Urban-enhanced groundwater recharge: review and case study of Austin, Texas, USA

B. Garcia-Fresca

The John A. and Katherine G. Jackson School of Geosciences - The University of Texas at Austin

P.O. Box B, University Station - Austin, TX 78713-8902

beatritxe@mail.utexas.edu

ABSTRACT: Cities and urban populations are growing at a high pace and so are the anthropic impacts on the hydrologic cycle on the local scale. The shallow urban underground is an intricate network of tunnels, conduits, utilities, and other buried structures comparable to a natural karstic system, except that the "urban karst" is generated much more rapidly. Urbanization also introduces new sources of water that increase groundwater recharge. These sources include irrigation of parks and lawns, leakage from water mains and sewers, and infiltration structures. Geologic, land use, and utilities information for the city of Austin, Texas, was compiled and processed by means of a GIS in order to make a water balance for the city. The areal extent of Austin, has increased five-fold since the 1960's. Direct recharge from rainfall has decreased, due to impervious pavements, from 53 mm/a under preurban conditions to 31 mm/a in the year 2000. However, 85 mm/a of the treated tap water never reaches the wastewater treatment plants and potentially contributes to recharge. A conservative estimate yields 63 mm/a of recharge from urban sources and a total recharge rate that nearly doubles that of preurban conditions.

1 INTRODUCTION

The magnitude of anthropic impacts upon their environment makes humans the major geologic agent on the surface of the planet (e.g. Heiken et al. 2003). These effects are most severe where population concentrates and, today, half of the world's population live in urban areas.

Urban development alters all aspects of the water cycle: the climate; the quantity, quality, and regime of surface water and groundwater; and the land surface and subsurface. Urbanization affects the local climate by altering surface temperatures, albedo, precipitation, evaporation and transpiration rates, and the atmospheric energy balance (e.g. Changnon 1976, Bornstein and Lin 2000). Urban growth and urban population growth increase water demand. This imposes a higher stress over the surface and groundwater resource and often requires interbasinal transfers, which affect the natural water budget in the area. Water quality is a prime issue in urban settings as shallow aquifers and surface waters in cities are subject to pollution by a multitude of point and non-point sources, some of which are still poorly understood. Urbanization affects stream regimes by modifying both base flow and flood discharge, bank erosion, sedimentation, landsliding, declines in water quality, and increased flooding (Leopold 1968 and 1973). Changes in surface water systems are commonly visible and apparent even to casual observers while effects on groundwater systems that may be equally significant may not always be obvious. Human effects on groundwater in urban areas include overexploitation, subsidence, seawater intrusion, groundwater contamination, changes in recharge and discharge, alteration of the permeability structure, and destruction of important environmental resources, including wetlands and urban streams (e.g. Chilton et al. 1997, Garcia-Fresca and Sharp *in press*, Howard 2002).

The covering and replacement of natural rocks, soils, and vegetation by pavements, foundations, buildings, metallic structures, dams, tunnels, and other structures has profound impact on the hydrology of an area. The urban underground is an intricate and rapidly changing network of tunnels, buried utilities, garages, and other buried structures that disturb the natural structure of the ground and alter its porosity and hydraulic conductivity. Based on the studies of porosity of karstic aquifers by Worthington (2003), and the volume of underground tunnels and installations catalogued for Quebec City by Boivin (1990), Garcia-Fresca and Sharp (*in press*) conclude that the urban underground has secondary porosities and perhaps permeability distributions comparable to those of a karstic system (Table 1).

Table 1: Porosity values for four karstic aquifers (after Worthington 2003) and estimated porosity from human construction in Quebec City (after Boivin 1990).

	POROSITY (%)		
	Matrix	Fractures	Conduits/channels
Smithville, Ontario, Canada	6.6	0.02	0.003
Mammoth Cave, Kentucky, USA	2.4	0.03	0.06
Chalk, England	30	0.01	0.02
Nohoch Nah Chich, Mexico	17	0.1	0.5
Quebec City, Canada	n/a	unknown	0.06

Boivin (1990) did not provide estimates for the porosity created by smaller utility lines, trenches, pipes, and conduits. Krothe (2002) and Krothe et al. (2002) documented orders of magnitude increases in field permeability measurements along utility trenches and showed by finite-difference numerical modeling that high permeability utility trenches alter groundwater flow direction and velocity. Thus, the urban underground is comparable to a shallow karstic system (Sharp et al. 2001, Krothe et al. 2002, Sharp et al. 2003, Garcia-Fresca 2004, Garcia-Fresca and Sharp *in press*). Utility trenches are analogous to naturally fractured systems and larger underground openings, excavations, and tunnels are analogous to natural conduits, caves, and channels; permeabilities are highly anisotropic and heterogeneous and, in some instances, exceptionally high; storm drains that are analogous to dolines, swallets, and sink holes; rain water can be stored in the shallow underground just as in the epikarst; and recharge can be from both diffuse (precipitation and irrigation return flows) and discrete sources (i.e. leaky pipes). This “urban karstification” is in continuous evolution as new structures are built over the older ones, buried structures are abandoned, and as existing geological structures, lithofacies, and other features are leveled and buried by construction. However, the development of the urban karst takes place at much faster rate than the natural karst.

In the following sections urban effects on groundwater recharge and the mechanisms of recharge are discussed. Then the urban water balance and an estimate of recharge for the city of Austin are presented.

2 GROUNDWATER RECHARGE IN THE URBAN ENVIRONMENT

The hydrologic community has recognized that natural groundwater recharge can be inhibited in urban areas as impervious cover enhances runoff and limits infiltration (i.e. Leopold 1968, Coldewey and Meßer 1997). However urban development introduces new sources of recharge: leakage from water and wastewater distribution and collection systems, leaks from storm sewers, and irrigation return flow from lawns, parks, and golf courses (Lerner 1986). Quantifying groundwater recharge in urban areas is especially challenging because the urban environment is quite complex as a large variety of land uses coexist and overlap and because of the heterogeneity of the shallow underground. The uncertainties intrinsic to quantifying the different sources make it desirable to simplify with water balances based on the amount of groundwater abstractions, imports, water use, and wastewater outflows.

Numerous examples of significant water table-rise and increase on recharge to the groundwater have been reported in the last decade (e.g. Foster et al. 1994, Chilton et al. 1997, Chilton 1999, Howard and Israfilov 2002). A compilation of groundwater recharge data for various cities is portrayed in Figure 1 as a function of aridity as expressed by the mean annual rainfall of each location. The figure is expanded from Foster et al. (1994), who suggested ranges of natural recharge for non-urban environments, probable minimum recharge rates for comprehensively sewered and drained cities, and probable maximum recharge rates for unsewered and undrained cities which have been revised after adding nineteen data points to Foster et al's (1994) original four. In all cases, except for Birmingham, UK, the total recharge to the groundwater is increased by urban development. For the exception of Birmingham, Lerner (1997) estimates a 4% loss in recharge, and is expressed as a downward pointing arrow in Figure 1. Urban-enhanced recharge is most significant in arid climates and in cities in developing countries. In a broader sense, urbanization introduces new sources and pathways of recharge (Lerner 1986) and affects water quality.

3 MECHANISMS OF RECHARGE IN URBAN AREAS

Simmers (1998) and Garcia-Fresca (2004) describe four types of recharge: 1) direct recharge: vertical percolation of rainwater through the unsaturated zone; 2) indirect recharge: water losses from surface water bodies and from water and sewage distribution systems; 3) localized recharge: percolation through preferential pathways (desiccation cracks, burrows, lithologic contacts, faults, fractures, and karstic features); and 4) artificial recharge: return flows from irrigation of parks and lawns, and designed infiltration systems. The four mechanisms of recharge generally combine to increase recharge with urbanization, but the categories can overlap and are not mutually exclusive.

3.1 *Direct recharge*

Direct recharge in cities takes place by percolation in unpaved areas, and to a lesser extent through paved surfaces that are not always perfectly "impervious". The significance of direct recharge decreases as the aridity of the climate or the amount of impervious cover increases. Direct recharge can be estimated by assessing the amount of pervious cover in the city. Precipitation and potential evapotranspiration data are transformed into effective precipitation (e.g. Lerner et al. 1993) with a daily soil moisture balance. This method uses root constants and wilting points to account for different crops and soil types. A proportion of the impervious cover should be treated as permeable, as some infiltration does take place through asphalt, concrete, bricks etc. According to Lerner (2002) roughly 50% of the impervious cover should be treated as permeable.

3.2 *Indirect recharge*

Indirect recharge is the sum of the recharge coming from seepage out of surface water bodies, leakage from water mains, wastewater and storm sewers, and on-site sanitation systems.

Recharge from losing streams in urban areas changes as stream flows are altered by urbanization. Decline in aquifer heads caused by pumpage can alter the hydraulic gradients between the surface and the aquifer and between adjacent formations to enhance recharge.

A simple way to assess the water available for recharge is to make a balance of the water served versus the wastewater treated. Yang et al. (1999) quantified the recharge in the city of Nottingham, UK, with a groundwater flow model calibrated with solute balances for chloride, sulfate, and nitrogen. They concluded current recharge to the aquifer is less than prior to urbanization; however, mains leakage is the main current source of recharge in Nottingham.

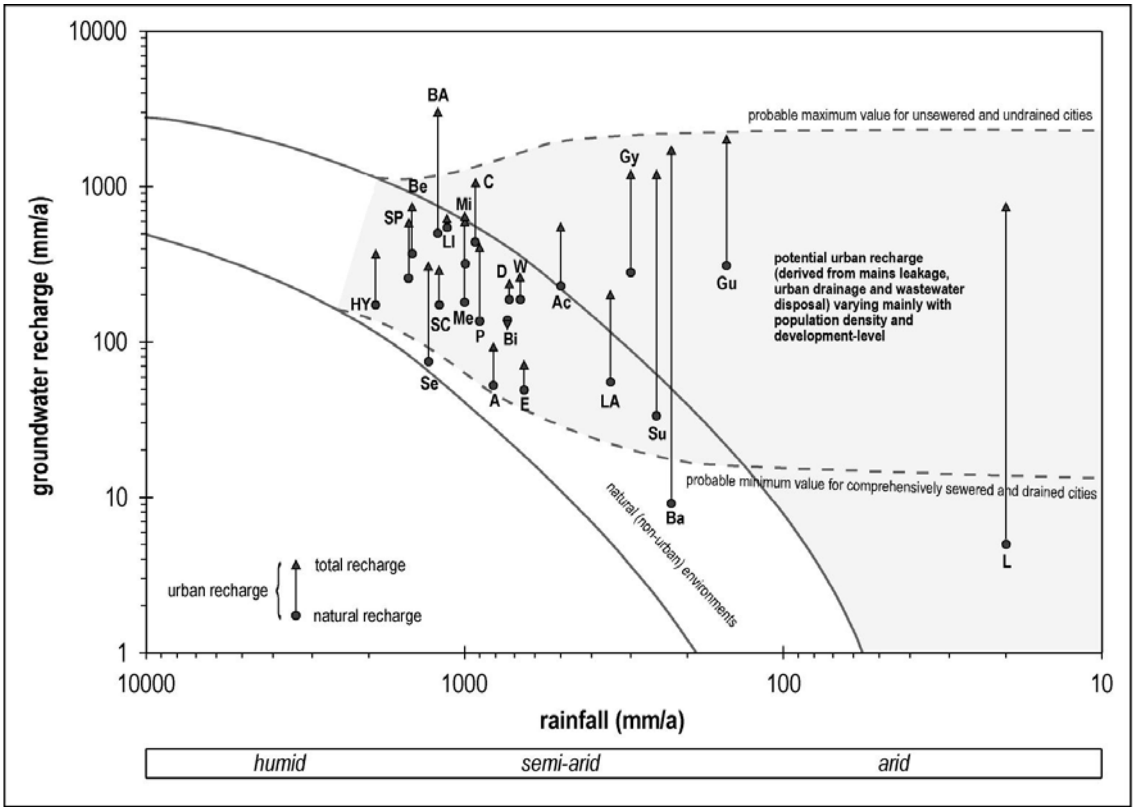

Figure 1: Urban-enhanced groundwater recharge in twenty-three cities around the world (modified from Foster et al. 1994). **HY**: Hat Yai, Thailand (Foster et al. 1994); **SP**: São Paulo, Brazil (Menegasse et al. 1999); **Be**: Bermuda, UK (Lerner 1990a); **Se**: Seoul, Korea (Kim et al. 2001); **BA**: Buenos Aires, Argentina (Foster 1990); **SC**: Santa Cruz, Bolivia (Foster et al. 1994); **LI**: Long Island (New York), USA (Ku et al. 1992); **Mi**: Milan, Italy (Giudici et al. 2001); **Me**: Mérida, México (Foster et al. 1994); **C**: Caracas, Venezuela (Seiler & Alvarado Rivas 1999); **P**: Perth, Australia (Appelyard et al. 1999); **A**: Austin (Texas), USA (Garcia-Fresca 2004); **Bi**: Birmingham, UK (Knipe et al. 1993); **D**: Dresden, Germany (Grischek et al. 1996); **W**: Wolverhampton, UK (Hooker et al. 1999); **E**: Évora, Portugal (Duque et al. 2002); **Ac**: Aguascalientes, México (Lara & Ortiz 1999); **LA**: Los Angeles (California), USA (Geomatrix 1997): **Ba**: Baku, Azerbaijan (Israfilov 2002); **Su**: Sumgayit, Azerbaijan (Israfilov 2002); **Gy**: Gyandja, Azerbaijan (Israfilov 2002); **Gu**: Gulistan, Uzbekistan (Ikramov & Yakubov 2002); **L**: Lima, Perú (Foster et al. 1994).

3.2.1 *Leakage from water mains*

Water mains are pressurized to avoid infiltration of contaminants and to insure distribution to the far reaches of the water system. Pressure is the main cause of leakages in water distribution systems. A review of the literature shows that typical values of water loss from the distribution system are around 20 to 30% (Table 2). The most efficient cities report loses around 10%, and values of 30 to 60% are common in the less developed countries. In arid climates, the amount of water distributed in a city is often significantly greater than rainfall (Foster et al. 1994). Thus, mains leakage is a consistent source of indirect groundwater recharge.

Lerner et al. (1990) proposed several indirect methods to estimate leakage from water distribution networks as direct measurements are often not practical. One method is to assume a certain percentage of the water supplied; Thornton (2002) suggests that about 60% of unaccounted water can be attributed to leakage. Other methods include mass balances of inputs and outputs to the network. External losses on consumers' premises (the "consumer's side of the water meter") are not accounted by water supply authorities. These losses may be reflected as legitimate use per property, but this can be the leakiest part of the system. Leakage rates vary spatially depending on the pressure of the water, the age and the material of the pipes, and the maintenance of the system.

Table 2: Compilation of water main or distribution system losses in various cities of the world. Some general rates are given in *italics*.

City	Water main loss [%]	Reference
Hull, UK	5	Chastain-Howley, *pers. comm.*
Los Angeles, USA	6 - 8	Geomatrix 1997, *unpub*.
Hong Kong, China	8	Lerner 1997
San Antonio, USA	8.5	Austin American Statesman 1998
Évora, Portugal	8.5	Duque et al. 2002
Milan, Italy	10	Giudici et al. 2001
Austin, USA	12	Austin American Statesman 1998
N. Auckland, NZ	12.3	Farley and Trow 2003
Toronto, Canada	14	City of Toronto 2001, *pers. comm*.
Calgary, Canada	15	Grasby et al. 1997
US average	*16*	*Thornton 2002*
Dresden, Germany	18	Grischek et al. 1996
São Paulo, Brazil	16	Menegasse et al. 1999
UK general rates	*20 - 25*	*Lerner 1997*
Göteborg, Sweden	26	Norin et al. 1999
Round Rock, USA	26	Austin American Statesman 1998
Tomsk, Russia	15 - 30	Pokrovsky et al. 1999
Amman, Jordan	30	Salameh et al. 2002
Kharkiv, Ukraine	30	Jakovljev et al. 2002
Sana'a, Yemen	30	Alderwish & Dottridge 1998
Brushy Creek, USA	33	Austin American Statesman 1998
Calcutta, India	36	Basu & Main 2001
San Marcos, USA	37	Austin American Statesman 1998
St. Petersburg, Russia	~ 30	Vodocanal 2000, *unpub*.
Developing countries	*30 - 60*	*Foster et al. 1998*
Lusaka, Zambia	45	Nkhuwa 1999
Mérida, México	~ 50	Foster et al. 1994
Lima, Perú	45 - 60	Lerner 1986
Cairo, Egypt	> 60	Amer & Sherif 1997
Some Italian systems	*> 80*	*Farley and Trow 2003*

3.2.2 *Leakage from wastewater sewers*

Reports of groundwater contamination by sewage or wastewater are numerous (e.g. Eiswirth and Hötzl 1997, Blarasin et al. 1999, Rieckermann et al. 2003) and indicate that leakage from sewers is common and widespread. When sewer lines are located below the water table, they may infiltrate groundwater, and when located above the water table they may leak. Because flows in these pipes are not under pressure, it is reasonable to assume they leak less than water mains.. Many cities lack sewerage networks and rely on septic tanks or similar systems to dispose of grey water. In these cases, most of the supplied water is recharged to the subsurface (Foster et al. 1994).

Albeit scarce within the literature, increasing efforts have recently been made to quantify wastewater leakage from sewers. The few published estimations seem to agree on leakage rates of 5% of the sewage flow through the network; these include Barcelona (Vázquez-Suňé 2003), Nottingham (Yang et al. 1999), Munich (Lerner 1997), Dresden (Grischek et al. 1996), and several other German cities (Foster et al. 1994). However, Giudici et al. (2001) report 20% losses from the sewage network in Milan.

Recently, more sophisticated methods to quantify leakage from sewage networks have been developed. For instance, Eiswirth et al. (2004) propose a software model to simulate the urban water, wastewater and stormwater systems. Another method consists on adding artificial tracers on the network, and analyzing the composition downflow in order to make a mass-balance of the introduced solutes (Rieckermann et al. 2003).

3.2.3 *Leakage from storm sewers*

Recharge from stormwater occurs under transient high-flow conditions and it is very difficult to measure and model. Lerner (2002) proposes to use an empirical approach, or to assume some proportion of the surface of the city is not impermeable, to account for this water.

3.2.4 *Septic tank infiltration*

On-site wastewater treatment systems can be assumed to recharge all the water they receive, except for some small losses to evapotranspiration, and perhaps stream baseflow. Thus, about 90% of the water supplied in unsewered cities can recharge the groundwater (Foster et al. 1994).

3.3 *Localized recharge*

Localized recharge takes place through faults, fractures, etc. and thus, it depends mainly on the geologic materials and structures, as well as the soil types in each particular area. As defined above, localized recharge is not directly related to urbanization although it can be affected by it. Numerous approaches exist for modeling flow through fractures and conduits (e.g. Sharp 1993, Halihan et al. 1999, Zahm 1998).

3.4 *Artificial recharge*

Artificial recharge consists of water intentionally applied to the subsurface and includes devices designed to enhance infiltration, as well as irrigation water in excess of plant needs.

3.4.1 *Designed infiltration structures*

A variety of man-made structures are constructed to reduce flooding, relieve the sewerage networks, and promote groundwater recharge. Such structures include recreational lakes and ponds, soakways, runoff detention ponds, retention basins, artificial infiltration ponds, spreading basins, recharge ditches, and injection wells.

It can be assumed that infiltration devices recharge all the water they receive, except for some losses to evapotranspiration and stream interflows, as is the case of septic tanks. The importance of such recharge sources depends on their abundance in a city, their location with respect to the aquifers and the particular design characteristics of each device. Maintenance plays an important role, and when clogging takes place they may become ineffective and minimize recharge.

3.4.2 *Irrigation return flow*

The water directly applied to parks and lawns, in excess of the plant requirements, will percolate and recharge the groundwater, except for some loss to evaporation and interflow. What makes this source of recharge different from effective precipitation is the intentionality of its application, as well as the uncertainties related to its quantification.

This source of recharge can be especially significant in arid and semi-arid climates. La Dell (1986) and Lerner (1990b) illustrate this with the example of Doha (Qatar), where the water table rise is directly related to the excessive irrigation of parks and lawns.

Recharge from excess irrigation can be quantified by mass balancing water supply, water use, the physical properties of the soils, and evapotranspiration (e.g. Berg et al. 1996). In arid and semi-arid areas, variations in these parameters should be obvious when comparing the drier and wetter months.

4 URBAN-ENHANCED RECHARGE IN AUSTIN, TEXAS

Austin is located in central Texas (Figure 2) has a subtropical humid climate with a mean annual temperature of 20ºC and a mean annual precipitation of 813 mm/a. It is situated within the Colorado River basin, the main source of water supply. Austin sits over a major fault zone which juxtaposes a variety of geologic materials (Rose 1972, Garner and Young 1976) including the Edwards aquifer, one of the most prolific karstic aquifers in the world, and minor hydrogeologic units within Quaternary fluvial deposits. The population has increased steadily since 1985 and at exponential rates since the 1960's, reaching 656,562 people in the year 2000.

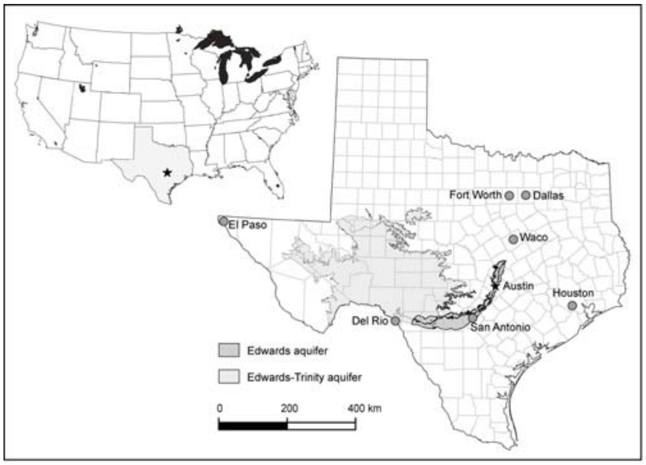

Figure 2: Location of the City of Austin and some of the major aquifers in central Texas.

This section analyzes the effects of urban development on groundwater recharge in the city of Austin. Estimations of direct recharge from precipitation were carried out by means of spatial analysis using a GIS. Contributions to groundwater recharge from urban sources were estimated by means of a water balance. The results are summarized in Table 3 and fully described in Garcia-Fresca (2004).

4.1 *Direct recharge*

A comparison of direct recharge from precipitation, before and after urbanization, was conducted in order to assess the effects of development on this type of recharge. The spatial distribution of land-uses prior and after urban development was conducted by means of a GIS (ArcGIS).

4.1.1 *Direct recharge under preurban conditions*

Direct recharge from effective precipitation prior to urban development was estimated based on the hydraulic properties of the different lithologies cropping out within the city limits. Each hydrogeological unit was isolated and an infiltration coefficient assigned, as a percentage of precipitation. Values of the infiltration coefficients were compiled from the literature for the particular outcrops, or for similar units in Texas. The infiltration coefficient for clays and shales was assumed to be 0%. Figure 3 illustrates the outcrop analysis process and two of the resulting separated outcrops: the Barton Springs segment of the Edwards aquifer, and the Quaternary deposits, with infiltration coefficients of 8 and 9% respectively. Pre-urban recharge is estimated at 53 mm/a.

4.1.2 *Direct recharge under urban conditions (year 2000)*

In this case direct recharge from precipitation was assessed in a similar fashion, as a function of the type of outcrop and the amount of impervious cover for the different urban land uses in the year 2000 (Figure 4). Direct recharge in the year 2000 is estimated to be 31 mm/a and, thus, it has decreased with increasing urban development.

4.2 *Urban sources of recharge*

A water balance of urban water supply, uses, and sewage volumes assesses the recharge available from strictly urban sources. In the year 2000, Austin put into the distribution system an average of 541,000 m^3/d, and an average of 318,000 m^3/d was treated at the wastewater treatment plants. Of interest is the fact that the maximum wastewater treatment capacity (492,000 m^3/d) cannot accommodate even the average volume of water supplied. "Excess urban water" is estimated by balancing the drinking water supplied and the wastewater treated, 85 mm/a on average, and represents the amount of water of exclusively urban origin potentially available for recharge, both as indirect and artificial recharge (Figure 5). A fraction of the excess urban water is lost to leakage from the utility networks, and the rest is assumed to be used to irrigate parks and lawns.

Table 3: Water and wastewater statistics and water balance for Austin for the year 2000. Sources of data: 1) US Census Bureau, *online*; 2) City of Austin, *online*; 3) NOAA, *online*; 4) Garcia-Fresca 2004; 5) City of Austin Water and Wastewater Utility, *personal communication*; 6) Austin American Statesman 1998; 7) TexasET, *online*.

				mm/a	
Population		656,562			*(1)*
Area		704	km^2		*(2)*
Population density		933	p/km^2		*(4)*
Mean annual precipitation				813	*(3)*
Direct recharge (preurban)				53	*(4)*
Direct recharge (urban)				31	*(4)*
Served water (w)	population served	738,229			*(2)*
	area served	710	km^2		*(2)*
	average	541,000	m^3/d	278	*(2)*
	peak	856,000	m^3/d	440	*(2)*
	max. capacity	984,000	m^3/d	506	*(2)*
Treated wastewater (ww)	population served	685,783			*(2)*
	area served	601	km^2		*(2)*
	average	318,000	m^3/d	193	*(2)*
	max. capacity	492,000	m^3/d	299	*(2)*
Excess urban water	avg w - max ww			-21	*(4)*
	avg w - avg ww			85	*avg (4)*
	max w - max ww			207	*max (4)*
Gross unbilled water	12%	64,920	m^3/d	33	*(5,6)*
Mains leakage rate	7.7%	41,657	m^3/d	21	*(4)*
Sewer leakage rate	5%	16,737	m^3/d	10	*(4)*
Irrigation	not area weighted			54	*avg (4)*
				175	*max (4)*
	area weighed to adjust for pervious/impervious cover			90	*avg (4)*
				291	*max (4)*
Plant water requirement (PWR)	not area weighted			364	*(7)*
	area weighed			219	*(4)*
	from irrigation only			22	*(4)*
Irrigation return flow				32	*(4)*
Total recharge	ET not accounted			116	*(4)*
	after subtracting PWR			94	*avg (4)*

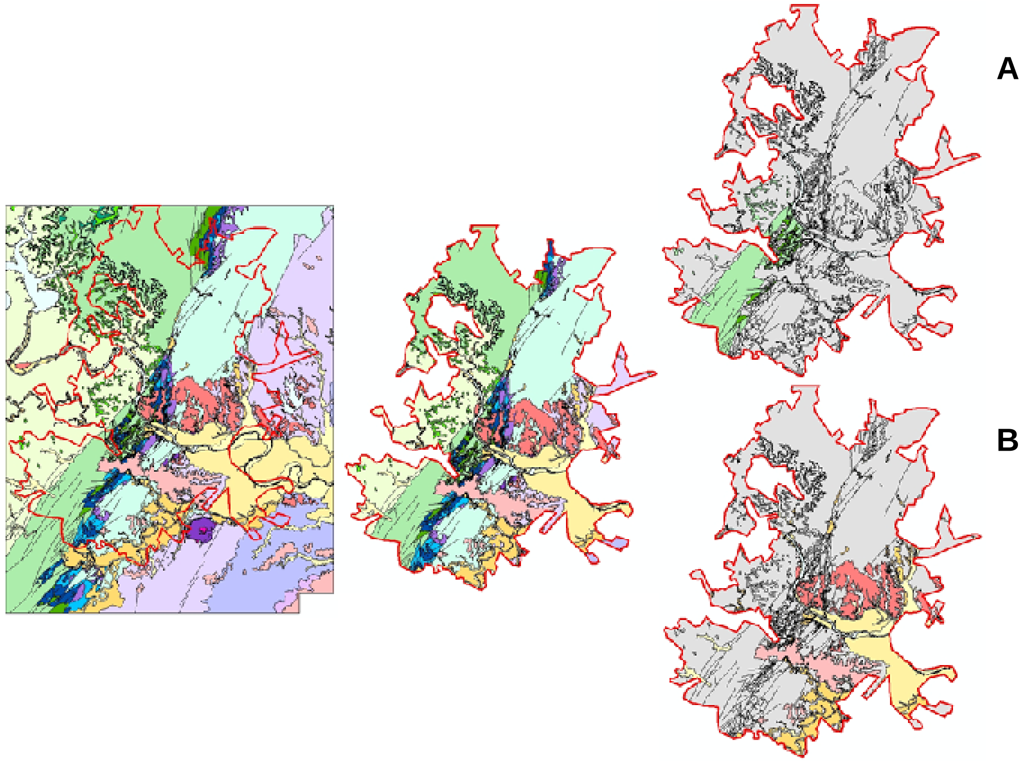

Figure 3: Outcrop analysis. The geology of the area is cropped to match the shape of the full service jurisdiction of the City of Austin (i.e. the portion of the city fully served by mains and sewers). As an example, two of the resulting separated outcrops are presented: A) the Barton Springs segment of the Edwards aquifer (infiltration coefficient, 8%) and B) Quaternary deposits (infiltration coefficient 9%).

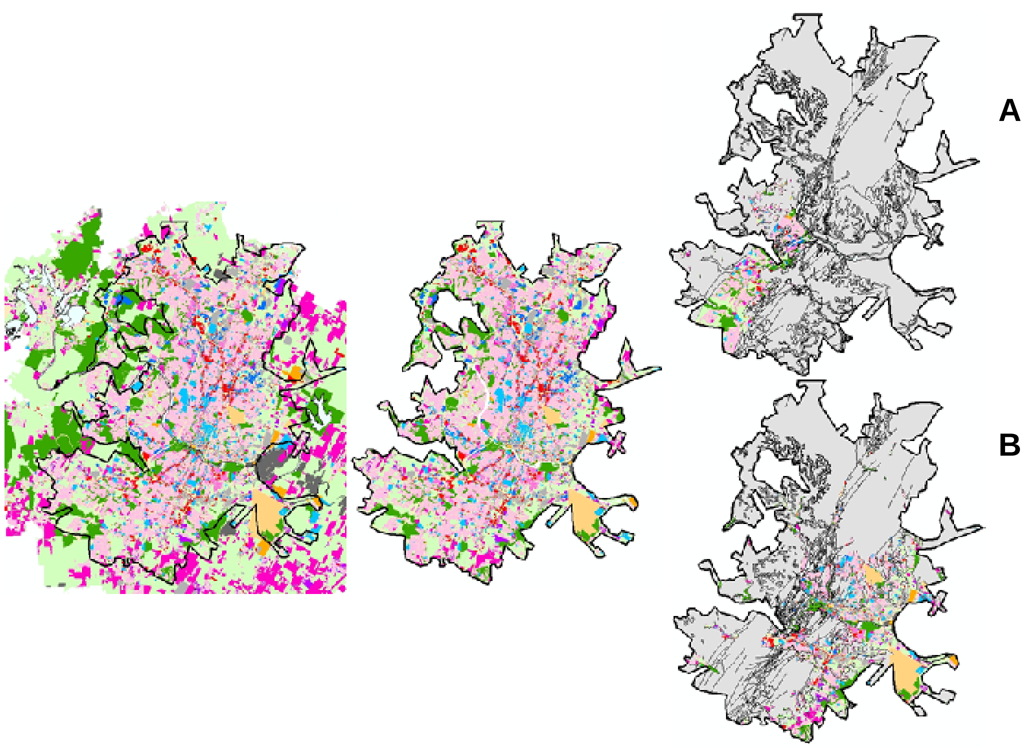

Figure 4: Land use analysis, consisting of an assessment of the different types of land cover and their percentage of impervious cover, within each outcrop. A) the Barton Springs segment of the Edwards aquifer (impervious cover, 58%) and B) Quaternary deposits (impervious cover, 2%). Data for year 2000.

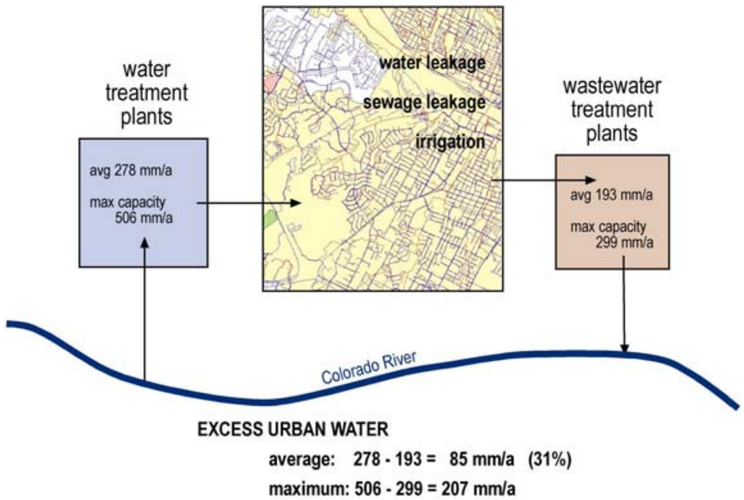

Figure 5: Excess urban water is defined as the difference between the amount of drinking water treated and the amount of waste-water treated. For the city of Austin it was a total of 85 mm for the year 2000.

The City of Austin estimates water losses as the difference between served water and billed consumption (Pedersen 2003, personal communication) as summarized in Figure 6. 12% of the water usage is "unaccounted for" or "gross unbilled" treated water. Unaccounted-for water can be broken into "unbilled uses", and "losses". Unbilled uses are estimated at 6.8% of the total treated water; these include fire fighting water, thefts, municipal swimming pools, leakage and water mains breakages (the last two represent less than 2.01% of the total treated water). The other 5.7% of the water is simply "lost". Accordingly, the water potentially available for recharge is approximately 7.7% of the water treated, which for 2000 amounts 21 mm/a. This amount is consistent with Thornton's (2002) estimate of leakage rates of approximately 60% of gross unbilled water.

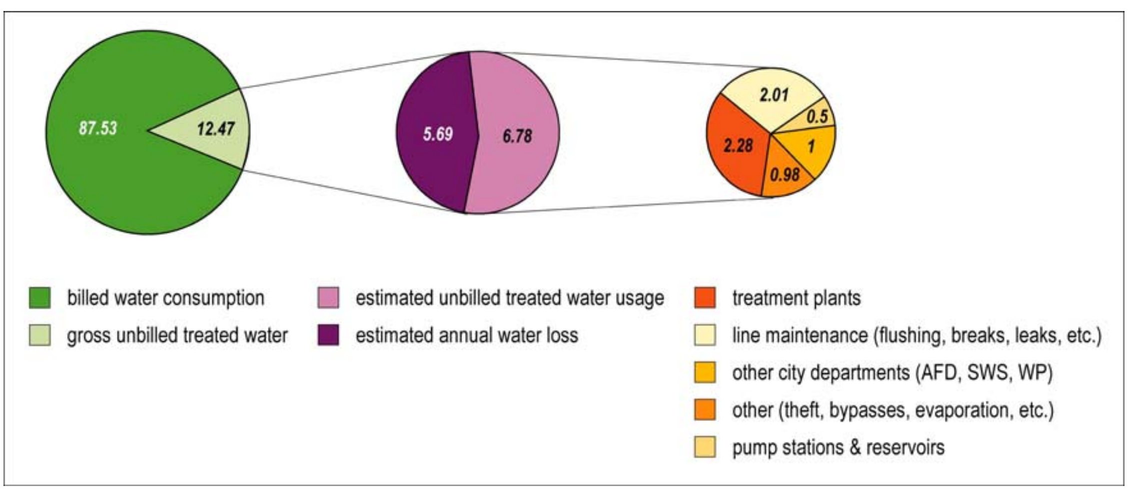

Figure 6: Water demand, usage and losses in the city of Austin, year 2000.

To estimate the sewer leakage rate, 5% of the wastewater was assumed to leak from the sewers and thus, the original amount of water that should have reached the wastewater treatment is calculated, and a leakage rate of 10 mm/a established.

Subtracting leakage rates from the excess urban water, artificial recharge must account for about 54 mm/a. Irrigation of parks and lawns is assumed to be the only source of artificial recharge and, thus, the 54 mm/a over the entire city actually represents 90 mm/a over the pervious fraction. Irrigation water not lost to evapotranspiration turns into either runoff or recharge. Plant water requirements are computed from monthly reference evapotranspiration rates for Austin for the year 2003, crop coefficients, and allowable plant stress coefficients. The relative contributions of precipitation and irrigation to evapotranspiration are assumed to be equal to their relative proportions. Irrigation and evapotranspiration are assumed to only take place in "pervious areas" and thus calculations are weighted to adjust for the relative proportions of pervious and impervious cover. Evapotranspiration from irrigation is estimated at 22 mm/a, which yields 32 mm/a of recharge from irrigation return flow.

Finally, the average total recharge in Austin is determined as the sum of direct recharge from infiltration and excess urban water, minus the plant water requirement satisfied by irrigation: 31 + 85 – 22 = 94 mm/a.

5 CONCLUSIONS

The complex network of utility trenches, tunnels, and other buried structures below cities alter the natural permeability field and affect groundwater flow and transport. Thus, the shallow urban underground can be compared to a karstic system. The "urban karst" is generated and evolves much rapidly than natural karsts.

Direct, indirect, and artificial recharge mechanisms are significantly affected by urbanization. Direct recharge from precipitation decreases with increasing urban development and is directly related to land use and the amount of impervious cover. Indirect recharge is greatly enhanced by leakage from water mains, wastewater and storm sewers, and on-site sanitation systems. Artificial recharge can be significant in cities in arid regions due to excessive irrigation and in areas with abundant designed infiltration structures. As a result, net recharge to the groundwater is enhanced by urban processes in cities globally.

In Austin, direct recharge decreased from 53 mm/a under pre-urban conditions to 31 mm/a in the year 2000. However urban sources of recharge account for an additional 85 mm/a, and a total potential recharge (94 mm/a) that almost doubles that prior to urban development.

6 AKNOWLEDGEMENTS

Thanks to professor J.M. Sharp Jr., who inspired this work, and to the kind anonymous reviewers who helped improve this paper. The Geology Foundation of The University of Texas at Austin, the Travel Grants Program of the 28th International Geological Congress Organizing Committee, and the Chevron Professorship at the Department of Geological Sciences of The University of Texas generously contributed to finance different aspects of the research presented here.

7 REFERENCES

Alderwish AM & Dottridge J (1998) Recharge components in a semi-arid area: the Sana'a Basin, Yemen. In Robins NS (ed) *Groundwater pollution, aquifer recharge and vulnerability*. London, Geological Society Special Publication No 130, p 169-177

Amer AM & Sherif MM (1997) Groundwater rise in Greater Cairo: Cause and effects on antiquities. In Chilton J (ed) *Groundwater in the Urban Environment: Problems, Processes and Management*. Rotterdam, Balkema, p 213-217

Appelyard SJ, Davidson WA, and Commander DP (1999) The effects of urban development on the utilisation of groundwater resources in Perth, Western Australia. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 97-104

Austin American Statesman (1998) 16 July 1998 edition

Basu SR & Main HAC (2001) Calcutta's water supply: demand, governance and environmental change. *Applied Geography*, v 21, p 23-44

Berg A, Byrne J, and Rogerson R (1996) An urban water balance study, Lethbridge Alberta: estimation of urban lawn overwatering and potential effects on local water tables. *Canadian Water Resources Journal*, v 21, No 4, p 17-27

Blarasin M, Cabrera A, Villegas M, Frigerio C, and Bettera S (1999) Groundwater contamination from septic tank system in two neighborhoods in Rio Carto City, Cordoba, Argentina. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 31-38

Boivin DJ (1990) Underground space use and planning in the Quebec City area. *Tunnelling and Underground Space Technology*, v 5, No 1-2, p 69-83

Bornstein R & Lin Q (2000) Urban heat islands and summertime convective thunderstorms in Atlanta: tree case studies. *Atmospheric Environment*, v 34, p 507-526

Changnon SA Jr (1976) Inadvertent weather modification. *Water Resources Bulletin*, v12, p 695-718

Chilton J et al. (1997) *Groundwater in the Urban Environment: Problems, Processes and Management*. Balkema, Rotterdam, 682 p

Chilton J (1999) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, 356 p

City of Austin (online) Water and Wastewater Utility. http://www.ci.austin.tx.us/water/ [accessed February 2003]

Coldewey WG & Meßer J (1997) The effects of urbanization on groundwater recharge in the Ruhr region of Germany. In Chilton J et al. (eds) *Groundwater in the Urban Environment: Problems, Processes and Management*. Balkema, Rotterdam, p 115-119

Duque J, Chambel A, and Madeira M (2002) The influence of urbanisation on groundwater recharge and discharge in the City of Evora, south Portugal. In Howard KWF and Israfilov RG (eds) *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres*. NATO Science Series. IV Earth and Environmental Sciences, v 8, p 127-137

Eiswirth M & Hötzl H (1997) The impact of leaking sewers on urban groundwater. In Chilton J et al. (eds) *Groundwater in the Urban Environment: Problems, Processes and Management*. Balkema, Rotterdam, p 399-404

Eiswirth M, Wolf L, and Hötzl H (2004) Balancing the contaminant input into urban water resources. *Environmental Geology* v 46, p 246-256

Farley M & Trow S (2003) Losses in water distribution networks: A practitioner's guide to assessment, monitoring and control. *International Water Association*, IWA Publishing, London, UK, 282 p

Foster SSD (1990) Impacts of urbanisation on groundwater. In Massing H, Packman J, and Zuidema FC (eds) *Hydrological Processes and Water Management in Urban Areas*. International Association of Hydrological Sciences, Publication No 198, p 187-207

Foster SSD, Morris BL, and Lawrence AR (1994) Effects of urbanization on groundwater recharge. In Wilkinson WB (ed) *Groundwater Problems in Urban Areas*. Tomas Telford, London, p 43-63

Foster SSD, Lawrence AR, and Morris BL (1998) *Groundwater in urban development – Assessing management needs and formulating policy strategies*. Washington DC, World Bank Technical Paper 390, 55 p

Garcia-Fresca B (2004) *Urban effects on groundwater recharge in Austin, Texas*. MS thesis, The University of Texas, Austin, 173 p

Garcia-Fresca B & Sharp JM Jr (in press) Hydrogeologic considerations of urban development – urban-induced recharge. In Ehlen J, Haneberg B, and Larson R (eds) *Humans as Geologic Agents*. Geological Society of America Reviews in Engineering Geology

Garner LE & Young KP (1976) *Environmental geology of the Austin area: an aid to urban planning*. The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No 86, 39 p

Geomatrix Inc. (1997) *Conceptual hydrogeologic model, Charnock wellfield regional assessment*. Unpublished report, Los Angeles

Giudici M, Colpo F, Ponzini G, and Romano E (2001) Calibration of groundwater recharge and hydraulic conductivity for the aquifer system beneath the city of Milan, Italy. International Association of Hydrological Sciences, Publication No 269, p 43-50

Grasby SE, Hutcheon I, and Krouse HR (1997) Application of the stable isotope composition of SO4 to tracing anomalous TDS in Nose Creek, southern Alberta, Canada. Applied Geochemistry, v 12, p 567-575

Grischek T, Nestler W, Piechniczek K, and Fischer T (1996) Urban groundwater in Dresden, Germany. *Hydrogeology Journal*, v 4, p 48-63

Halihan T, Sharp JM Jr, and Mace RE (1999) Interpreting flow using permeability at multiple scales. In Palmer AR, Palmer MV and Sasowsky ID (eds) *Karst Modeling*. Karst Waters Institute Special Publication No 5, Charlottesville, p 82-96

Heiken G, Fakundiny R, and Sutter J (2003) Earth Science in the City. *American Geophysical Union Special Publication Series*, v 56, 440 p

Hooker PJ, Mc Bridge D, Brown MJ, Lawrence AR, and Gooddy DC (1999) An integrated hydrogeological case study of a post-industrial city in the West Midlands of England. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 145-150

Howard KWF (2002) Urban groundwater issues – an introduction. In Howard KWF and Israfilov RG (eds) *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres*. NATO Science Series. IV Earth and Environmental Sciences, v 8, p 1-15

Howard KWF & Israfilov RG (2002) *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres*. NATO Science Series. IV Earth and Environmental Sciences, v 8, 504 p

Ikramov RK & Yakubov KHI (2002) A survey of groundwater level rise and recommendations for high water table mitigation for the city of Gulistan, Republic of Uzbekistan. In Howard KWF and Israfilov RG (eds) *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres*. NATO Science Series. IV Earth and Environmental Sciences, v 8, p 425-436

Israfilov RG (2002) Groundwater anomalies in the urban areas of Azerbaijan. In Howard KWF and Israfilov RG (eds) *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres*. NATO Science Series. IV Earth and Environmental Sciences, v 8, p 17-37

Jakovljev VV, Svirenko LP, Chebanov OJU, and Spirn OI (2002) Rising groundwater levels in North-Eastern Ukraine: Hazardous trends in urban areas. In Howard KWF and Israfilov RG (eds) *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres*. NATO Science Series. IV Earth and Environmental Sciences, v 8, p 221-241

Kim Y-Y, Lee K-K, and Sung IH (2001) Urbanization and the groundwater budget, metropolitan Seoul area, Korea. *Hydrogeology Journal*, v 9, p 401-412

Knipe CV, Lloyd JW, Lerner DN, and Greswell R (1993) *Rising groundwater levels in Birmingham and the engineering implications*. CIRIA Special Publication No 92, 114 p

Krothe JN (2002) *Effects of urbanization on hydrogeological systems: the physical effects of utility trenches*. MS thesis, The University of Texas, Austin 190 p

Krothe JN, Garcia-Fresca B, and Sharp JM Jr (2002) Effects of urbanization on groundwater systems. *Abstracts for the International Association of Hydrogeologists XXXII Congress, Mar del Plata, Agentina*, p 45

Ku HFH, Hagelin NW and Buxton HT (1992) Effects of urban storm runoff control on groundwater recharge in Nassau County, New York. *Ground Water*, No 30, p 507-514

La Dell T (1986) Rising groundwater in Doha, Qatar. Geological Society of London News, v 15, abstract

Lara GF & Ortiz FG (1999) Feasibility study for the attenuation of groundwater exploitation impacts in the urban area of Aguascalientes, Mexico. In Chilton J (ed) *Groundwater in the Urban Environment-Selected City Profiles*. Balkema, Rotterdam, p 181-187

Leopold LB (1968) *Hydrogeology for urban land planning – A guidebook on the hydrologic effects of urban land use*. US Geological Survey Circular 554, 18 p

Leopold LB (1973) River channel change with time; an example. *Geological Society of America Bulletin*, v 84, No 6, p 1845-1860

Lerner DN (1986) Leaking pipes recharge ground water. *Ground Water*, v 24, p 654-662

Lerner DN (1990a) Groundwater recharge in urban areas. In Massing H, Packman J, and Zuidema FC (eds) *Hydrological Processes and Water Management in Urban Areas*. International Association of Hydrological Sciences, Publication No 198, Wallingford, UK, p 69-76.

Lerner DN (1990b) Groundwater recharge in urban areas. *Atmospheric Environment*, v 24B, p 29-33

Lerner DN (1997) Too much or too little: Recharge in urban areas. In Chilton J et al. (eds) *Groundwater in the Urban Environment: Problems, Processes and Management*. Balkema, Rotterdam, p 41-47

Lerner DN (2002) Identifying and quantifying urban recharge: a review. *Hydrogeology Journal*, v 10, p 143-152

Lerner DN, Issar AS, and Simmers I (1990) Groundwater recharge – A guide to understanding and estimating natural recharge. *IAH International Contributions to Hydrogeology*, v 8. Heise, Hannover, 345 p

Lerner DN, Burston MW, and Bishop PK (1993) Hydrogeology of the Coventry region (UK): an urbanized, multilayer, dual porosity aquifer system. *Journal of Hydrology*, v 149, p 111-135

Menegasse LN, Duarte U, and Pereira PRB (1999) Effects of urbanisation on aquifer recharge and superficial runoff in the Sumare and Pompeia basins, Sao Paulo Municipality, Brazil. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 195-199

NOAA - National Oceanic and Atmospheric Administration (online) http://www.noaa.gov/ [accessed July 2003]

Nkhuwa DCW (1999) The need for consideration of groundwater resources in urban planning in Lusaka, Zambia. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 201-208

Norin M, Hulten A-M, and Svensson C (1999) Groundwater studies conducted in Goteborg, Sweden. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 209-216

Pokrovsky DS, Rogov GM, and Kuzevanov KI (1999) The impact of urbanization on the hydrogeological conditions of Tomsk. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 217-223

Rieckermann J, Kracht O, and Gujer W (2003) How "tight" is our sewer system? Swiss Federal Institute for Environmental Science and Technology, *EAWAG News* No 57, p 29-31

Rose PR (1972) *Edwards Group, surface and subsurface, central Texas*. The University of Texas Bureau of Economic Geology Report of Investigations No 74 198 p

Salameh E, Alawi M, Batarseh M, and Jiries A (2002) Determination of trihalomethanes and the ionic composition of groundwater at Amman City, Jordan. *Hydrogeology Journal*, v 10, p 332-339

Seiler K-P & Alvarado Rivas J (1999) Recharge and discharge of the Caracas Aquifer, Venezuela. In Chilton J (ed) *Groundwater in the Urban Environment- Selected City Profiles*. Balkema, Rotterdam, p 233-238

Sharp JM Jr (1993) Fractured aquifers/reservoirs: approaches, problems, and opportunities. In Banks D and Banks S (eds) Hydrogeology of Hard Rocks. *Memoir of the XXIV Congress, International Association of Hydrogeologists*, Oslo, v 24, No 1, p 23-38

Sharp JM Jr, Hansen CN, and Krothe JN (2001) Effects of urbanization on hydrogeological systems: the physical effects of utility trenches. In Seiler K-P and Wohnlich S (eds) *New Approaches Characterizing Groundwater Flow, supplement volume*. Proceedings of the International Association of Hydrogeologists XXXI Congress, Munich, Germany, 4 p

Sharp JM Jr, Krothe J, Mather JD, Garcia-Fresca B, and Stewart CA (2003) Effects of urbanization on groundwater systems. In Heiken G, Fakundiny R, and Sutter J (eds) *Earth Science in the City*. American Geophysical Union Special Publication Series, v 56, p 257-278

Simmers I (1998) Groundwater recharge: an overview of estimation 'problems' and recent developments. In Robins NS (ed) *Groundwater Pollution, Aquifer Recharge and Vulnerability*. Geological Society Special Publication No 130, London, p 107-115

TexasET – Texas Evapotranspiration network (online) http://texaset.tamu.edu [accessed March 2004]

Thornton J (2002) *Water Loss Control Manual*. McGraw-Hill, New York, 526 p

US Census Bureau (online) http://www.census.gov/ [accessed November 2003]

Vázquez-Suñé E (2003) *Urban groundwater. Barcelona City case study*. Doctoral Thesis, Universitat Politécnica de Catalunya, Departament d'Enginyeria del Terreny, Cartográfica I Geofísica, unpublished, 134 p

Worthington SRH (2003) A comprehensive strategy for understanding flow in carbonate aquifers. In Palmer AN, Palmer MV, and Sasowsky ID (eds) *Speleogenesis and Evolution of Karst Aquifers*. Karst Modeling Special Publication No 5, The Karst Waters Institute, Charles Town, p 30-37

Yang Y, Lerner DN, Barrett MH, and Tellam JH (1999) Quantification of groundwater recharge in the city of Nottingham, UK. *Environmental Geology*, v 38, p 183-198

Zahm CK (1998) Use of outcrop fracture measurements to estimate regional groundwater flow: Barton Springs segment of Edwards Aquifer, central Texas. MS thesis, The University of Texas, Austin, 154 p