aquifer is recharged in the Sierra San Miguelito and beyond.

Shallow aquifer

The 300 km^2 shallow aquifer underlies the urban zone and its periphery. The thickness of the aquifer is within a range estimated at four to 60 meters, while the depth of the phreatic level has been reported in general terms at between five and 30 meters. The less deep levels are to be found within the urban zone and they deepen towards the east and northeast in the area of peripheral farmland, following the direction of the flow. In situ accessibility at a low cost made this resource one of the main sources of supply from the end of the 16^{th} century until the 1950s (Martinez *et al.*, in press).

Urbanisation modifies natural infiltration systems as surfaces are sealed, natural drainage patterns changed, and water service networks introduced, invariably with the loss of large volumes through leakage at the mains and wastewater seepage (Morris *et al.,* 1997). In addition, land on the urban fringes has been extensively used for effluent discharge and waste disposal. Together with the irrigation with raw sewage, these have been common practices in San Luis Potosí, as in most Mexican cities. The effects on underlying groundwater resources are adverse in two ways. On one hand, the patterns and rates of recharge are changed; on the other, the poor quality of the recharge is a common cause of severe pollution of groundwater. These adverse effects conflict with the use of groundwater for urban water supply.

Until 1960, the 175 000 inhabitants of the urban area were almost all supplied by the San José dam and the shallow aquifer, which together provided 153 litres per inhabitant per day (Stretta and del Arenal, 1960). In the second half of the 20th century, shallow wells were progressively abandoned in the urban area as a result of anthropogenic pollution and the installation of a drinking-water supply system fed by deep wells. Meanwhile, on the urban fringes, about 280 shallow wells continue to operate for agricultural irrigation.

Results of monitoring of the water quality in shallow wells of the urban and rural areas have been presented in Cardona and García-Rangel (2003) and Cardona *et al* (2004). The authors report electrical conductivity values of 153-3190 µmhos/cm in shallow wells, compared with 1476-1940 µmhos/cm in wastewater samples. Sulphate and chloride concentrations generally present low values of less than 200 mg/l and of more than 60 mg/l, respectively. Salinity values are low (200-250 mg/l TDS) at the foot of the Sierra San Miguelito and high (up to 2000 mg/l TDS) towards the east. With respect to $CaCO_3$ and nitrates, more than 50 percent of the samples surpass the national drinking water standard of 500 mg/l and 10 mg/l, respectively.

The areas where high values of electrical conductivity, sulphate, chloride, salinity and total hardness ($CaCO_3$) have been measured in the shallow aquifer correspond to those reported in previous studies (IIZD, 1961; Carrillo and Armienta, 1989; Vargas, 1994; Conagua, 1996), but their extension and the measured concentrations have increased considerably. Distribution of electrical conductivity, salinity, total hardness and nitrates follows a pattern that coincides with the general groundwater flow direction from the west to the northeast. The lowest values are found in the recharge zone at the foot of the Sierra San Miguelito, increasing to maximum values in the area of wastewater irrigation and close to the industrial zone.

In all the shallow-well samples, faecal and total coliforms have been found to exceed the maximum permitted by the national drinking water standard. The maximum value of

$4x10^4$ UFC/100ml indicates the impact of wastewater infiltration on the shallow aquifer. The maximum concentrations of manganese (2.15 mg/l), copper (0.27 mg/l), nickel (0.005 mg/l) and aluminium (0.27 mg/l) have been detected in an area eastwards from the industrial zone and are consistent with contamination values expected from the type of industrial activity that prevails there.

On the other hand, the abandonment of abstractions in the urban area and increasing recharge due to leakage from the network have caused the water table to rise. Resultant problems include i) cellar and basement flooding, ii) increased infiltration of groundwater into the sewage system, and iii) increased construction costs for new buildings. These problems have never been recognized or considered by the authorities responsible for water management and urban planning; therefore, no records of the water level are available for assessment of the change. In order to obtain reliable estimates, water level depth was measured during the dry season in about 90 shallow wells located in the urban area. The results show that the water level lies between 2.4 and 12.1 metres below the surface. Additionally, it was estimated that the water level increases by about 0.50 metres in the rainy season; buildings and other structures that reach depths of more than two metres are, therefore, likely to be affected. Cellar flooding and infiltration of groundwater into the stormwater collectors were detected during the dry season in the vicinity of the Rio Santiago Boulevard (Figures 3 and 4).

Deep aquifer

The deep aquifer covers about 1980 km^2 and underlies the municipalities of San Luis Potosí and Soledad de Graciano Sánchez, as well as part of Cerro San Pedro, Mexquitic de Carmona and Zaragoza. The aquifer consists of granular material and fractured volcanic rock. It is confined over most of the flat part of the basin and has a depth to the water level of between 80 and 170 metres. Usually, wells tapping this aquifer terminate at a depth of 350-450 metres, and exceptionally at 700 metres.

From the 1960s, exploitation of the deep aquifer met the growing water demand in the urban area in terms of quantity and quality (Figure 2). Between 1960 and 2004, total withdrawal of deep groundwater rose from 25.4 hm^3/year to 116 hm^3/year (Gallegos, 2002; Conagua, 2005). Demand for domestic use led the increase as a result of rapid growth in the population. Between 1960 and 2004, domestic water use increased from 6.8 to 88.3 hm^3/year.

Because of its good quality, local availability, and reliability as a source during droughts, groundwater has been of great importance in the development of the ZMSLP. Deep groundwater accounts for more than 90 percent of the volume used for urban supplies and 100 percent of that used by self-supplied industries. However, intensive utilisation of deep groundwater resources has exceeded its threshold. This is due, on one hand, to the absence of other nearby sources to meet growing demand and on the other, the relatively low capital costs involved compared with other supply options. The volume granted in user concessions (136.7 hm^3/year) far surpasses the estimated natural recharge rate of 80.8 hm^3/year. As result of an average annual deficit of 55.9 hm^3/year, the National Water Commission (Conagua by its acronym in Spanish) reported the aquifer as over-exploited, and no volume is legally available for new concessions. The mismatch has led to an increase in negative impacts on groundwater quantity and quality.

Usually, a decline in the aquifer's water level is cited as the first sign of intensive abstraction. Over the last decade, systematic measurements provided reliable data to assess the evolution of deep groundwater level in the ZMSLP. In the 1995-2005 period, an average drawdown of 11.7 metres (1.06 m/year) was observed, with minimum and maximum values of 2.4 and 22.9 metres respectively (Conagua, 2005). Drawdown has been observed to be most intense in the southeast and south, where wells are pumping 24 hours a day for urban and industrial supply. The depth of the groundwater level in the first deep wells constructed during the 1950s was between 80 and 100 metres; nowadays, the maximum water level has been found to be between 165 and 170 metres. This confirms an average drawdown of a little more than 1 m/year (Figure 5). The increase in water withdrawal and the localized concentration of pumping is amplifying the zone where levels are depressed. The area in which the depth of the water level is more than 150 metres increased from 23.4 km^2 in 1995 to 70 km^2 in 2005 (Figure 6).

A decline in the water level increases pumping costs as a result of the reduced performance of the wells and equipment. This can eventually lead to the deepening, abandonment, or relocation of wells (Escolero, 1993). As many as 83 wells in the ZMSLP had been so affected by 1995. Data are not available about the efficiency loss in wells; however the water utility reported a 28 percent increase in consumption of electricity in 2002–2003, partly due to production from new, ever-deeper wells (700 m).

In an effort to organize access to water in aquifers subject to intensive use, Conagua opened a water market in 1992. This mechanism has permitted the transfer among users of titles of concessions or allocations that establish the right to withdraw and use an annual volume of water from a specific aquifer. In the aquifer's area, most water transfers took place when small farmers sold their water rights to industries and real-estate developers. This pattern of water transfer has substantially modified the areas where water abstractions are most heavily concentrated, as well as the price of water rights and the profits to be made from its use (Escolero and Martinez, 2007).

Inorganic groundwater contamination caused by the dissolution of minerals from the aquifer is common in many regions of Mexico. During circulation through fractures in volcanic rocks, deep water is enriched by dissolved fluoride, reaching concentrations that exceed the national limit for drinking water (NOM-127-SSA1-1994) of 1.5 mg/l. Fluoride concentration present in samples from deep wells varies between 0.45 and 4.47 mg/l, the higher concentrations being associated with deep wells tapping fractured volcanic units.

In recent years, drilling of new wells has concentrated on fractured volcanic units; results indicate production of more than 80 l/s but also high temperatures and elevated fluoride content (SARH. 1988; Cardona. 1990). By contrast, wells tapping the granular material have lower productivity and better water quality (Carrillo-Rivera *et al*., 2002). Increasing extraction has raised the proportion of wells producing high-fluoride water from 33 percent in 1983 to about 65 percent in 2005 (Table 2). At present, it is estimated that about 550 000 inhabitants of the metropolitan area are exposed to concentrations of fluorine that exceed the limit for drinking water (Ortiz *et al.,* 2006). In order to alleviate this problem, the water utility adopted a strategy based on mixing water from a variety of sources so as to reduce fluoride concentrations before distribution.

In addition, cities that have high fluoride content in groundwater also report concentrations that exceed the national standard (0.7 mg/l) in bottled water, juices and soft drinks. In the ZMSLP, studies results showed high fluoride concentrations in these products (Ortiz *et al.,* 2006; Carreón, 1999). The introduction of fluoride removal processes and monitoring campaigns have helped to standardize production.

URBAN WATER SYSTEMS MANAGEMENT

At present, the ZMSLP's potable water, sewage and sanitation services are provided by a de-centralised public body known as Interapas, its Spanish acronym. Interapas is in charge of operating and maintaining the potable water infrastructure, construction of new water sources, and everything to do with sewage infrastructure up to the point of discharge into the principal collectors. From there on, the State Water Commission (CEA in Spanish) takes over responsibility.

Water supply system

The potable water system covers 96.9 percent of the ZMSLP. Some 1 095 500 inhabitants are supplied by 358 kilometres of primary network, 2675 kilometres of secondary network and 254 937 connections (Interapas, 2005).

Problems related to water supply in the metropolitan area extend well beyond the sources. The system shows serious deficiencies. Inappropriate management, old pipes, inexistent or inadequate maintenance over prolonged periods, and poor construction practices are contributing to supply problems, while large volumes of water are unaccounted for. The absence of a division by sectors in the supply system and of investment in infrastructure leads to problems of low pressure and a lack of transportation capacity. These problems affect 90 717 users who receive only partial supplies.

It is estimated that 36.83 percent of all the water is lost in distribution; 22.87 percent corresponds to losses in connections (Table 3) and 13.96 percent to leakage at the mains (Table 4) (Interapas, 2005). Leaks are commonest in pipes and connections that are 15 to 25 years old, or more than 35 years old. A high incidence is to be expected in the older infrastructure as a result of the corrosion of the principal materials that were used (copper and galvanised iron), and some 31 percent of the leaks occur there. However, the incidence could be expected to be much lower where the infrastructure is

15 to 25 years old. At this juncture, it needs to be pointed out that urban growth reached a peak between 1980 and 1990, as did the consequent demand for basic services. During that period 715 kilometres of pipes were installed and potable water was supplied to 87 980 users. The institutions in charge of the service suffered from technical, economic and management limitations that were reflected in poor-quality materials and lack of supervision. The combination of these two factors contributes to the high percentage of leaks reported in the parts of the system that are 15 to 25 years old. Where materials are concerned, 69 percent of the leaks occur in tubing and connections made with low-quality multi-purpose pipes. In addition, 89 percent of the losses through filling occurred where the filling was earth and stones (sand is the optimum).

Of a total of 90.75 hm^3/year supplied by surface and groundwater sources, 33.43 hm^3/year is lost through leaks; it has also been estimated that 6.39 hm^3/year of water is not accounted for because of errors in micro-measurement and in estimation of the fixed quota (Interapas, 2005). On that basis, the system's physical efficiency has been estimated to be 56 percent. Only 50.94 hm^3/year is billed to the 254 937 registered users (Table 5).

The system's low level of efficiency causes social, economic and environmental problems that can be measured in terms of i) the cost of the construction and operation of 35 deep wells with an average flow of 30 l/s each (equivalent to the losses through leaks); ii) recovery of the aquifer's water level if extraction is reduced by more than 30 hm^3/year; iii) the increase in the costs of construction and public works as a result of the rise in the phreatic level; ii) the benefits for some 180 000 inhabitants who would gain access to potable water; iv) unfairness in payments for the service due to underestimates of the volume billed to major users compared with users whose billing is based on measured consumption.

This situation forced the Interapas to develop a strategy to improve the efficiency of the drinking water system. The strategy currently includes i) sectorisation and rehabilitation of 136 km of water supply mains, ii) substitution of 120 000 water connections, iii) rehabilitation and equipment of 84 wells, iv) the installation of 151 000 micro-meters.

These measures are put into practice by the programme for integral improvement of the management of Interapas that is financed by the National Infrastructure Fund.

In terms of billed volume, the principal user is the domestic sector, which consumes 89 percent of the total by means of 242 367 connections (95 percent). According to the billing register, the sector's annual average consumption is 187 m^3/year.

The commercial and services sectors are supplied by Interapas, and also by wells built and operated by the users themselves. These sectors consume 3.15 hm^3/year from the public network and 2.34 hm^3/year from their own wells, making a total of 5.49 hm^3/year. The profits obtained from the use of water in these sectors are substantial, given that they generate more than 60 percent of employment in the ZMSLP. Industry is basically supplied by private wells that extract a total of 7.1 hm^3/year and, to a lesser extent, from the public network (1.6 hm^3/year) and CEA wells (0.9 hm^3/year). Although industry has improved efficiency in water use as a way gaining access to international markets and in order to reduce costs, the total amount of water reported for industrial use (9.6 hm^3/year) is estimated to be less than the real level of consumption. However, industry is currently the most profitable sector in the ZMSLP, where it produces 80.5 percent of the municipal gross product (PDUSLP, 2000).

Sewer system

The sewer system covers 94.8 percent of the ZMSLP, providing service to some 1 072 000 inhabitants by means of 249 600 connections, a network of 1702 km, and 99 km of collectors and sub-collectors. In the ZMSLP, as in most Mexican cities, urban drainage is achieved by a combined sewer system that works by gravity. This combined system transports both stormwater and wastewater to collectors that discharge at 19 points. The average discharge has been estimated at 69.79 hm^3/year (Interapas, 2005). Domestic wastewater accounts for the bulk of the discharge by means of 237 200 connections (95 percent of the total).

Adequate operation is fundamental considering that overflows and leakage from the sewage system are perceived as the major problems for the sustainability of urban water and human health (Eiswirth, 2001). Data about the system in the ZMSLP is very scarce. Currently, no data is available on whole sewer networks or on the state and operation of the overall network. Management for optimal operation requires reliable knowledge of the system, but that remains a distant goal given growing demand for the service and limited resources.

The ageing infrastructure, the absence of design and planning, and inappropriate construction practices can be assumed to be the main causes of the system's operational problems. Estimates of the age of the infrastructure based on urban growth indicated that 75 percent of the network is more than 25 years old (Table 6). Interapas maintenance records indicate that 9380 metres of pipeline (0.55 percent of the total network) were rehabilitated in the 2001-2004 period. Rehabilitation was concentrated on stretches of piping that collapsed as a result of their age, causing major spills of wastewater. Leaks from a defective network are not readily visible, though several studies have identified this as the dominant of pollution of urban aquifers (Eiswirth and Hötzl, 1997; Wolf, 2006). Consequently, leakage detection and the rehabilitation of damaged sewers are important in the remediation of shallow aquifers. No information is available on defects in the sewer network, nor has the leakage rate been estimated. It is not, therefore, possible to measure the impact on the quality and quantity of the recharge to the shallow aquifer. The absence of monitoring of the sewers prevents the establishment of priorities for rehabilitation and maintenance that would improve the efficiency of the application of the limited resources available for remedial work on the shallow aquifer.

During rain events, the combined system is filled with stormwater that also contains a small proportion of wastewater. Wet weather flows in sewers are estimated often to exceed dry weather flows tenfold (Eiswirth, 2001). During these events, the capacity of the system is frequently exceeded and the water is released into the environment where it causes flooding and pollution. These problems have encouraged the construction of rain collectors with the sole aim of diverting part of the runoff to the periphery. The challenge today is to move from such individual considerations to an integrated management strategy for stormwater reuse.

From the city's very beginnings, and due to its closed-basin characteristics, wastewater was discharged to the periphery following the incline of the terrain. High crop yields and limitations on fresh water are assumed to be the main driving forces behind the use of raw wastewater to irrigate farmland. Some 61 percent of discharges (44 hm^3/year) were used to irrigate 2652 hectares of crops (mainly of maize and lucerne, a fodder also known as alfalfa) located mainly in the municipality of Soledad de G. Sánchez (Cirelli, 2004). Studies have reported the existence of diffuse contamination in the shallow aquifer (Martinez-Banda, 2005), and in Soledad de G. Sanchez the presence of microorganisms (bacteria, protozoa and helminths) in the soil and in the faeces of children (Flores, 1996). The high risk to which the population is exposed as a result of contamination corresponds to the elevated incidences of diseases reported by the health agency. In the municipalities of San Luis Potosí and Soledad de G. Sánchez, microbiological contamination is among the 10 main causes of diseases, and infectious intestinal diseases are the seventh most common cause of death.

Against this background, the local government has undertaken the sanitisation of the area. Over the last decade, the sewer system has been divided by sectors into three basins, known as Norte, El Morro and Tenorio, in accordance with the discharge locations of days gone by. This set the basis for planning of sanitation of the ZMSLP by stages that included the construction of treatment plants and adjustments that would provide good-quality water for some industrial uses and in agricultural irrigation (Figure 7). By 2006, treatment capacity in the ZMSLP had grown to 85 percent, far above the national average of 30.74 percent (Conagua, 2007). However, weak control over wastewater discharges to the sewer system still constitutes a risk for the adequate operation of the treatment plants.

WATER PRICING POLICIES

In the ZMSLP, the Law of Potable Water, Sewerage, Treatment and Disposal of Wastewater by the State and Municipalities of San Luis Potosi (LAATDAR, by its acronym in Spanish) provides the framework for tariffs for these services. The LAATDAR establishes that tariffs must encourage: i) rational consumption, ii) access to these services for low-income groups, taking account of their payment capacity, iii) financial autonomy and self-sufficiency for the service providers, and iv) the direction taken by urban and industrial development. The LAATDAR allows Interapas to set and update tariffs that are meant to cover the costs of service provision, maintenance and rehabilitation of the existing infrastructure, and investment in new infrastructure.

The tariffs in the ZMSLP, as in most of the country, are classified by user type and include a series of crossed subsidies that cause distortions while inhibiting rational use. Attempts to reconcile the different user types and their payment capacity, as well as recovery of service costs, has led to a very large number of billing categories that promote inequality, corruption and inefficiency. As an example, the cost per cubic metre for domestic use increases by 93 percent when it goes up from 30 m^3 to 31 m^3 (and to 40 m^3), while the increase is 30 percent for increments of 40 m^3 to 41 m^3 (and to 70 m^3) (Table 7). A more equitable price structure needs to be devised that takes account of increases by stages from the minimum consumption level.

On the other hand, the average billed tariff since 2002 for domestic use has been 2.43 pesos/m^3, compared with an estimate of 3.39 pesos/m^3 that would be required to cover the costs of the service (Interapas, 2005). It is important to note that the 3.39 pesos/m^3 does not take into account the investments that are needed to ensure continuance of the service and its expansion to meet future demand. This indicates that tariffs need to be increased by approximately 30 percent merely to cover the costs of the service.

One of the main challenges that Interapas faces is the low level of efficiency of the potable water system. Of the 90.75 hm^3/year currently extracted, only 50.94 hm^3/year (56%) is billed. Of the amount billed, only 23.86 hm^3/year (26.3 percent of the total extracted) is metered while the remaining 27.07 hm^3/year (28.8 percent) corresponds to fixed rate (Table 5). Interapas has registered 52 percent of users at fixed rate, while 48 percent have metered service (Table 8). It should be noted that the metered service includes users on the basis of their – real or estimated – consumption over the last three months. Such users account for 57 percent of metered billing and 33 percent of the total amount billed (Interapas, 2005). These distortions show that billing is far from representing real consumption levels, even among users with metered service.

The local authorities have recognized the importance of measuring consumption in order to rationalize the use of resources, and a great number of flow meters have been installed in recent years. However, delays in implementation have led to a large backlog, and the proportion of users whose consumption is metered has failed to surpass 48 percent in recent years. In addition, the register of users, first drawn up in 2001, needs to be updated in order to identify illegal users.

Economic resources hold the key to improving the provision of drinking water. But only 50.4 percent of the total amount owed on bills is recovered, and that proportion has remained fairly constant in recent years. This means that payment is received for only 23.7 percent of the total volume of water produced.

The local government and the water utility have recognized the limitations they face in supplying the population with water. The main problems related to pricing policies whose complexities have been made clear. This has led to recognition of the importance of using economic strategies and instruments in order to meet the challenges that relate to management of urban water systems. Measures such as updates of tariffs and the register of users, along with modernization of meter-reading, billing and debt collection will be implemented as part of a program of integral improvement of the management of Interapas.

DISCUSSION AND CONCLUSIONS

The water management background in the ZMSLP and its main challenges has been described in this paper. The problems are many and complex. On one hand, constraint on new groundwater extractions limits supplies for future growth, and alternative sources are developed outside the urban area. On the other hand, large volumes of water are lost in the supply system, while no use is made of stormwater and resources from the shallow aquifer in order to meet demand for lower-quality water. The resulting mixture merges the needs of a developing city with lack of planning, investment and technology, as well as inefficient management.

The future challenges within urban water management will be to overcome the division of responsibilities for the water supply, urban planning and development that exist among the agencies involved in their provision. This process falls within the concept of integrated water resources management (IWRM), which has been defined as a process that promotes the coordinated development and management of water, land and related resources in order to maximise welfare (GWP, 2004).

The local government and the water utility have recognized the limitations that they face in supplying the population with water. Strategies to be undertaken include a programme for integral improvement of the Interapas management, and the development of alternative water supplies from neighbouring catchments. The Interapas programme encompasses rehabilitation of wells and the distribution system, among other measures, with the aim of increasing overall efficiency to 75 percent. Meanwhile, the El Realito dam on the Santa Maria River that borders on the neighbouring state of Guanajuato, will supply 31.5 hm^3/year (Conagua-Cotas, 2007). This volume means that future next year's forecast demand should be met. However, strategies are required not only to meet growing urban water demands by the traditional means of increasing supply, but also to explore the opportunities offered by integrated management.

New technologies and new solutions need to be developed in order to steer urban water systems towards sustainability. These solutions should encompass supply, quality-dependent consumption, and methods of wastewater and stormwater reuse. Software tools for this task have been developed within the framework of the total urban water cycle – that is, the holistic view of water supply, stormwater and wastewater. (Mitchell and Diaper, 2004). The benefit of a total water cycle view is that it provides a means of assessing conventional and non-conventional approaches to the provision of water supply, stormwater and wastewater services.

Sustainable solutions that need to be introduced include new stormwater systems in order to mitigate floods and to decrease the release of pollutants in the city and in downstream areas. These solutions should be implemented in the construction of new urban areas and infrastructure. A new challenge is the further development of methods for recycling of stormwater for uses such as toilet flushing or aquifers recharge that demand less quality.

In addition, strategies are needed to ensure protection of the shallow aquifer resources, so reversing the current trend towards degradation. In order to be effective, these strategies have to mesh hydro-geological understanding and requirement into land-use policies, and the extension and rehabilitation of sewers, which often have a strong economic foundation. This implies prioritisation and, in effect, the zoning of land on the basis of simple but consistent criteria. Mapping the vulnerability of aquifers to pollution would make a good beginning. The vulnerability concept has some serious limitations in a scientific sense, but it does provide a general framework within which to base groundwater protection policy (Morris et al., 1997). These strategies, together with the use of shallow groundwater to meet lesser quality demands, must be developed in order to ensure water supply and solve the problems associated with a rising water table.

Wastewater treatment has reached levels that are well above the national standard; however, measures are required to promote greater efficiency in re-use. Growing implementation of local solutions will change the city, and technical approaches to the use of non-traditional resources should become standard in the construction of new housing.

Water pricing is the cornerstone of any urban water policy. San Luis Potosí's current situation is not economically viable: water is so cheap that no incentive could exist that would protect its quantity and quality. A change in water policy must include modifications to the tariff structure, with the aim of bring it closer to the principles of "polluter pays" and "user pays". Economic and social development must be accompanied by an increase in the price of water because improvements will require higher water standards. Local government has to pay attention to this linkage. If socio-economic and water goals are properly linked, overall progress will be sufficient to meet the cost of water programs.

Change on this scale represents an immense task, but innovative water technologies, management systems and institutional arrangements must be introduced in order to meet the goals of equity, environmental integrity and economic efficiency.

ACKNOWLEDGEMENTS

The authors appreciate the support they received from the General Head of Postgraduate Studies and the Geology Institute of the Universidad Nacional Autónoma de México.

REFERENCES

Biswas, A.K. (2006) Water management in the 21st century for the developing world, Lecture at Phnom Penh, Cambodia, http://www.thirdworldcentre.org/publi.html Cited April 2008.

Cardona, A. (1990) Caracterización físico-química y origen de los sólidos disueltos en el agua subterránea del Valle de San Luis Potosí: Su relación con el sistema de flujo, Tesis Maestría, Facultad Ingeniería, Universidad de Nuevo León, México, p. 97.

Cardona, A. and Garcia-Rangel, A. (2003) Diffuse contamination assessment in shallow groundwater of San Luis Potosi: effects of wastewater management. Paper presented at the 1st International workshop on aquifer vulnerability and risk, Celaya, Mexico, 28-30 May 2003.

Cardona, A., Garcia-Rangel, A., Carrillo-Rivera, J.J. (2004) Wastewater contamination affecting local flow systems, implications on intermediate and regional systems used for water supply, San Luis Potosi, Mexico. Paper presented at the XXXIII Congress IAH and 7th Congress ALHSUD, Zacatecas, Mexico, 11-15 October 2004.

Carreón, M.S. (1999) Determinación analítica de fluoruros en las bebidas carbonatadas (refrescos) que se consumen en la ciudad de San Luis Potosí, Tesis, Facultad de Ciencias Químicas, UASLP, SLP, México.

Carrillo-Rivera, J.J. and Armienta, M. (1989) Diferenciación de la contaminación inorgánica en las aguas subterráneas del Valle de la ciudad de San Luis Potosí, SLP, México. Geofísica Internacional, 28(4), pp. 763-783.

Carrillo-Rivera, J.J., Cardona, A., Edmund, W.M. (2002) Use of abstraction regime and knowledge of hydrogeological conditions to control high fluoride concentration in abstracted groundwater: basin of San Luis Potosi, Mexico. Journal of Hydrology 261, pp. 24-47.

Cirelli, C. (2004) Agua desechada agua aprovechada, El Colegio de San Luis A.C., San Luis Potosí, México.

Conagua (1996) Estudio hidrogeológico de la contaminación del agua subterránea en la zona industrial de SLP. Informe técnico. Realizó: Geoingeniería Internacional.

Conagua (2004) Manejo integrado y sostenible del agua en la Región Centro de San Luis Potosí. Informe OMM/PROMMA Nº 190. Realizó: Organización Meteorológica Mundial.

Conagua (2005) Actualización hidrogeológica de los acuíferos de Ceballos y Oriente Aguanaval Edo de Dgo, Villa de Arista y San Luis Potosí, Edo de SLP. Informe técnico. Elaboró: Sabinfosistem SA de CV.

Conagua (2006) Water in Mexico, Document printed for 4th World Water Forum, México.

Conagua (2007) Estadísticas del agua en México, Secretaria de Medio Ambiente y Recursos Naturales, Comisión Nacional del Agua, México.

Conagua - Cotas (2007) Estudio para determinar el modelo de explotación del agua disponible en el Valle de San Luis Potosí, considerando la demanda actual y futura, bajo un marco de sustentabilidad, Informe Final, SLP, México, p. 121.

Conagua, (2008) Estadísticas del agua en México, Edición 2008. Secretaria de Medio Ambiente y Recursos Naturales, Comisión Nacional del Agua, México.

Eiswirth, M. and Hötzl H. (1997) The impact of leaking sewers on groundwater, in J. Chilton and *el at.* (Eds) *Groundwater in the urban environmental*, Vol.1, Problems, process, pp. 399-404, Balkema, Rotterdam.

Eiswirth, M (2001) Hydrogeological factors for sustainable urban water systems, in K. Howards and R. Israfilov (Eds) *Current problems of hydrogeology in urban areas, urban agglomerates and industrial centers*, pp. 159-183, Kluwer.

Escolero, O. (1993) Panorámica del agua subterránea en México, in: *El Agua: Recurso Vital*, Universidad Tecnológica de la Mixteca. Acatlima, Huajuapan de León, Oaxaca, México, pp 37-52.

Escolero, O., and Martinez, S. (2007) The Mexican experience with groundwater management, in: Bergkamp, G. and McKay, J. (Eds) *The global importance of groundwater in the 21st century*, pp. 97-103, NGWA Press.

Flores, L.M.L. (1996) Evaluación de riesgo en la salud en el Municipio de Soledad de Graciano Sánchez, Tesis, Facultad de Ciencias Químicas, Universidad Autónoma de San Luis Potosí, México, p 45.

Gallegos, G.Y. (2002) Una interpretación hidrogeoquímica del acuífero profundo del Valle de San Luis Potosí: Información para una estrategia de abastecimiento. Tesis, Maestría, Facultad de Ingeniería, Universidad Autónoma de San Luis Potosí, México, p 282.

Global Water Partnership – GWP, (2004) Catalyzing Change: A handbook for developing integrated water resources management (IWRM) and water efficiency strategies, http://www.gwpforum.org/gwp/library/handbook.pdf Cited June 2007

H. Ayuntamiento de San Luis Potosí (2003) Plan del centro de población estratégico San Luis Potosí-Soledad de Graciano Sánchez, Proyecto de actualización 2003.

IIZD–UASLP (1961) Estudios geohidrológico y físico-químico de los suelos en el Municipio de Soledad Diez Gutiérrez, San Luis Potosí. Informe técnico, México, p. 39.

INEGI (1999) Censo económico, Instituto Nacional de Estadística, Geografía e Informática, México.

Interapas (2005) Estudio de diagnóstico y planeación integral. Informe técnico. Realizó: Tecnología ASSUL SA de CV.

Martinez, S. (2005) Los dilemas de la urbanización en zonas áridas: una visión de San Luis Potosí desde la hidrogeología urbana y la geografía regional, Tesis Maestría, Facultad de Filosofía y Letras, Universidad Nacional Autónoma de México, México, p. 117.

Martinez, S., Delgado, J., Escolero, O., Domínguez, E., Suárez, M., (in press) Socio-economic development in arid zones: The influence of water availability in the San Luis Potosí Basin, Mexico, in: A. Fernandez-Bernal and M. A. De La Rosa (Eds) *Arid Environmental*, Nova Science Published, New York.

Martínez-Banda, L. (2005) Identificación de la contaminación difusa en el acuífero somero de la ciudad de San Luis Potosí, Tesis, Facultad de Ingeniería, Universidad Autónoma de San Luis Potosí, México, p 106.

Mitchell, V.G.; Diaper, C. (2004) UVQ: a tool for assessing the water and contaminant balance impacts of urban water development scenarios. Paper presented at the IWA world water forum. http://www.urbanwater.de/results/publications/mitchell-diaper-uvq-iwa-2004.pdf. Cited June 2007.

Morris, B.L., Lawrence, A.R., Foster, S. (1997) Sustainable groundwater management for fast-growing cities: mission achievable or mission impossible?, in: Chilton et. al.

(Eds) *Groundwater in the urban environment: problem, processes and management*, pp. 55-66, Balkema, Rotterdam.

Ortiz, P.M., Bocanegra, S.M., Landín, R.L. (2006) Evaluación de la contaminación por flúor y arsénico en el agua de pozo para consumo humano de las zonas centro, altiplano y media del estado de San Luis Potosí. Universidad Autónoma de San Luis Potosí.

PDUSLP- Plan Estatal de Desarrollo Urbano del Estado de San Luis Potosí 2001-2020 (2000) Elaboró: Gobierno del Estado de San Luis Potosí, Universidad Autónoma de San Luis Potosí.

Rodriguez, R. (2003) The role of the urban areas in aquifer vulnerability assessments, the Salamanca Mexico case, Geofisica Internacional 43(4), pp. 583-589.

Sandoval, R. (2004) A participatory approach to integrated aquifer management: The case of Guanajuato State, Mexico, Hydrogeology Journal 12, pp. 6-13.

SARH (1988) Estudio geofísico geohidrológico del Valle de San Luís Potosí. Informe técnico. Realizó: Instituto de Geofísica UNAM.

Stretta, E. and del Arenal, R. (1960) Estudio para el abastecimiento de agua potable para la ciudad de San Luis Potosí, Instituto de Ciencias Aplicadas, UNAM, México, p.32.

Tortajada, C. (2006) Water management in Mexico City Metropolitan Area, Water Resources Development, 22(2), pp.353–376.

Vargas, C. (1994) Los acuíferos de la cuenca de San Luís Potosí, Manejo integral de información química de aguas subterráneas, Informe técnico, UASLP, UNAM, Consejo Británico. México.

Wolf, L (2006) Influence of leaky sewer system on groundwater resource beneath the City of Rastatt, Germany, Doctoral thesis (in English), University of Karlsruhe, Karlsruhe, Germany, p. 205.

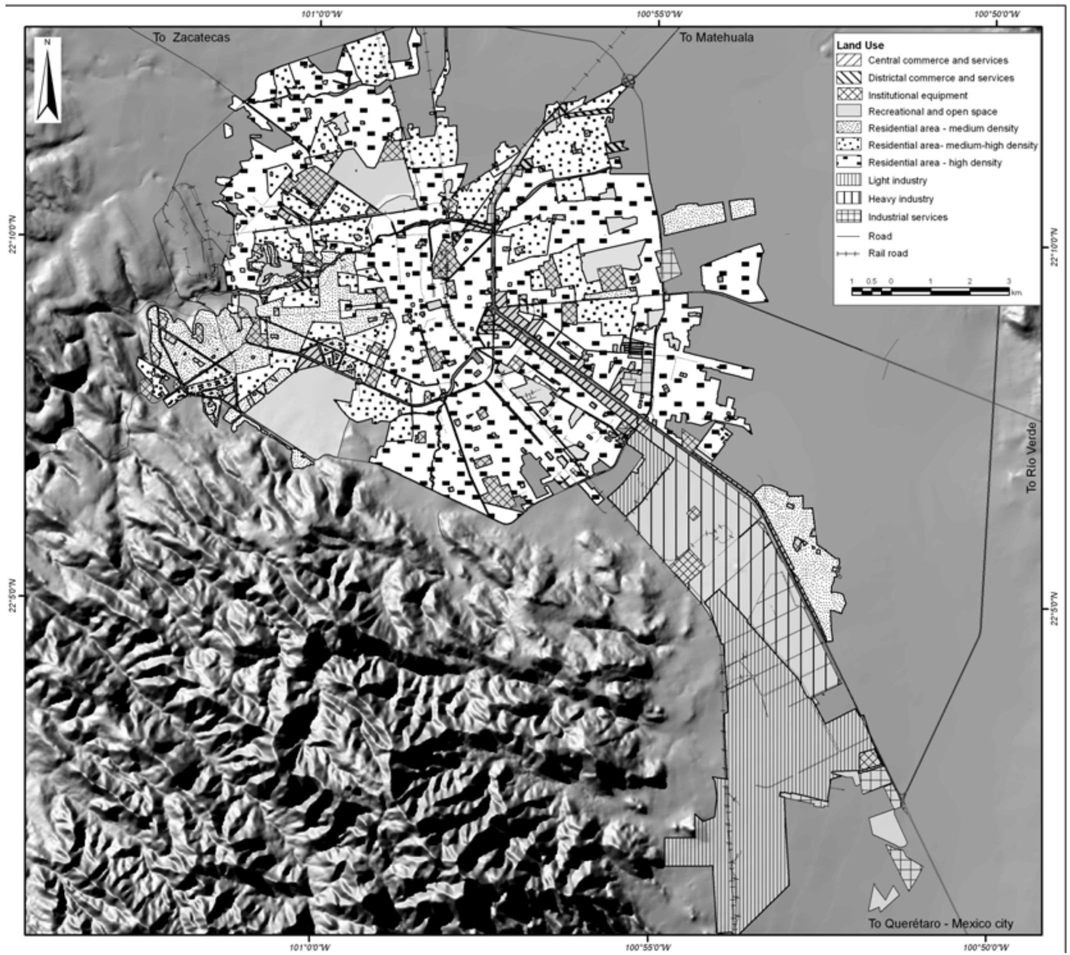

Figure 1. Simplified land use in ZMSLP

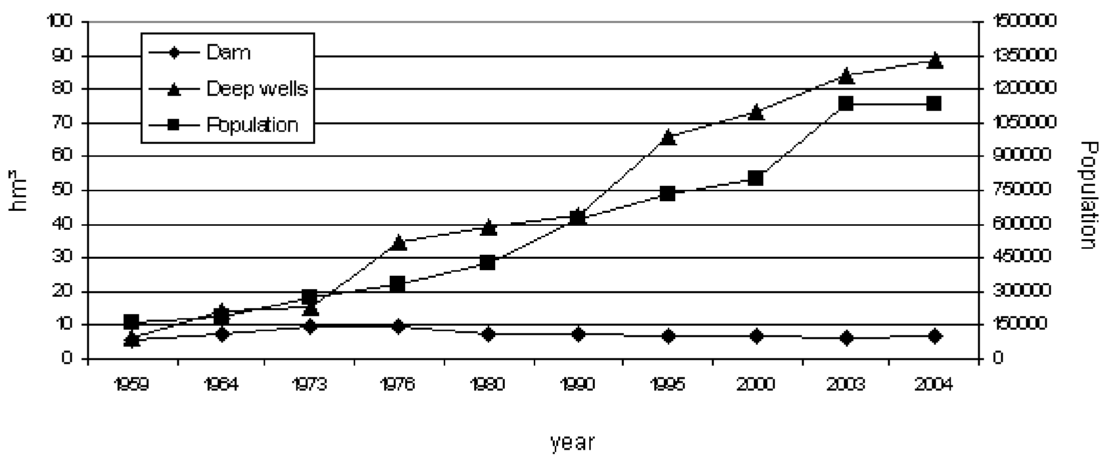

Figure 2: Development of water sources and growth of population

Figure 3. Groundwater infiltration in Hernán Cortés Stormwater collector (December, 2007)

Figure 4: Cellar flooding in Díaz Infante Hospital building (January, 2008)

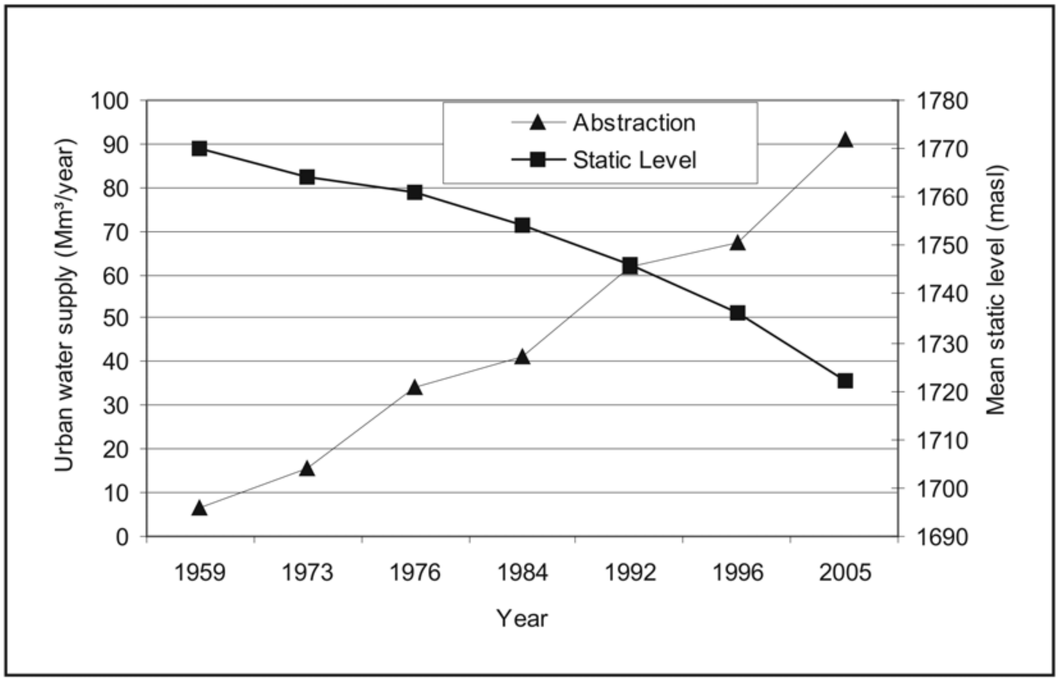

Figure 5. Evolution of static level and abstraction for urban supply

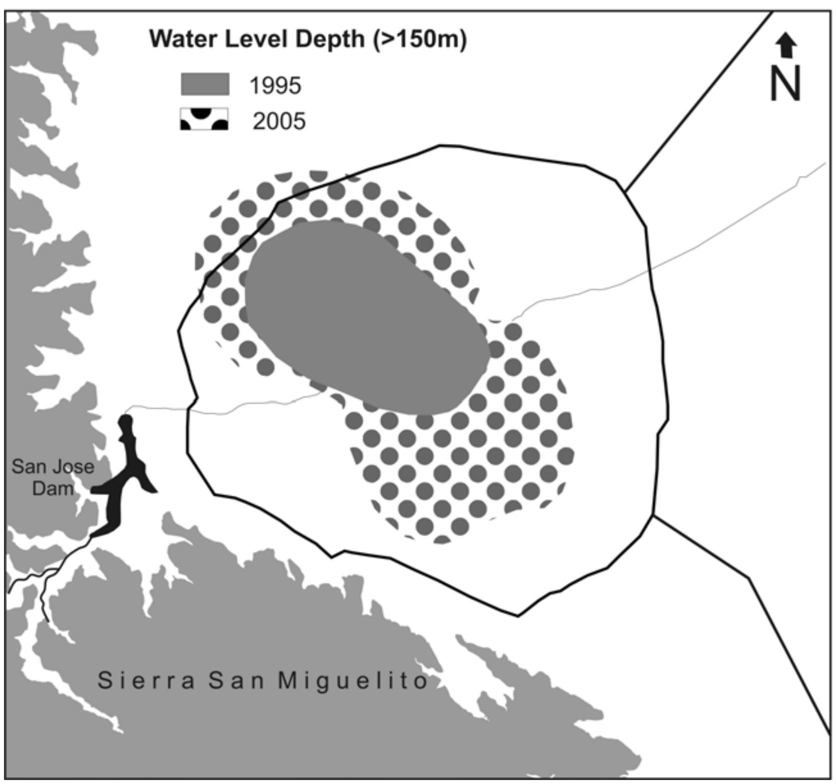

Figure 6. Spatial evolution of water level depth in deep aquifer

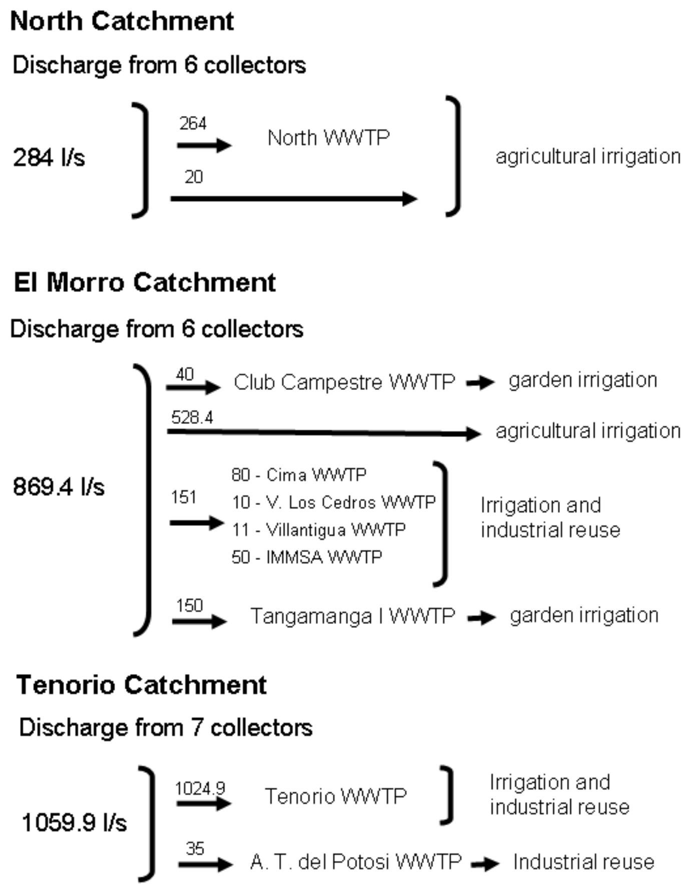

Figure 7. Overview of treatment and reuse in sanitary catchments of ZMSLP

Dam	Principal River	Drainage area (Km^2)	Storage capacity (hm^3)		Year of construction
			Inicial	Actual	
San Jose	Santiago river	265	8.2	4.56	1905
El Peaje	Grande o Azul stream	81	8.0	6.65	1950
El Potosino	El Potosino river	57	0.76	0.76	1988

Table 1: Principal characteristics of the dams that constitute the system for use of surface water.

Year	Nº wells sampled	Fluoride concentration (mg/l)	% wells exceeding the standard (1.5 mg/l)
1983	21	0.2 – 4.2	33.3
1987	45	0.2 - 3.6	46.6
1989	55	0.4 - 4.0	56.4
1995	62	0.2 - 4.0	56.4
2003	117	0.04 – 5.54	64.9
2005	116	0.45 – 4.47	64.6

Table 2. Increase in fluoride concentration in wells

Infrastructure age	Connections with leakage	Average leakage (l/s)	Leakage in connections (l/s)	Index of system use [a] (%)	Total leakage in connections (l/s)
0-15	405.00	0.029	11.74	94.7	11.12
15-25	5515.00	0.037	201.34	94.7	190.68
25-35	3626.00	0.034	123.7	94.7	117.15
+ 35	8143.00	0.044	358.4	94.7	339.42
Total	17689.00		695.2		658.36
				Total water supply (l/s)	**2878**
				Total leakage in connections (%)	**22.87**

Table 3: Leakage volume in connections

[a] Percentage of system with uninterrupted supply
Source: Interapas (2005).

Age of infrastructure	Length of mains [b] (km)	Average leakage (l/km/h)	Leakage in mains (l/s)	Index of system use [a] (%)	Total leakage in mains (l/s)
0-15	60.39	1467.053	24.61	94.7	23.31
15-25	715.53	964.977	191.80	94.7	181.63
25-35	414.07	762.338	87.68	94.7	83.04
+ 35	934.51	462.902	120.16	94.7	113.79
Total	2124.50		424.25		401.77
				Total water supply (l/s)	**2878**
				Total leakage in mains (%)	**13.96**

Table 4: Leakage volume in mains

[a] Percentage of the system with uninterrupted supply
[b] Length of mains measured in plans by Interapas
Source: Interapas (2005).

User	Total Connections	% Connections	Connections with partial service	Volume billed (hm^3/year)			% Billed
				Metered	Estimated	Total	
Doméstico	242 367	95.1	87 034	20.14	25.19	45.34	89.0
Comercial	10 808	4.2	3348	2.04	1.11	3.15	6.2
Industrial	698	0.3	202	0.99	0.42	1.41	2.8
Instituciones públicas	1069	0.4	135	0.69	0.35	1.04	2.0
Total	254 937		90 719	23.86	27.07	50.94	

Table 5: Volume of water billed (year 2003)

[a] Volume estimated by fixed quota and average consumption.
Source: Interapas (2005).

Network	Diameter (cm)	Length (Km.)	Age of infrastructure (%)			
			0-15	15-25	25-35	+ 35
Sewer	20-30	1702	9	21	41	29
Sub-collectors	38-45	29	10	21	38	31
Collectors	61-183	70	1	9	57	33
Open channel	-	3.5	-	-	-	-
Total		1804.5	153.2	357.4	697.8	493.6

Table 6: Basic characteristics of the sewer system

Source: Interapas, estimates based on urban growth

Domestic users with fixed rate (billed every two months)			
Low-income	S.G.Sanchez economic	San Luis Potosi economic	Upscale housing
44.98	71.3	89.28	262.5

Domestic users with metered service (billed every two months)	
Consumption rate (m^3)	**pesos/m^3**
Minimum consumption (to 10)	16.32
to 30	1.61
to 40	3.11
to 70	4.15
to 100	5.47
to 200	6.76
to 250	10.7
+ 250	16.98

Table 7: Structure and cost of domestic water tariff (in Mexican pesos)
Tariff in use from 2002. An additional 15 percent is charged for sanitisation.
Source: Interapas.

User	Number of users				Total
	Fixed rate	%	Metered service	%	
Domestic	126942	52	115425	48	242367
Commercial	4069	38	6739	62	10808
Industrial	52	7	646	93	698
Public Inst.	548	52	516	48	1064
Total	131611	52	123326	48	254937

Table 8: Users' register (2003)
Source: Interapas

CAPÍTULO V. QUANTIFYING THE TOTAL URBAN WATER CYCLE AS TOOL TO INTEGRATED MANAGEMENT. RESULTS TO THE AREA OF SAN LUIS POTOSÍ, MEXICO

Sandra Martínez, Oscar Escolero, Leif Wolf

Artículo preparado para enviar a
“Water Resources Management”

Quantifying the total urban water cycle as tool to integrated management. Results to the area of San Luis Potosi, Mexico

[1]Sandra MARTINEZ, [2]Oscar ESCOLERO, [3]Leif WOLF

[1]Posgrado en Ciencias de la Tierra, Instituto de Geología, Universidad Nacional Autónoma de Mexico, Ciudad Universitaria, Coyoacan 04510, Mexico City, Mexico. seddam2002@yahoo.com.mx
[2]Departamento de Geología Regional, Instituto de Geología, Universidad Nacional Autónoma de Mexico, Ciudad Universitaria, Coyoacan 04510, Mexico City, Mexico. escolero@geologia.unam.mx
[3] Department of Applied Geology (AGK), University of Karlsruhe, Kaiserstr.12, 76128 Karlsruhe, Germany wolf@agk.uka.de

Abstract

Systems view thinking and holistic urban water cycle concepts are increasingly called upon for integrated analysis of urban water system to mitigate water stress in large urban agglomerations. However, integrated analysis is frequently not applied due to the inherent complexity, limitations in data availability and especially the lack of guidelines and suitable software tools. The paper presents the application of the total urban water balance model UVQ to the City of San Luis Potosi (1,2 Mio inhabitants) under the arid conditions of Northern Mexico. UVQ is a lumped parameter model which describes water and contaminant flows from source to sink in urban areas and includes all water types such as rainwater, imported water, surface runoff, wastewater and groundwater. The results were especially useful for spatially explicit groundwater recharge calculation in urban areas. A range of urban water scenarios, including different supply strategies and the effect of externalities such as demand change, were simulated and compared to a calibrated baseline scenario. The analysis demonstrated that especially the shallow urban groundwater resources can substantially mitigate problems of water scarcity and overexploitation of deep aquifers if appropriate water quality protection or fit-for-use paradigms are put into place. The modelling exercise delivers relevant information for the decision making process and identifies the most relevant shortcomings in current monitoring systems. This represents a key step on the path to water sensitive and sustainable urban development, including the urban aquifers which have been neglected in the management policy of most cities of the Mexican arid zone.

1. Introduction

Recently, water resources management is changing from a focus devised to supply-side solutions to a focus on integrated management. Driving forces such as increasing urbanization, population growth, and rising water demand have enlarged the anthropogenic footprint on the hydrologic cycle. In urban areas, the process of urbanisation and development has changed significantly the inputs and outputs creating highly inefficient systems in terms of utilisation and degradation of water resources. This is particularly true for many cities of Mexican arid zone situated above of a productive aquifer, with high growth rate and, only rudimentary environmental legislation and urban regulate. Table 1 summarizes the threats currently faced by major cities in Mexico.

This background calls for an increased awareness of the total water resources available in urban areas and appropriate, long-term management practices.

The emergent paradigm of integrated urban water management promotes the consideration of water supply, stormwater, and wastewater as components of the total urban water cycle. The view of total urban water cycle provides the knowledge of the interaction between the different flows and increases the range of opportunities for more sustainable solutions to be tailored to local circumstances.

Recently, a model called UVQ (Urban Volume and Quality) has been developed by CSIRO, Australia within the AISUWRS project (Assessing and Improving the Sustainability of Urban Water Resources and Systems) (Wolf et al. 2006[b]). The UVQ model overcomes the typical representations of the urban water cycle (Mitchell et al, 2003[a]) integrating the water flows and contaminants of both, man-made and natural systems.

In this paper, UVQ model is applied to quantify the urban water and contaminant balance, as well as to detail the flow paths and contaminant concentrations within the San Luis Potosi Metropolitan Zone (ZMSLP, by its acronym in Spanish) in Mexico. The study was undertaken to illustrate the impact of urbanization and management practices on the water cycle, assess the effect of changes on the system in terms of the recharge components, and to demonstrate the suitability of the approach for developing more sustainable urban water systems.

This study is a step on the pathway to water sensitive and sustainable urban development, including the urban groundwater resources, which have been neglected, and omitted of management strategies due to contamination. The strategy is supported by the ability of UVQ to be coupled to other tools such as pipe leakage and groundwater flow models.

2. Materials and Methods

2.1. Study area description

The ZMSLP, located approximately 400 km northwest of Mexico City, encompasses the cities of San Luis Potosi and Soledad de G. Sánchez with an estimated population of 1,1 million inhabitants.

The metropolitan zone lies in the San Luis Potosi valley at an altitude between 1850 and 1900 m a.s.l. and is flanked by the Sierra San Miguelito in the west and Cerro San Pedro in the east. The area is a horst and graben structure with a sequence of about 1700 m of Tertiary fractured lava flow, tuff and ignimbrites that cover the inferred hydrogeological basement (Carrillo-Rivera el al. 1996). The graben's fill is a clastic sequence of gravels, sands, silt and clays derived from the Tertiary volcanic rocks. These sediments are inter-bedded with pyroclastic material and are referred to as Tertiary Granular Undifferentiated (Carrillo-Rivera el al. 2002). The granular sequence reaches a maximum thickness of 450 m, and includes a 50 to 150 m thick bed of fine-grained compacted sand. This layer extends over about 300 km^2, underlying most of the flat part of the valley, except at the edges, and permits the separation of two aquifers in a vertical direction (Figure 1). The connection between both aquifers is limited by the low hydraulic conductivity of the compacted sand layer (on average 10-9 m/s) that limits vertical percolation (Carrillo-Rivera et al. 2002).

The shallow unconfined aquifer is situated in the alluvial material that overlies the compacted sand layer. The water table in the urban area lies between 2.4 m and 12.1 m below the surface, meaning that sewers are situated above the groundwater table. The deep aquifer encompasses both the granular sequence and the fractured volcanic rocks. It is confined by the compact-sand layer over most of the flat part of the valley. Due to the regional distribution of the volcanic rocks the recharge area stretches out far beyond the valley limits.

The ZMSLP is one of the key urban centres of the Mexican arid region, with remarkable socio-economic development in recent decades. The growing urban water demand has been met almost exclusively by groundwater extraction. About 94% of the total urban water supply is abstracted from wells that capture the deep aquifer, and only 6% is provided from the San José Reservoir that collects intermittent runoff from the Sierra San Miguelito. Intensive groundwater use has resulted in negative impacts in terms of i) water level drawdown (Conagua, 2005), ii) increases in pumping costs (Interapas, 2005), iii) land subsidence and surface fracturing (Trueba, 2005), and iv) induced changes of the natural groundwater quality (Carrillo-Rivera et al, 1996). The shallow aquifer covered most of the total water demand from the end of the 16th century until the 1950s, when shallow wells were progressively abandoned due to contamination and the drinking-water network fed by deep wells was installed (Martinez et al, in press).
The balance area that has been considered for this publication covers 14 754 hectares. Table 2 lists the key features of this study area:

2.2. Urban water and contaminant cycle

To simulate the integrated urban water system, the urban water and contaminant balance model Urban Volume Quality - UVQ (Mitchell and Diaper, 2005[a]) was used. UVQ is a conceptual model with daily time steps that combines the man-made and natural systems into a single framework using simplified algorithms and conceptual routines to provide a holistic and integrated view of the urban water cycle. The model estimates the contaminant loads and the volume of water flowing through the urban area, from sources (precipitation and imported water) to discharge points (e.g. drainage systems or groundwater), providing a method to estimate onsite infiltration (Figure 2).
The UVQ approach represents the water services in a flexible way and provides a tool for assessing the impacts of conventional and non-conventional water supply, stormwater and sanitation options for either an existing urban area or a site which is to be urbanised (Mitchell and Diaper, 2006). The flexibility of the model was tested for a range of existing urban water supply and disposal scenarios in cities of Europe and Australia, where groundwater constitutes the principal drinking water source (Klinger et al, 2006).

Three nested spatial scales are used in UVQ to simulate the urban area therefore input parameters must be defined for each one: The land block represents a building and associated indoor and outdoor water usages as well as paved and pervious areas (roof, paved and gardens). The neighbourhood comprises a number of identical blocks as well as roads and public open space. The study area represents the grouping of one or more neighbourhoods that may or may not have the same land-use or water-servicing approach. The stormwater and wastewater flows from one neighbourhood to another can be represented and have to be specified by the user.

Required climate input data are representative daily rainfall and potential evaporation time series for the whole simulation period.

Data describing contaminant concentrations for outdoor water and contaminant loads for the indoor water use are required. The use of contaminant loads rather than event mean concentrations in these instances allows the model to account for changes in water demand or quality of water used within the house (e.g. non-potable water recycle) on the contaminant concentrations in the wastewater.

2.3. UVQ setup

Due to the large number of processes considered, UVQ requires more than a hundred different input parameters which were acquired and processed. An overview of the input and calibration parameters is shown in Table 3.

To account for the climatic conditions UVQ requires records of daily potential evaporation and precipitation. The meteorological office of the National Water Commission in San Luis Potosi provided the complete daily records from 1989 to 2006.

Both criteria, similar land use and sewer system (combined or separate) provide the means to identify neighbourhood types. As ZMSLP is characterized by a combined sewer system, neighbourhood types were defined for similar land uses which are homogeneous in terms of water use and occupation rates. A land use classification for town planning (HASLP, 2003) has been simplified, resulting in ten neighbourhood types that represent the dominant land uses in the urban area (Figure 3). This was facilitated by the fact that neighbourhoods in UVQ do not necessarily have to be spatially continuous. Cadastral data on the level of individual lots are not available for the whole urban area; therefore, land blocks were defined by groups of lots generally delimited by streets.

Specification of the impervious and pervious area at both, neighbourhood and land block scale is important for the runoff- and infiltration process. The data for both scales were gathered through the aerial imagery and GIS analysis (Table 4). Typical blocks were selected for each neighbourhood in order to calculate the average garden, roof and paved areas, as well as the percentage of irrigated garden. Due to the importance of irrigation with treated wastewater in recreational areas and public open spaces, the percentage of irrigated areas was determined for the whole neighbourhood by interpretation of aerial imagery and GIS analysis. The process was facilitated by the local climate characteristics that allow for quick identification of irrigated areas during dry season.

The average occupancy was obtained by spatial analysis of the official data for the so-called geo-statistical units (AGEB´s, for its Spanish acronym). Therefore, the average number of inhabitants per land block was estimated for each neighbourhood, maintaining consistency with the total population supplied in the study area.

From the average occupancy and water consumption data for the domestic, industrial, commercial and institutional sectors, we estimated the water use per capita in each neighbourhood. This step also required the quantification of water losses from pipe leakage and water usage for garden irrigation prior to consumption. Average physical water losses in the water supply network have been estimated as 36.8% by the local water utility (Interapas, 2005). The average water use per capita was calculated in 160 l/cap/d, estimating 4% of this being consumption for irrigation.

UVQ requires indoor water consumption to be broken down based on where the water is used (e.g. kitchen, toilet). These data could not been found for the local and national context, therefore, literature values have been used (Rueedi and Cronin, 2005). In the industrial neighbourhoods the majority of wastewater is considered black water and therefore represented via the toilet flow balance element in UVQ (Cook et al, 2005).

Data on contaminant loads that are produced by in-house water use are based on the field assessment undertaken for the calibration process. Contaminant concentrations for imported drinking water are based on the water quality data provided by the water utility.

Rainfall quality data were obtained from six stations installed in the urban area, which collected rainfall during one year. Likewise, data on contaminant concentrations in runoff were measured, distinguishing road-, roof- and pavement runoff (Table 5). The first flush runoff values were considered the double of the concentration of subsequent roof runoff (Mitchell and Diaper. 2005[b]). Fertilizer application to gardens is not common in San Luis Potosi. Nevertheless, recreation areas and open spaces are partially irrigated with treated wastewater. Input values for “Fertilizer to garden” were estimated based on contaminant concentrations measured at the discharge points of wastewater treatment plants. These values were applied only to the before mentioned areas, as wastewater irrigation in private gardens is not a habitual practice.

2.4. Calibration process

The model takes into account 18 calibration parameters that control stormwater, wastewater and potable water flows. Due to the fact that UVQ simulates an integrated water system each calibration parameter can influence more than one of the simulated output flows; therefore a good understanding of the relations between model parameters is crucial in the calibration process.

In a first step, water flow quantities have been calibrated with respect to local observed data. This includes combined and imported water quantities, as well as recharge volumes. The observed value for imported water is based on the volume abstracted annually for the urban area from deep wells and the San José Dam (approx 98.8 hm^3). Wastewater flows were compared with the results of measurement campaigns carried out by the water utility for the whole area (recalculated for the whole year). The influence of stormwater on the combined sewage system is taken into account by using a parameter called percentage of surface runoff as inflow. Initially, this parameter was set to zero until the observed values were matched.

UVQ calculates the surface runoff based on the impervious area and its drainage characteristics. However, no measurements have been carried out to define these drainage characteristics. These parameters were adjusted base on literature data. To account for the initial losses from impervious surface (depending on surface roughness), it was assumed that surface runoff occurs when daily rainfall exceeds 1 mm (for roofs and paved areas) and 2 mm (for roads) respectively. The effective area refers to the part of impervious area that is connected to the sewer system. Field observations in the urban area showed that most of the impervious areas in residential and commercial neighbourhoods are connected to the sewer system, wherefore the effectiveness of impervious surfaces was set between 90-100 %. In industrial neighbourhoods the reduction of effective area to 80% considers potential losses leading to runoff into the surrounding garden area.

The soil parameters have been adjusted to meet a natural groundwater recharge typical for San Luis Potosi. A recharge value of approx. 10% of the local precipitation was proposed by Cardona (2005), based on the Cl^{-}-$SO4^{2-}$ concentration relationship in shallow groundwater and rainwater samples of the study area. Based on the soil characteristic, a maximum storage capacity of 300 mm was assumed and the field capacity was adjusted to be 30 mm. The maximum daily drainage depth was set to 30 mm. This was done to ensure that no surface runoff occurs for precipitation events smaller than 30 mm. Sensitive parameters linked to the infiltration process have been determined by Ruedi and Cronin (2005). The drainage factor could not be identified as a sensitive parameter, given that this concept has been strongly simplified within UVQ. Variations of this ratio between 0 and 1 just lead to slight changes in groundwater recharge for the study area, wherefore it was decided to use the default value of 0.5.

Under the assumption that gardens are only irrigated when it is needed and that the irrigation volumes exactly cover the demand, the trigger to irrigate was calibrated using the quantities of treated wastewater and imported water set to irrigation.

In the second calibration step, modelled contaminant concentrations and loads had to be adapted to real world observations. This step was performed by discharge measurements and chemical analysis of wastewater at the outlet of a small single catchment. Therefore a predominantly residential catchment of 117 ha and approx. 11 400 inhabitants was chosen, covering the Balcones, Himno Nacional and Graciano Sánchez areas. A separate model was built for this small catchment and the results were extrapolated to the study area.

Water sampling in sewers provided average contaminant concentrations in the domestic sewage, which were used to estimate the concentrations in each compartment and therefore contaminant loads produced by each in-house water use. The results shown in Table 6 reveal that the model reproduces satisfactorily the measured concentrations with only small deviations. Therefore, the results confirm properly the input loads used on household scale for this urban setting.

Discharge measurements at the outlet of the pilot catchment allowed for assessing the representativeness of the modelled flow and estimating the percentage of surface runoff as inflow to the sewer system. The discharges modelled reproduce a satisfactory approximation of the discharge measured during the dry weather period, but the model fails to model changes in the daily usage pattern. Discharge quantities measured at the outlet of the catchment during dry weather days vary from 1614 to 2453 m^3/d. UVQ instead calculates a constant discharge of 2427 m^3/d, due to the fact that daily changes in demand (e.g. holidays and weekends) are not represented (Figure 4). Nevertheless, these effects are considered of limited importance for the flows measured in the catchment as well as for the total urban area. Therefore, the approximation to the real discharge quantities was considered satisfactory.

Complications occurred with respect to the flow measurements during and following rain events. It has to be taken into account that the combined sewer system of the metropolitan area was designed 50 years ago. As consequence of accelerated city growth and the lack of urban planning, the capacity of the system is frequently exceeded, even during medium intensity precipitation events. Therefore, the inflow of stormwater to the sewer system can just be estimated. Figure 4 shows a comparison between the measured and modelled flow volumes at the outlet of the testing catchment, during a rain event (21.8 mm) on July 19, 2008. Based on this, we estimated a 70 % of stormwater discharge to the combined sewer system. This result was transferred to the whole study area.

2.5. Estimating exfiltration and infiltration

The position of the sewer network relative to the groundwater level indicates the potential for exfiltration or infiltration. If a pipe is positioned above the water level exfiltration of wastewater occurs, whereas otherwise infiltration of groundwater to the pipe prevails. As calculations of exfiltration and infiltration are not performed in the UVQ model, these parameters have to be determined separately.

In order to obtain the groundwater level plot, water level depth was measured during dry season in about 90 shallow wells located in the urban area. Variations in groundwater levels have not been included in this analysis, due to the lack of historic records.

Digital maps of the sewer network are available for about 2/3 of the area urban, including information on pipe diameter, length and depth. The values of pipe depth for the rest of the area were deduced following general engineering practice.

The determination of the distance to groundwater or the water column above the pipe was performed by a GIS query. Like this, the pipe's position relative to the groundwater level was determined for each manhole. The results show that more than 99% of the manholes lie above the water table, therefore exfiltration prevails in the urban area. Figure 5 illustrates that the sewers generally lie between 2 - 7 meters above the water table (89% of the manholes) and that only 0.3% of the network is situated in the zone of groundwater fluctuation (verbal communications with owners of shallow wells indicate that the water levels rise about 0.50 meters during the wet season.

No data or estimations on sewer defects and pipe leakage are available in the study area, as is the case in most urban areas. In order to obtain an exfiltration rate for the ZMSLP, we considered data derived from modelling exercises performed within the AISUWRS project (Wolf et al, 2006[a]). Data have been obtained for three case study cities, using the Network Infiltration and Exfiltration Model, NEIMO (DeSilva el at, 2006). NEIMO is currently the most advanced and detailed modelling tool available for this purpose. The calculated exfiltration rates for the study cases are 9.19 l/d/m for the city of Rastatt (Wolf, 2006), 3.64 l/d/m for Doncaster (Morris et al, 2006) and 10.2 l/d/m for Ljubljana (Souvent et al, 2006). Taking an average of the exfiltration rates from these study cases and based on the length of the sewer network, an exfiltration rate of 34 mm/y was calculated for the study area of the ZMSLP. Still. This is a rather conservative estimate, since the sewer condition is likely to be worse in San Luis Potosi.

3. Results

To generate the daily water balance for the ZMSLP, the reference year 1998 was chosen, which represents the characteristic climatic conditions within the time line 1989–2006. From the calibrated baseline scenario, three different scenarios have been developed and compared. The designed scenarios represent both, the effects of changes that are outside the control of local stakeholders, such as demand change by growth of economy and population and those that depend of engineering- and regulatory interventions, such as repairing of leaks and strategies for increasing the groundwater recharge. The presented annual summaries provide an overview of water fluxes into and out of the study area, and allow to compare the impacts of different scenarios on the flow volumes in the urban water cycle.

Baseline Scenario

A baseline scenario was constructed based on the physical characteristics, demographic conditions and water usage patterns of the year 2003.

The results (Figure 6) clearly show that the water balance strongly depends on groundwater input from the deep aquifer system while the shallow aquifer receives a major input from the urban water system. About 626 mm/y of drinking water (approx. 94% of total imported water) are introduced into the urban system from the deep aquifer, whose main recharge area lies in the mountain ranges outside of the UVQ model domain. Inflow from these recharge areas is not included in the water balance, but contributes significantly to this one.

Large volumes of stormwater runoff are expected in urban areas with high population density and a high degree of surface sealing. The high portion of impervious surface (80% in the study area) generates a surface runoff volume of 205 mm/y, about 60% of total precipitation. The largest contribution come from roof areas, which make up 58% of the total sealed surface, generating a runoff volume equivalent to 34% of the precipitation.

The high runoff volumes significantly increase the water volume in the sewer system. Stormwater contributes with 144 mm/y to the sewer system, 30% of the total discharge. Only 61 mm/y are drained by a separate collector system to natural streams. This results in high discharge peaks, sewer overflow and flooding, the latter being observed during precipitation events of mean to high intensity in the study area.

Local aquifer recharge from precipitation and urban irrigation amounts to 45 mm/y. This is far below the value of 227 mm/y incidental recharge by leakage from the drinking water supply system, which makes up 74% of total recharge in the urban area (Figure 7). The concentrations of N_{total} (2.5 mg/l) and P (0.93 mg/l) in drinking water strongly exceed values from the case study in Rastatt, Germany (0.11 mg/l and 0.007 mg/l respectively) (Klinger et al, 2006), however infiltration of potable water through leakage does not represent a threat to groundwater quality. Contrarily, it has the potential to attenuate the effects of high contaminant loads stemming from other recharge sources.

Results show that leakage from the sewer network is on average 6.2% of the total wastewater volume, representing an exfiltration of 34 mm/y. Higher leakage volumes are associated to collapsing and cracking concrete pipes, built over 35 years ago, which make up approx. 30% of the network. Exfiltration volumes contribute 11% to the total groundwater recharge, a comparable amount to the recharge by precipitation (approx. 35 mm/y). In spite of this relatively small contribution compared with leakage from the drinking water network, it contributes more than 55% of the total nitrogen load and approximately 70% of phosphate load to the subsurface (Figure 7). Nevertheless, the colmation layer that forms around the leaks can act to increase attenuation of contaminant concentrations in the exfiltrating wastewater (Cook et al, 2005), and a significant removal in the unsaturated zone should also be happening (IMMSA, 2009). Additionally, dilution with potable water from leakage in the water supply system should play a significant role in decreasing contaminant concentrations in the shallow aquifer. Results from analyses of 24 shallow wells located in the urban area registered average concentrations of 4.96 mg/l of nitrate and 5.03 mg/l of phosphate.

Demand change scenario

The demand change scenario was designed for the year 2033, in accordance to the planning horizon established in the INTERAPAS plan (Interapas, 2005). The population growth was estimated using a geometric model with compound rate, which first takes into account the average historical growth rate for San Luis Potosi and then decreases this trend until matching the average national growth rate. According to this projection, the number of supplied inhabitants in the study area will increase from 1.09 million in 2003 to 2.04 million in 2033.

The industrial and service sectors show a development framework similar to the population increase and no changes in the water consumption patterns are expected (HASLP, 2003; PDUSLP, 2000). Thus, water use patterns were assumed constant and water consumption was set to grow proportionally to the population. Water use for each neighbourhood was recalculated from the estimated use in 2033 and incorporated in UVQ as change in water usage.

In the resulting UVQ scenario, imported water increases by 109% with respect to the baseline scenario, due to the approximately population double (Figure 8). This would require new water sources and a high number of new household connections. Nevertheless, as a result of the negative impacts by intensive groundwater use, the aquifer system is reported as over-exploited by Conagua, and no additional abstraction volume is legally available. Only a portion of the increase in the industrial use (48 mm/y) is estimated to be provided by water re-allocation from the agricultural sector, therefore being outside of the UVQ model domain. Thus, growing water demand would have to be met from sources outside of the catchment, such as El Realito dam that borders on the neighbouring state of Guanajuato and will supply 31.5 hm^3/year from the year 2011.

The impact on the sewer network and treatment facilities is marked by the fact that wastewater generation increases by more than 100%. The effect on the underlying aquifer is considerable, as leakage from the combined sewer would increase by approximately 34 mm/y.

As water losses in the drinking water supply network in UVQ are expressed as a percentage of total supply, the recharge volume from this source would also increase substantially, contributing an additional 254 mm/y (481 mm/y in total) to recharge. Leakage from water mains is potable water and represents no threat to groundwater quality, however, can lead to rising groundwater levels and therefore to flooding of cellars and underground parking facilities.

Leakage from sewer pipes poses a relevant threat to the groundwater if most important interventions for pipe renovations are not considered. In the last years, only 2.7 km/y of pipe (0.15% of the total network) on average are rehabilitated. Comparing with the baseline scenario, the nitrogen and phosphate loads in wastewater for the 10 study area neighbourhoods increase by 11% in their maxima value and 22% in the minima value (Table 7).

Rainwater infiltration scenario

This scenario redirects surface runoff from impervious area to garden spaces for infiltration. Only those neighbourhoods were taken into account, where local regulations can be put in practice faster and the required space for infiltration structures is available. Surface runoff from paved and roof areas of commercial, institutional and industrial lots (which represent 20% of the total impervious area) is collected and delivered to infiltration. To implement this, 70% of the considered impervious area has been uncoupled from the sewer system, whereas the rest of the stormwater was still directed to the sewer network, considering that collection and infiltration of the whole runoff volume would not be feasible.

In terms of the water balance (Figure 9), the detouring of the surface runoff has the effect of diminishing the amount of total runoff generated (10% decrease in comparison to the baseline scenario) and also decreases wastewater output. The amount over the entire study area can be considered as modest; nevertheless a much more significant impact is estimated on the neighbourhood scale, with reductions of 41% and 75% in commercial areas and industrial areas, respectively. Beneficial impacts of these practices are a decrease in the hydraulic burden of the sewers, in reduced overflows from the combined sewer, and reduced flooding and overflow of untreated water from WWTP's. Additionally, the detouring of surface runoff reduces the total wastewater volume by 3%, resulting in a modest reduction in the costs of the WWTP's. As sewer leakage is expressed as a function of total network length, the leakage volume is maintained constant.

As result of surface runoff infiltration, groundwater recharge from soil store increases by approximately 30% (13 mm/y) over the entire study area, while the neighbourhoods affected by the infiltration measures are subject to increases of up to 500%. The reason of these differences is the comparatively small area of increased recharge compared to the entire study area domain. Figure 10 shows the comparison of recharge rates between the baseline- and infiltration scenario for each neighbourhood.

Scenario of water network rehabilitation and shallow groundwater use

This scenario combines an engineering intervention in the water supply system and the use of shallow groundwater as alternative water source with the intention to increase the available water volume and relieve some pressure from the deep aquifer. The measures in the urban water system consist in pipe rehabilitation and replacement to decrease the average leakage from 37% to 27%. When comparing the spatial distribution of the leakage record to the urban growth map, three areas stand out as priorities for rehabilitation: the city centre, as well as areas in the north-west and south-east. In these areas the network with concrete pipes older than 35 years is concentrated.

Additionally, water from the shallow aquifer is used to replace drinking water for toilet flushing in six of the ten neighbourhoods. The choice of the neighbourhoods is based on socio-economic considerations, meaning the likeliness that households and other sectors have the means to install the necessary facilities.

In the context of the total water balance (Figure 11) the effect of the water mains rehabilitation plays an important role to reduce the leakage by 36%, corresponding to a total of 81 mm/y. This results in economic reliefs for the water utility, as abstraction from 16 deep wells with an average flow rate of 22.5 l/s could be stopped. Or the other way round, the reduced water losses would provide drinking water supply for more than 213 000 inhabitants.

Additionally, the abstraction of 46 mm/y from the shallow aquifer, covering the requirement for toilet flushing of approx. 405 000 inhabitants, will result in further reduction of water losses, taking into account that abstraction is assumed to be on-site.

It can be assumed that the scenario would have a significant impact on water demand. Use of the shallow aquifer and reduction of pipe leakage are important part in an overall management strategy to reduce the abstraction volume from the deep aquifer. Within the scenario alone they lead to a reduction of 20% in pumping from the deep aquifer. Nevertheless, it has to be taken into account that the scenario also implies a reduction on groundwater recharge of 81 mm (Table 8). In order to reduce this effect, infiltration strategies can be combined. Results from the infiltration scenario show an increase in the recharge of 13 mm (Table 8), results even higher could be obtained by the extension of this measure to public parks such as Tangamanga I, II and Morales. Such a combination would allow abstraction from the shallow aquifer to be sustainable on the long run. It is evident that strategies to promote the use of shallow groundwater are needed, taking into account that under the demand change scenario the incidental recharge will augment to 254 mm (Table 8). A groundwater flow model requires to be developed to assess the effects on groundwater levels and to back up this strategy.

4. Discussion

The strong human intervention in the hydrological cycle has motivated the increasing application of water and contaminant balances to urban catchments. Typical water balances focus on evaluating the impact of urbanization on the hydrologic system, the provision of traditional water servicing and investigation of attenuation strategies (Stephenson, 1994; Grimmond and Oke, 1986; Binder et al, 1997). The applied methods vary; although the majority involves an accounting of input and output based on average annual or monthly or spreadsheet calculations. Generally, approaches concentrate on one aspect of the water cycle.

The increasing interest in integrated water management and the need for assessment of alternative water serving approaches, has promoted the development of more detailed analysis tools. Recently, urban water cycle models incorporate detailed analysis of specific components such as the models MUSIC (Wong et al, 2002) and PURRS (Kuczera and Coombes, 2002), which are designed to assess alternative stormwater management options on the local and catchment scale. Furthermore, advances have been made in the integration of complex models and their data transfer via GIS platforms. An example is the ICS model (Clifforde et al, 1999) that simulates the components of wastewater and allows to be integrated with other models. The Aquacycle model (Mitchell et al, 2003[b]; Lekkas et al, 2008) on the other hand has the ability of modelling stormwater and wastewater reuse options, but focuses on the water balance alone.

Currently UVQ is the only model available in which stormwater, wastewater, water supply, groundwater and contaminants are simultaneously considered. Data requirements for UVQ are demanding, a reason why the poor data availability and quality in developing countries could limit the use of such tool. However, the case study in ZMSLP demonstrates that the key requirements can be met. A lot of data produced for other purposes have been utilised to feed the tool, together with supplementary information from focused field studies.

The UVQ model has been successfully operated in this case study; nevertheless some general observations must be made about the effects of uncertainties on the outcome of the scenario modelling:

i) The connection of surface sealing with the drainage network is not very well known. Even though stormwater volumes were monitored to calibrate the model and constrain the assumptions, more extended measurements would be required. These would decrease the uncertainty in rainwater harvesting scenarios (e.g. decentralised rainwater infiltration).

ii) The contribution of effective precipitation to recharge may be highly variable in the study area. Although a reasonable representation of the recharge could be obtained, additional work is required in this aspect. Validation of natural recharge from precipitation by field observations (e.g. installation of urban lysimeters in representative neighbourhoods) would better establish the results of alternative scenarios such as rainwater infiltration in green spaces.

iii) Water use distribution inside the household (toilet, bath, laundry and kitchen) is only known from international references. It may vary depending on the region, culture, climatic conditions, and even on the size of a neighbourhood. A validation of the water use behaviour in the study area would restrict the uncertainty in those scenarios that take into account water usage in these compartments (e.g. shallow groundwater for toilet flush).

On the other hand, significant effort will be required in order to increase the reliability in estimating exfiltration from leaky sewers. Assessment of defective sewers as well as sampling programs in the shallow aquifer will be key steps in future research aiming at the protection of urban groundwater sources.

5. Conclusion

The urban water model UVQ was used to quantify flows and contaminant loads in the water system of San Luis Potosi, Mexico. A range of urban water scenarios, including different supply strategies and the effect of externalities like water demand change, were simulated from the calibrated baseline scenario. The results allowed to evaluate the impacts of alternative ways of urban water management on the total water cycle, as well as to estimate the components of recharge to the urban aquifer.

The output produced by UVQ is a key component for a broader assessment of water system sustainability. UVQ offers the opportunity to link other models such as pipe leakage and groundwater flow simulation models in order to widen the appraisal of flows and contaminant loads to productive urban aquifers and better integrate water resources management.

The Mexican arid zone includes many similar situations to San Luis Potosi where an aquifer underlies urban area. A wider appraisal of water quality and quantity would help establish measures so that these urban aquifers provide additional water sources, which would be relief at a point of regional water resource scarcity.

Acknowledgements

The authors appreciate support received from the UNAM's General Direction of Postgraduate Studies and the German Academic Exchange Service – DAAD. The authors would like to thank San Luis Potosi institutions for their fruitful collaboration. Special acknowledgement goes to CSIRO for the access to the UVQ model and to Grace Mitchell and Claire Diaper for her support. This work would not have been possible without the ideas of the late PD Dr. Matthias Eiswirth, who was the initiator and coordinator of the AISUWRS project funded by the European Commission.

References

Binder C, Schertenleib R, Diaz J, Bader HP, Baccini P (1997) Regional water balance as a tool for water management in developing countries, Water Resources Development, 13(1): 5-20.

Cardona A (2005) Hidrogeoquímica de sistemas de flujo regional, intermedio y local resultado del marco geológico en la mesa central: Reacciones, procesos y contaminación. Tesis, doctorado, posgrado en ciencias de la tierra, Univ. Nac. Autónoma de Mexico, Mexico, p 252.

Carrillo-Rivera JJ, Cardona A, Moss D. (1996) Importance of the vertical component of groundwater flow: a hydrochemical approach in the valley of San Luis Potosí, Mexico. J Hydrol, 185: 23-44.

Carrillo-Rivera JJ, Cardona A, Edmund WM (2002) Use of abstraction regime and knowledge of hydrogeological conditions to control high fluoride concentration in abstracted groundwater: basin of San Luis Potosí, Mexico. J Hydrol 261:24-47.

Clifforde I.T., Tomicic B., Mark O. (1999) Integrated water management, a European vision for the future, In Proceeding of the 9th International Conference on Urban Storm Drainage, Portland, USA 8-13 Sept.

Conagua (2005) Actualización hidrogeológica de los acuíferos de Ceballos y Oriente Aguanaval Edo de Dgo, Villa de Arista y San Luis Potosí, Edo de SLP. Informe técnico. Elaboró: Sabinfosistem SA de CV.

Cook S., Vanderzalm J., Burn S., Dillon P., Correll R., Vogel M., Rosemann S., (2005) Assessing and improving sustainability of urban water resources and systems AISUWRS Work-package 5: Field investigations final report. CSIRO. Melbourne, Australia.

DeSilva D, Burn S., Moglia M, Tjandraatmadja G, Gould S, Sadler P (2006) The models, Network exfiltration and infiltration model. In: Wolf L, Morris B, Burn S (eds), Urban Water Resources Toolbox – Integrating groundwater into urban water management. IWA, London, p 34–50.

Diaper C, Mitchell V.G. (2006) The models, Urban volume and quality. In: Wolf L, Morris B, Burn S (eds), Urban Water Resources Toolbox – Integrating groundwater into urban water management. IWA, London, p 16–33.

Grimmond C.S.B., Oke T.R. (1986) Urban Water Balance - 2. Results from a Suburb of Vancuover, British Columbia. Wat Resour. Res. 22(10) 1404-1412.

H. Ayuntamiento de San Luis Potosí (2003) Plan del centro de población estratégico San Luis Potosí-Soledad de Graciano Sánchez. Proyecto de actualización 2003.

Industria Metálica Monternach – IMMSA (2009) Identificación de sitios para la disposición in situ de residuos en formación geológicamente estable, en terrenos del complejo metalúrgico de IMMSA en San Luís Potosí. Realizó Instituto de Geología, UNAM.

Interapas (2005) Estudio de diagnóstico y planeación integral. Informe técnico. Realizó: Tecnología ASSUL SA de CV.

Klinger J, Schaefer M, Wolf L, Hötzl H. (2006) AISUWRS Work-package 10, D27, UVQ Report. Department of Applied Geology Commissioned Report, 43 pp.

Kuczera, G and Coombes, P.J., Towards Continuous Simulation: A Comparative Assessment of Flood Performance of Volume-Sensitive Systems, paper presented at SIA 2002 Conference on Stormwater Management, Orange, NSW, 23-24 April, 2002.

Lekkas DF, Manoli E, Assimacopoulos D. (2008) Integrated urban water modeling using the Aquacycle model, Global NEST Journal 10(3), 310-319.

Martinez, S, Delgado, J. Escolero, O. Domínguez, E. Suárez, M. Socio-economic development in arid zones: The influence of water availability in the San Luis Potosi Basin, Mexico, in Arid Environmental, edited by A. Fernandez-Bernal and M. A. De La Rosa, Nova Science Published, New York, in press.

Mitchell, V.G.; Diaper, C.; Gray, S.R.; Rahilly M. (2003[a]), UVQ: modelling the movement of water and contaminants through the total urban water cycle. Paper presented at the 28th international hydrology and water resources symposium, Wollongong, NSW.

Mitchell V.G, McMahon T, Mein R.G. (2003[b]) Component of the total water balance of an urban catchment, Environmental Management 32(6), 735-746.

Mitchell V.G., Diaper C. (2005[a]). UVQ User Manual. CSIRO Urban Water, CMIT Report Nº 2005-282. Melbourne, Australia.

Mitchell V.G., Diaper C. (2005[b]) UVQ: A tool for assessing the water and contaminant balance impacts of urban development scenarios. Water Sci. Technol., 52 (12), 91–98.

Mitchell G., Diaper C. (2006). Simulating the urban water and contaminant cycle. Environmental Modelling & Software, 21: 129-134.

Morris B, Rueedi J, Mansour M (2006): A sandstone aquifer: Doncaster, UK. In: Wolf L, Morris B, Burn S (eds), Urban Water Resources Toolbox – Models for Sustainability Assessment. IWA, London, p 144–190.

PDUSLP- Plan Estatal de Desarrollo Urbano del Estado de San Luis Potosí 2001-2020. 2000. Elaboró: Gobierno del Estado de San Luis Potosí, Universidad Autónoma de San Luis Potosí.

Rueedi J, Cronin AA (2005) AISUWRS Work-package 10: UVQ report. EU project code EVK1-CT-2002-0110. Robens Centre for Public and Environmental Health, Guildford, UK.

Trueba V (2005) La subsidencia regional y agrietamiento del subsuelo en San Luis Potosí por la sobreexplotación de los acuíferos. In: Proyecto de manejo integrado y sostenible del agua en la región centro de San Luis Potosí. Informe técnico. Programa de modernización del manejo del agua – PROMMA, Organización Meteorológica Mundial.

Souvent P, Vizintin G, Cencur Curk B (2006): A layered aquifer system: Ljubljana, Slovenia. In: Wolf L, Morris B, Burn S (eds), Urban Water Resources Toolbox – Models for Sustainability Assessment. IWA, London, p 191–216

Stephenson D. (1994) Comparison of the water balance for an undeveloped and a suburban catchment, Hydrological Sciences, 39(4), 295-307.

Wolf L (2006): Influence of leaky sewer systems on groundwater resources beneath the City of Rastatt, Germany – Abschätzung der Grundwasserbeeinflussung durch defekte Abwasserkanälem im Gebiet der Stadt Rastatt. Schriftenreihe Angewandte Geologie, 75, 205 p, Universität Karlsruhe, Karlsruhe, online accessible at <http://www.ubka.uni-karlsruhe.de/eva/index.html>

Wolf L, Morris B, Dillon P, Vanderzalm J, Rueedi J, Burn LS (2006[a]): AISUWRS Urban Water Resources Toolbox – A Brief Summary. In: Wolf L, Morris B, Burn S (eds), AISUWRS Urban Water Resources Toolbox – Integrating Groundwater into Urban Water Management. IWA, London, p 282–290

Wolf L, Morris BL, Burn S, Hötzl H (2006[b]). The AISUWRS approach. In: Wolf L, Morris B, Burn S (eds), Urban Water Resources Toolbox – Integrating Groundwater into Urban Water Management. IWA, London, 296 pp

Wong T, Coleman J, Duncan H, Fletcher T, Jenkins G, Siriwardena L, Wootton R. (2002) Music Model for Urban Stormwater Improvement Conceptualisation, User Manual, CRC Catchment Hydrology, Australia.

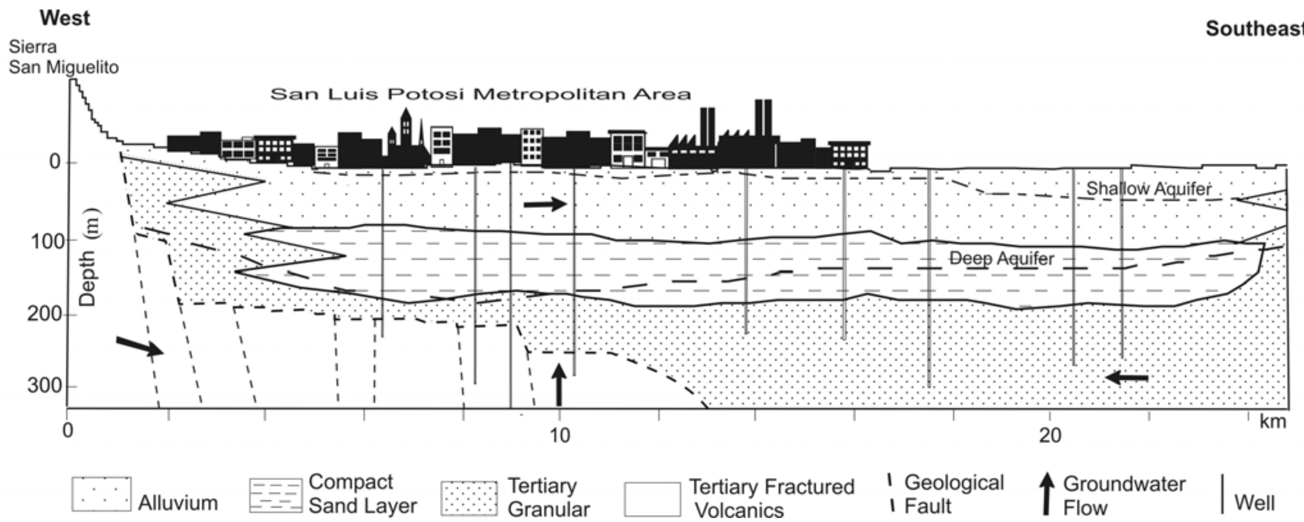

Figure 1 Cross section in the urban area of ZMSLP

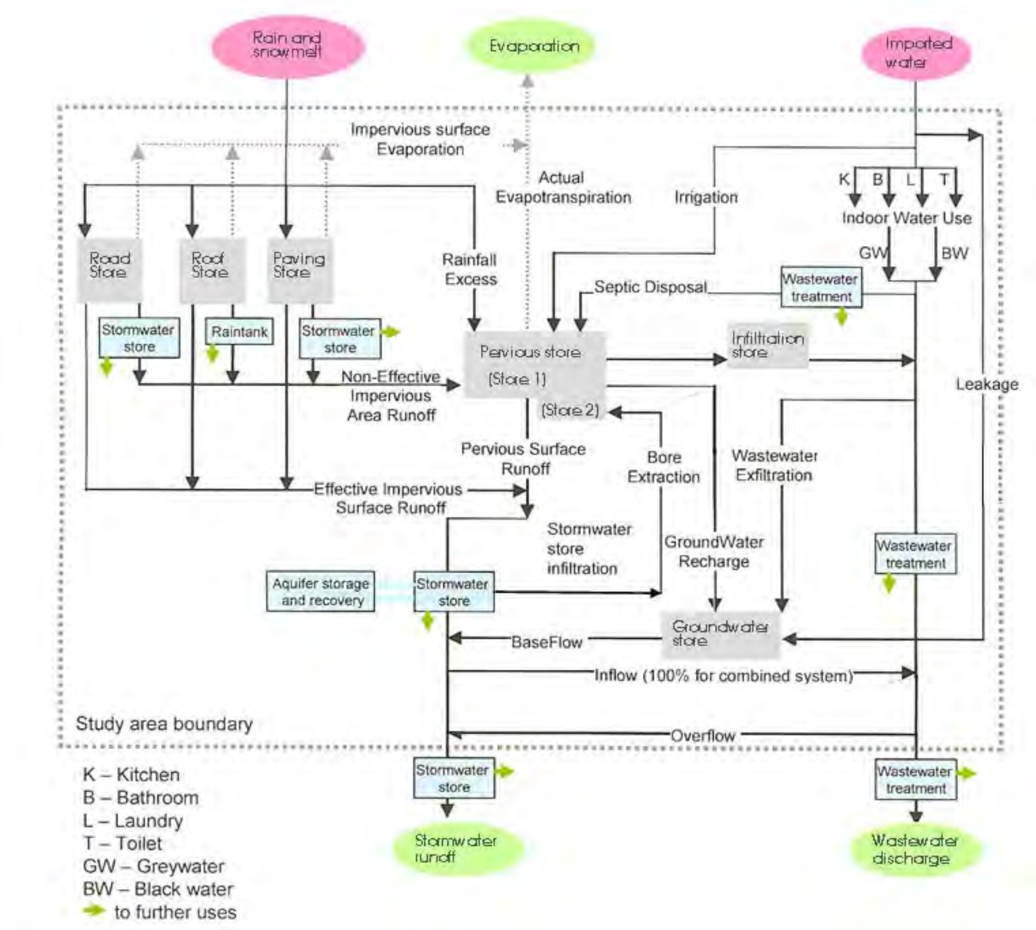

Figure 2. The UVQ flow diagram representation of the total urban water cycle (Diaper and Mitchell, 2006)

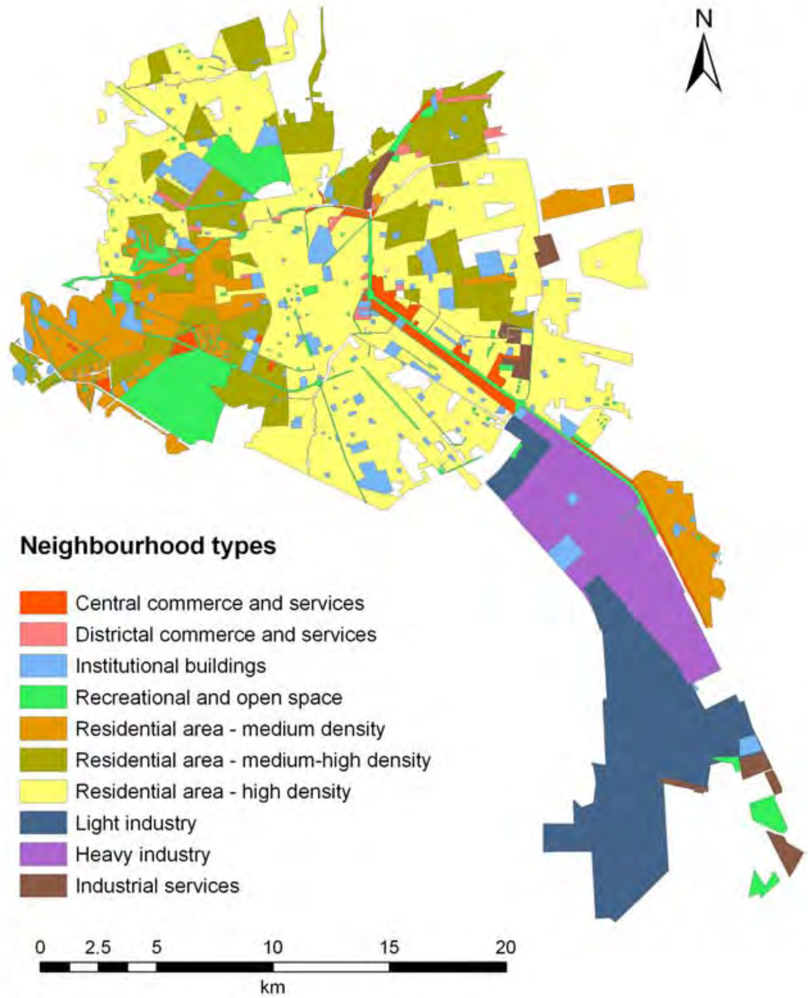

Figure 3. Neighbourhood types representing the ZMSLP

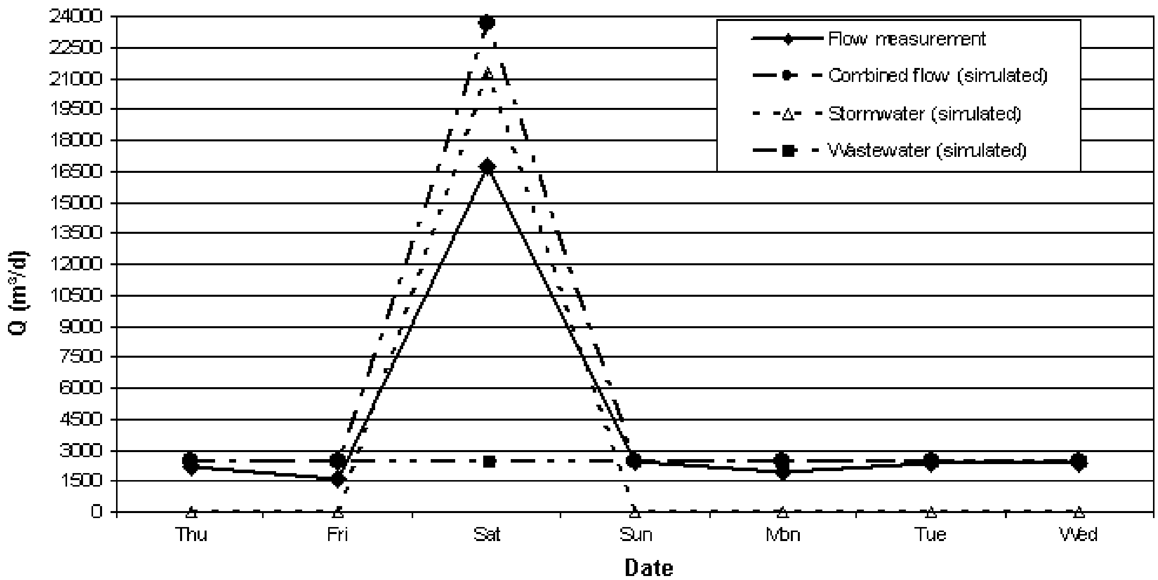

Figure 4. Measured and simulated discharge fluxes for the pilot catchment

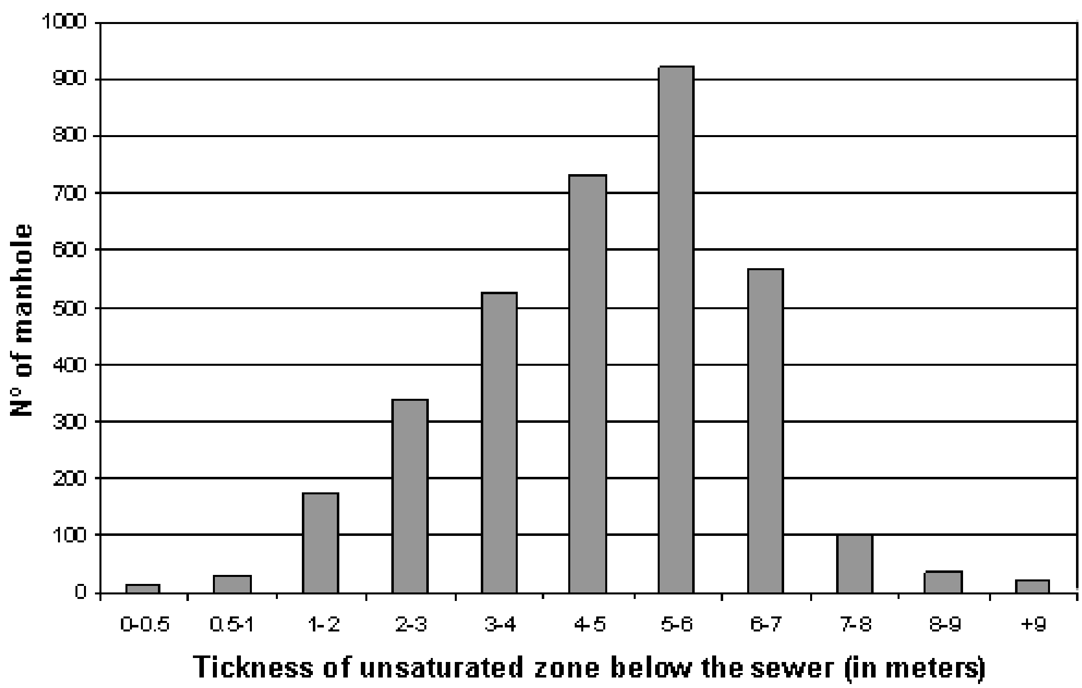

Figure 5. Position of sewers in relation to groundwater level

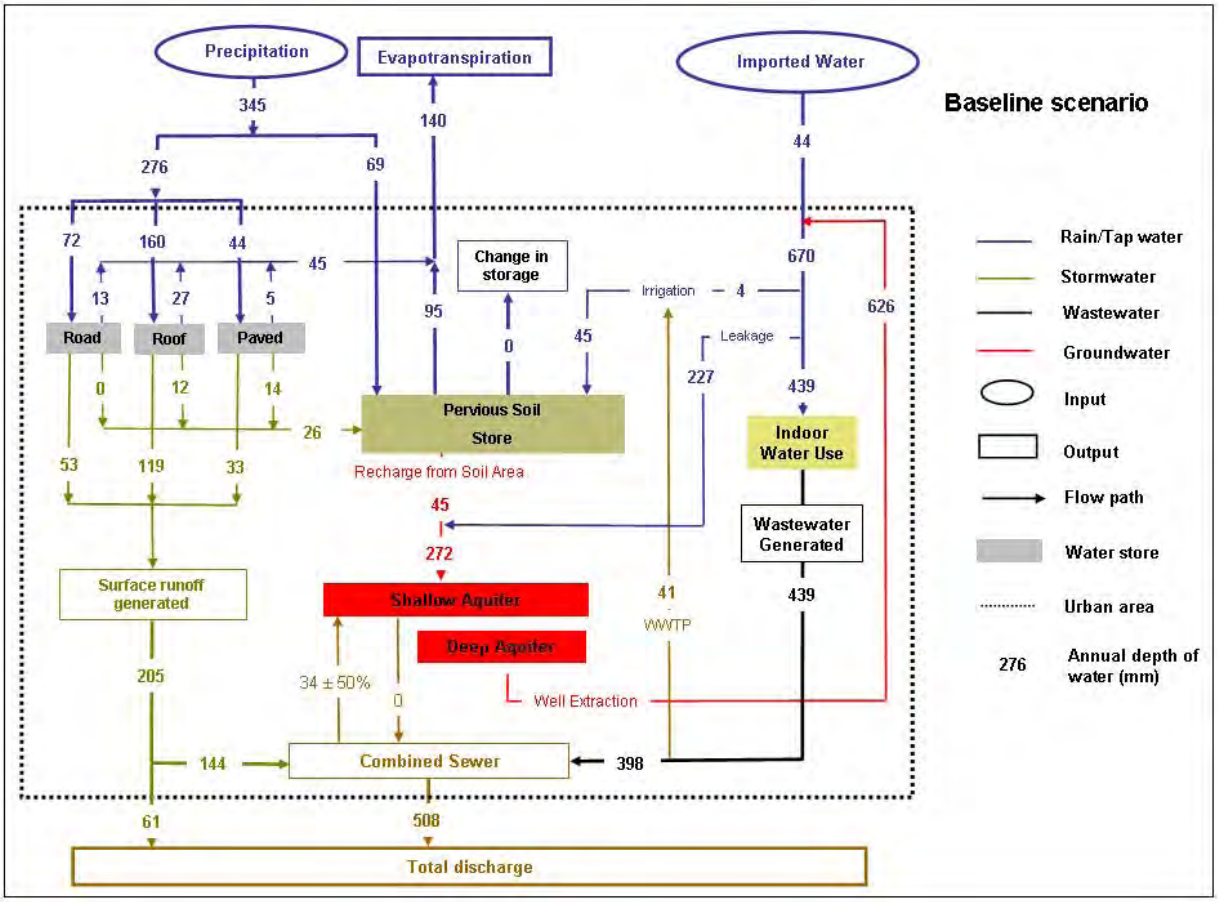

Figure 6. Water balance diagram for the ZMSLP, baseline scenario.

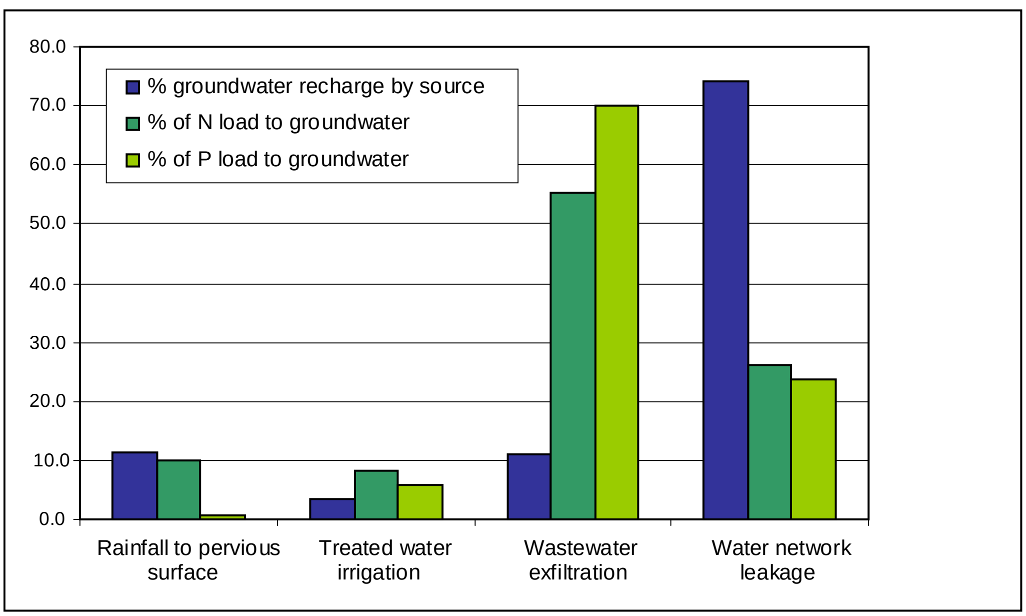

Figure 7. Contribution of different sources to recharge, N and P loads to groundwater - Baseline scenario.

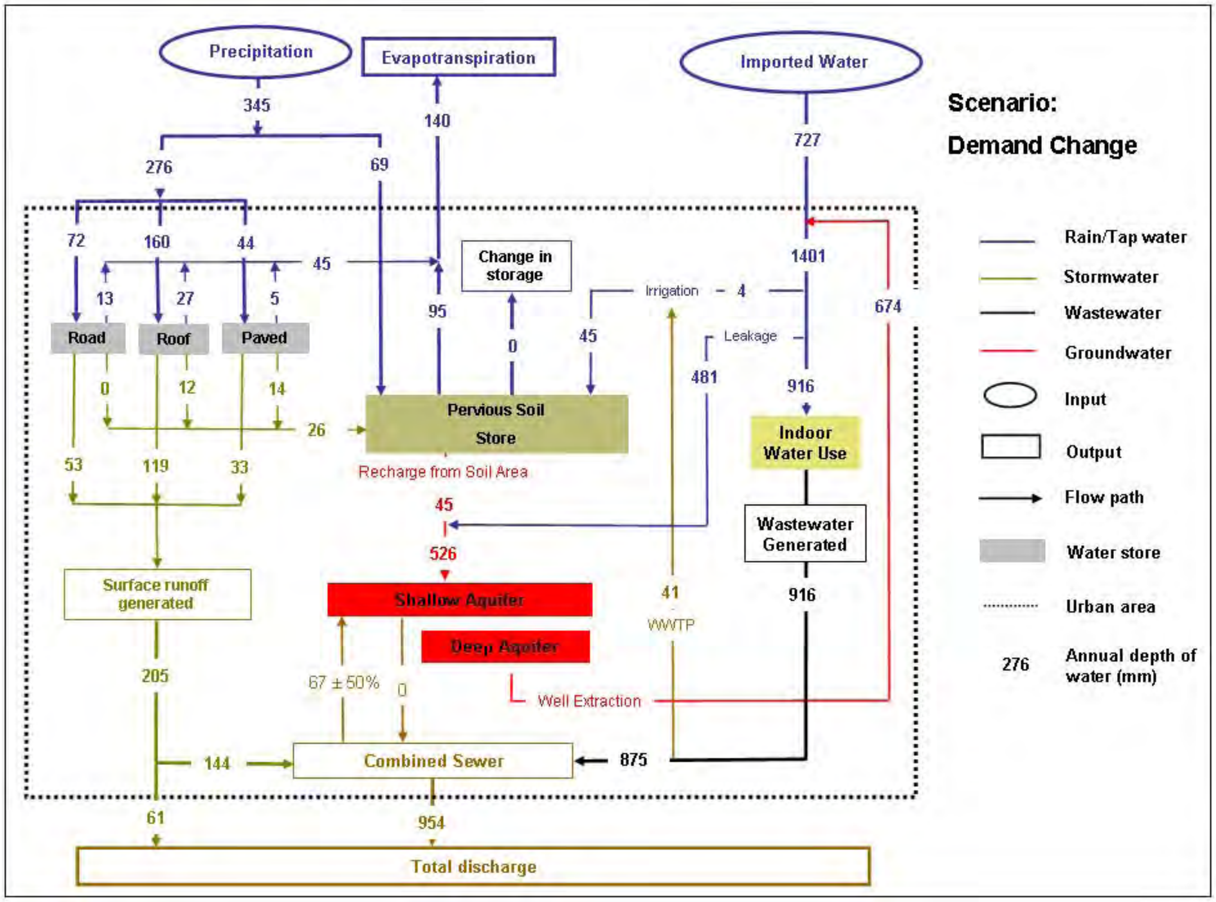

Figure 8 Water balance diagram for the ZMSLP, demand change scenario.

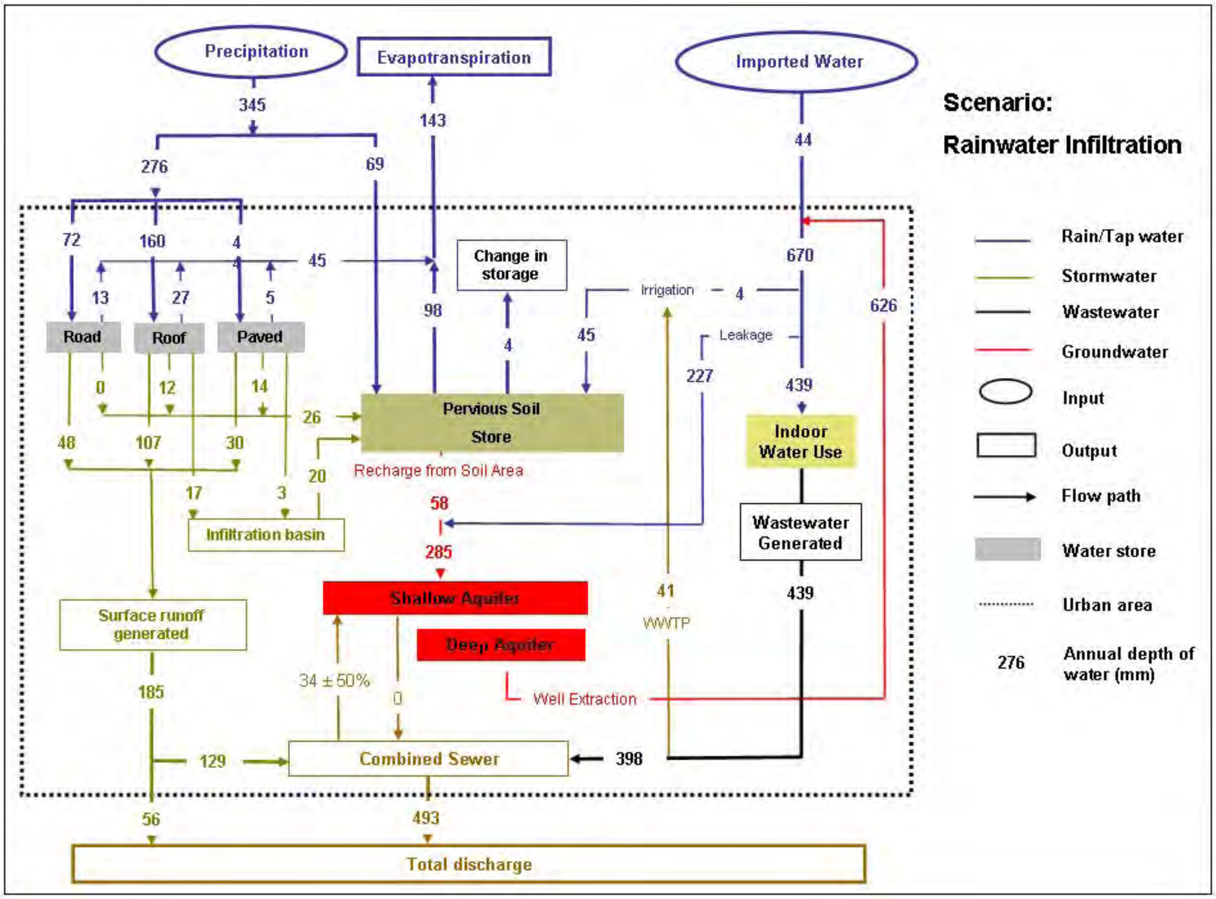

Figure 9 Water balance diagram for the ZMSLP, rainwater infiltration scenario

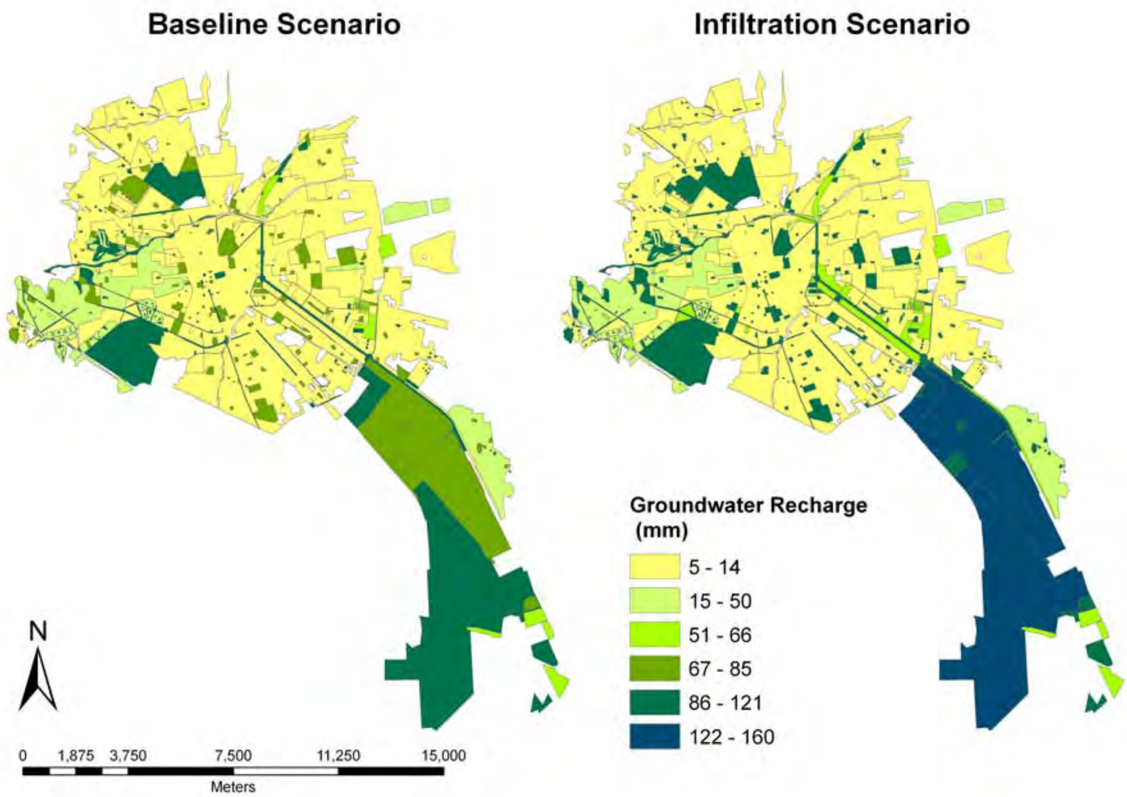

Figure 10 Comparison of groundwater recharge for the baseline- and rainwater infiltration scenario

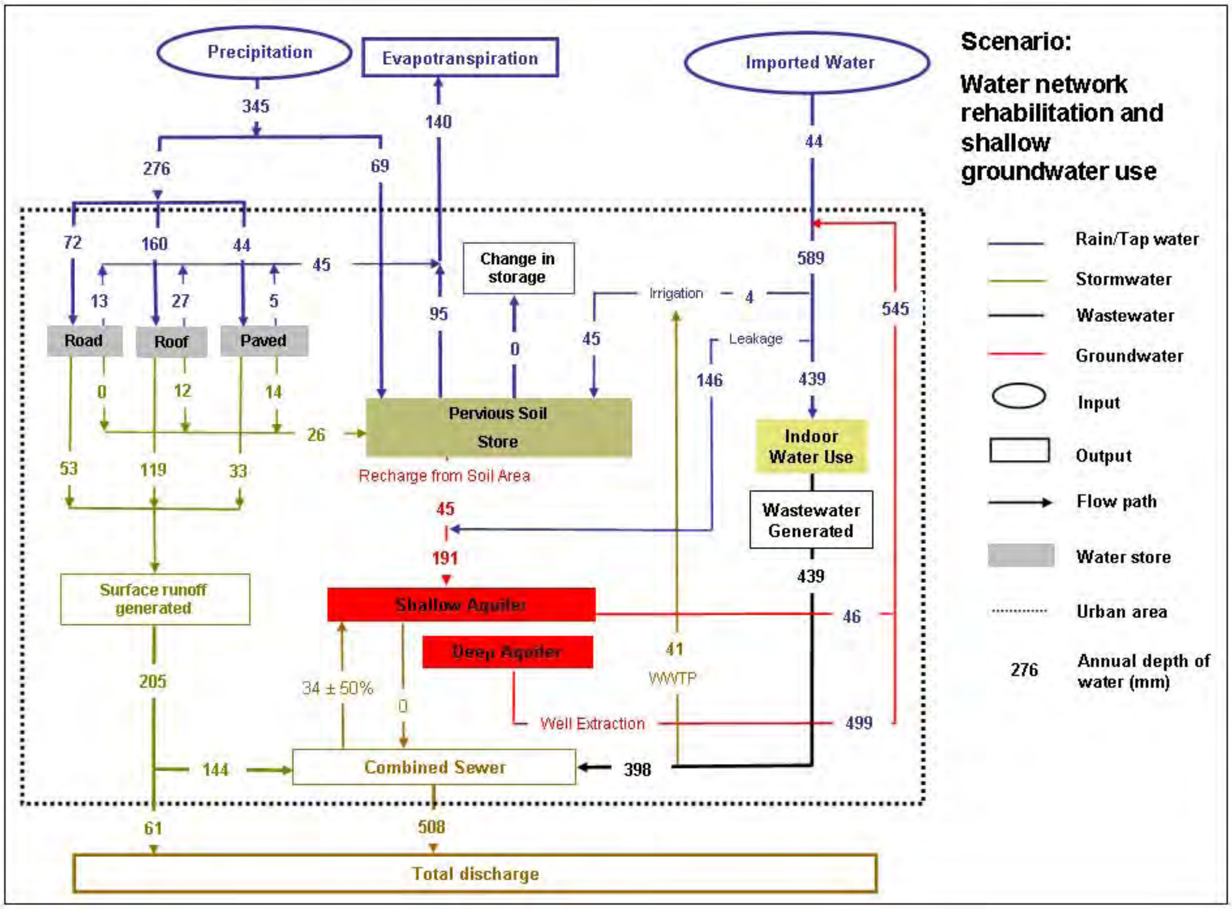

Figure 11 Water balance diagram for the ZMSLP, scenario of water network rehabilitation and shallow groundwater use

Status	Consequences	Example of Cities in Mexico
Rising groundwater level	Cellar and basement flooding, increased infiltration of groundwater into the sewer system, increased construction costs for new buildings.	San Luis Potosi, Monterrey, Puebla, Guadalajara, Toluca.
Declining groundwater level (principally on deep aquifers)	Water scarcity, land subsidence, damage to buildings, drying of groundwater dependent aquatic habitats	Mexico City, San Luis Potosi Toluca, Querétaro, Aguascalientes
Water quality deterioration	Health risks, usage restrictions, water scarcity.	León, Celaya, San Luis Potosi, Toluca, Monterrey
High sealing degree	Flooding, combined sewer overflow, mixture of wastewater and stormwater, health risks	San Luis Potosi, Toluca, Querétaro.
Water scarcity	Competition of users, potential conflicts for to meet increasing urban water demands	Querétaro, San Luis Potosi, Monterrey, Torreon.

Table 1 Water-related challenge in Mexican urban areas

Total supplied population in Metropolitan Area	1 095 000 inhabitants
Mean annual temperature and precipitation	17.4 ºC and 356 mm (period 1989-2006)
Land use	Residential, commercial, service and industrial (food, drink, chemicals, textile, paper, metallurgical, automotive)
Type of Urbanization	Accelerated growth from 175 000 inhabitants in 1960, to more than 1 million inhabitants in 2005
% sealed surface	80%
Water Supply sources	Groundwater: 94% (92.4 Hm^3/y), surface water 6% (6.4 Hm^3/y)
Tap water connections: number, users and material	Total 254 937. Domestic 95%, Commerce and Service 4.2%, Industry 0.4%, Institutional 0.4%. Copper, iron, and PVC/PE
Pipe length, material and age	361 km; asbestos-cement, iron, steel and PVC; 0-15 years 3%, 16-25 years 34%, 26-35 years 19%, more than 35 years 44%
Drainage system	Combined gravity system
Sewer length, material and age	1 801 Km, asbestos-cement, 0-15 years 9%, 16-25 years 21%, 26-35 years 42%, more than 35 years 29%
Per capita demand (incl. unaccounted for water)	160.5 l/cap/d

Table 2 Key features of the ZMSLP

Required input data	Unit	Data source				Reliability	Used for calibration
		A	B	C	D		
Number of neighbourhoods	[–]	X				High	
Road area per neighbourhood	[m²]	X				High	
Inhabitants per neighbourhood	[m²]	X				High	
Leakage in water supply mains	[%]			X		Medium	
Number of blocks	[-]	X				High	
Average roof area per block	[m²]		X			Medium	
Average paved area per block	[m²]		X			Medium	
Average garden area per block	[m²]		X			Medium	
Percentage of irrigated garden area	[%]	X	X			Medium	
Total water use per capita	[l/c/d]	X				High	
Water uses for compartments (kitchen, bathroom, laundry, toilet)	[l/c/d]				X	Low	
Loads generated by indoor water use for each contaminant considered	[mg/c/d]		X			Medium	yes
Contaminant concentrations in imported water	[mg/l]			X		High	
Contaminant concentrations in rainwater	[mg/l]	X				High	
Contaminant concentrations in runoff (pavement/roof/road/first flush)	[mg/l]	X	X			Medium	
Fertilizer application to gardens	[mg/m²]		X			Medium	
Maximum soil store capacity	[mm]			X	X	Medium	yes
Soil store field capacity	[mm]			X	X	Medium	yes
Maximum daily drainage depth	[mm]				X	Low	yes
Roof area maximum initial loss	[mm]				X	Medium	yes
Effective roof area	[%]				X	Medium	yes
Paved area maximum initial loss	[mm]				X	Medium	yes
Effective paved area	[%				X	Medium	yes
Road area maximum initial loss	[mm]				X	Medium	yes
Effective road area	[%				X	Medium	yes
Drainage Factor Ratio	[ratio]				X	Low	
Base flow recession constant	[ratio]				X	Low	
Contaminant soil store removal	[%]	set to zero				Low	
Wastewater infiltration index		set to zero				Low	
Percentage surface runoff as inflow to sewers	[%]	set to 100				Low	
Garden trigger to irrigate	[ratio]			X		Low	yes
Precipitation	[mm]			X		High	
Potential evaporation	[mm]			X		Medium	
Average imported water	Ml/y			X		High	
Average outflow from sewer system	Ml/y		X	X		Medium	

Table 3: Input & calibration parameters required for UVQ, including indication of data sources & reliability for the SLP Metropolitan Area: A = Site specific, measured for entire model area; B = Site specific, determined at selected spots and extrapolated; C = Literature data from local studies; D = Literature data from international studies.

Nº	NEIGHBOURHOOD	Area (Km²)	Avg. occupation per block	Block area (m²)	Nº of blocks	Total impervious area (Km²)	Total pervious area (Km²)
1	Central commerce and services	2.84	367	41505	57	2.74	0.10
2	Districtal commerce and services	1.09	269	8208	95	1.07	0.01
3	Institutional buildings	8.03	271	34024	201	3.62	4.41
4	Recreational and open space (public and private)	11.98	0	11039	799	3.16	8.82
5	Residential area - medium density	13.85	103	13376	798	11.66	2.18
6	Residential area - medium-high density	20.30	82	8164	1880	18.59	1.71
7	Residential area - high density	54.90	107	6909	5912	53.41	1.49
8	Light industry	19.63	1085	552196	33	13.55	6.08
9	Heavy industry	12.50	360	183075	59	7.74	4.76
10	Industrial services	2.44	1791	54589	37	1.93	0.51

Table 4. Summary of physical key characteristics for the ZMSLP.

Parameter	Unit	Imported	Rainfall	Pavement Runoff	Roof Runoff	Road Runoff	Roof First flush	Fertiliser to garden
Na^+	mg/l	42.55	1.1					
K^+	mg/l		0.93					
Cl^-	mg/l	22.10	0.98	1.6	1.6	15.9	3.2	47.44
N_{total}	mg/l	2.5		3.3	3.3	14.4	6.59	18.07
P (as PO_4)	mg/l			0.05	0.05	0.41	0.1	5.26
SS	mg/l							7.67
$SO4^{2-}$	mg/l	30.87	5.5	18	18	71.33	36	99.89
F^-_	mg/l	1.68	0.28	0.16	0.16	0.65	0.32	2.06

Table 5. Measured concentrations for outdoor water sources, used for UVQ modelling in the ZMSLP

		Water usage - cont loads per capita				Cont. Concentration (mg/l)	
Parameter	Unit	Kitchen	Bathroom	Toilet flush	Laundry	Modelled	Measured
Water usage	l/c/d	23.1	46.2	53.9	30.8		
Na^+	mg/c/d	92.4	231.0	6468.9	616.1	91.0	88.4
K^+	mg/c/d	46.2	92.4	2695.4	184.8	20.0	20.2
Cl^-	mg/c/d	184.8	323.4	16711.4	616.1	138.0	124.4
N_{total}	mg/c/d	57.8	115.5	4312.6	98.6	41.0	40.6
P (as PO_4)	mg/c/d	39.3	46.2	2964.9	154.0	21.0	21.3
SS	mg/c/d	1155.2	1386.2	15094.2	924.1	121.0	118.1
$SO4^{2-}$	mg/c/d	138.6	277.2	12129.3	308.0	114.0	113.4

Table 6. Contaminant loads used for the UVQ model, and measured and modelled concentrations.

Scenario	Nitrogen (mg/l)		Phosphate (mg/l)	
	Max	Min	Max	Min
Base case	59.3	26.9	34.7	13.6
Demand change	66.7	34.4	39.3	17.3

Table 7 Comparison of contaminant loads in wastewater output

Scenarios	Imported water from deep aquifer (mm)	Water input to the shallow aquifer (mm)
Baseline	626	272
Demand change	674	526
Rainwater infiltration	626	285
Water network rehabilitation and shallow groundwater use	545	191

Table 8. Comparison of imported water from deep aquifer and water input to the shallow aquifer.

CONCLUSIONES GENERALES

Ciudades localizadas en las zonas centro y norte de México donde prevalecen condiciones áridas, dependen fuertemente de los recursos de agua local para el abastecimiento. En las últimas décadas, la relación compleja entre gestión ineficiente, falta de planeación, inversión y tecnología ha propiciado servicios de agua urbana deficientes y degradación de los recursos locales, en un marco de desarrollo socio-económico y demanda acelerada.

Frente a los retos que enfrenta el futuro abastecimiento de agua en México, las estrategias impulsadas por la Conagua se han orientado a la regularización de usuarios y la apertura del mercado del agua al interior de cuencas y acuíferos, la conformación de organizaciones de usuarios para la gestión participativa y el ahorro de agua de uso agrícola. Mientras los gobiernos estatales han impulsado el saneamiento de áreas fuertemente degradadas promoviendo la instalación de grandes plantas de tratamiento de agua residual para el reuso agrícola. A escala urbana, los organismos operadores de agua y saneamiento han limitado sus esfuerzos a la aplicación de herramientas no-estructurales basadas en la educación para el ahorro del agua, las cuales han tenido escaso impacto debido a la falta de complementariedad con sistemas de incentivos de precios, regulaciones y/o restricciones.

La combinación de medidas para la apertura del mercado del agua y el uso de herramientas tradicionales de evaluación de los recursos a escala de cuencas y acuíferos, tales como balances y modelos de simulación- optimización, han sido valiosas para la reasignación del uso y la mayor productividad del agua. Sin embargo, en la mayor parte del centro y norte de México las concesiones de uso de agua han excedido los volúmenes disponibles. En este contexto, las autoridades empiezan a reconocer las limitaciones de la planeación tradicional que asume un abastecimiento ilimitado de agua potable, y se promueve un cambio para enfrentar los actuales retos.

A escala global, los retos que enfrentan el abastecimiento de agua y la sustentabilidad urbana han promovido el desarrollo de nuevas estrategias y herramientas desde el concepto de gestión integrada de los recursos de agua. Mientras en países desarrollados los avances y aplicaciones a diversos problemas urbanos tienen aproximadamente dos décadas, en el mundo en desarrollo los sistemas de agua urbana no han recibido una atención adecuada a las necesidades debido a factores institucionales, de inversión, planeación y del conocimiento.

Una primera aplicación del enfoque IUWM a partir de uno más amplio desarrollado en el proyecto AISURWRS, se practico en la ZMSLP. Este se basó en la integración del ciclo total de agua urbana, que se define como la consideración colectiva del abastecimiento de agua, agua de lluvia, agua residual y componentes de agua subterránea. La modelación aplicada proveyó el conocimiento de los flujos y su interacción, estimó la recarga urbana y su distribución espacial, identificó los defectos más importante del sistema actual y permitió obtener información relevante para el proceso de toma de decisión.

La situación actual de fuerte dependencia del acuífero profundo como fuente de abastecimiento no puede ser sostenida en el tiempo. Los impactos ambientales y económicos debido a la extracción intensiva, así como las restricciones para nuevas extracciones limitan esta fuente de abastecimiento para la futura demanda. La estrategia de importación de agua desde fuentes externas para el futuro abastecimiento indica un drástico incremento de las entradas al acuífero somero; si bien esto no presenta problema para la calidad del agua subterránea, invariablemente incrementará el riesgo de inundación de la infraestructura urbana.

Frente a un contexto de escasez de agua y cambio climático, el uso combinado de fuentes no-convencionales (agua subterránea somera, agua pluvial), estrategias de recarga e intervenciones ingenieriles aportan soluciones sustentables soportadas por: i) reducción del volumen de escurrimiento superficial de agua de lluvia y agua residual, ii) mitigación de la inundación en sectores de la zona metropolitana, iii) reducción del volumen de agua tratada y costo de tratamiento, iv) disminución del riesgo de inundación de la infraestructura urbana, v) reducción de los requerimientos de energía para la extracción, vi) mitigación de los efectos de extracción intensiva en el acuífero profundo, vii) incremento de las fuentes de agua disponible para demandas de menor calidad.

A partir del modelo base calibrado, nuevas estrategias de gestión y sus impactos en el sistema de agua urbana pueden ser evaluadas rápidamente. Adicionalmente, la habilidad que ofrece esta herramienta para acoplarse con modelos convencionales de simulación de flujo subterráneo y modelos de zona no-saturada permitirá ampliar la evaluación del agua subterránea somera, la cual constituye el principal recurso local para mitigar la escasez de agua y reducir la extracción intensiva del acuífero profundo.

Los resultados obtenidos permiten apoyar el proceso de toma de decisión que promueva el “desarrollo urbano sustentable y sensible al agua.” El cambio hacia una visión integrada de los recursos de agua urbana requerirá mejorar la coordinación y vinculación entre las actuales agencias encargadas de proveer el abastecimiento de agua y drenaje, la planeación y el desarrollo urbano, y la administración del agua. Este proceso podría ser facilitado por el COTAS del Valle de San Luis Potosí, sin embargo se requiere fortalecer su capacidad institucional y financiera para sostener un proceso de cambio a mediano y largo plazo. Adicionalmente, se requerirá impulsar estrategias de regulación para mejorar el aprovechamiento del acuífero somero, así como promover la eficiencia del organismo operador de agua y de las áreas responsables del desarrollo y planeación urbana.

Esta primera aplicación del análisis integrado a países en desarrollo muestra que las limitaciones dadas por el fuerte requerimiento de datos pueden ser superadas utilizando información del área para otros propósitos junto con información generada en campo. Esto demuestra que futuras aplicaciones podrán ser practicadas a un amplio contexto de servicios urbanos, marco hidrogeológico y escala urbana, basadas en la flexibilidad del enfoque y la herramienta.