# Identifying and quantifying urban recharge: a review

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**Abstract** The sources of and pathways for groundwater recharge in urban areas are more numerous and complex than in rural environments. Buildings, roads, and other surface infrastructure combine with man-made drainage networks to change the pathways for precipitation. Some direct recharge is lost, but additional recharge can occur from storm drainage systems. Large amounts of water are imported into most cities for supply, distributed through underground pipes, and collected again in sewers or septic tanks. The leaks from these pipe networks often provide substantial recharge. Sources of recharge in urban areas are identified through piezometry, chemical signatures, and water balances. All three approaches have problems. Recharge is quantified either by individual components (direct recharge, water-mains leakage, septic tanks, etc.) or holistically. Working with individual components requires large amounts of data, much of which is uncertain and is likely to lead to large uncertainties in the final result. Recommended holistic approaches include the use of groundwater modelling and solute balances, where various types of data are integrated. Urban recharge remains an under-researched topic, with few high-quality case studies reported in the literature.

**Résumé** Les origines et les trajets de la recharge des nappes en zones urbaines sont plus nombreux et plus complexes qu'en zones rurales. Les bâtiments, les routes et les autres infrastructures de surface se combinent avec les réseaux de drainage artificiels en modifiant les voies d'écoulements des précipitations. Une partie de la recharge directe est perdue, mais une recharge supplémentaire peut intervenir à partir des systèmes de drainage d'eaux pluviales. Des quantités importantes d'eau sont importées dans la plupart des villes pour l'alimentation, sont distribuées par des conduites souterraines et sont collectées dans des égouts ou des fosses septiques. Les fuites de ces réseaux de conduites constituent souvent une part importante de la recharge. L'origine de la recharge en zones urbaines est mise en évidence grâce à la piézométrie, aux signatures chimiques et aux bilans hydrologiques. Ces trois approches posent des problèmes. La recharge est quantifiée soit à partir de ses composantes individuelles (la recharge directe, les fuites d'eaux des réseaux, les fosses septiques, etc.), soit de façon globale. Pour travailler avec les composantes individuelles, il faut de grandes quantités de données, dont beaucoup comportent des incertitudes, et le résultat final présentera vraisemblablement des incertitudes importantes. Les approches globales recommandées s'appuient sur la modélisation de l'aquifère et les bilans de solutés, dans lesquels différents types de données sont intégrés. La recharge en zone urbaine reste un sujet délaissé par la recherche, offrant dans la littérature peu d'études de cas de bonne qualité.

**Resumen** Las fuentes y vías de recarga en zonas urbanas son más numerosas y complejas que en medios rurales. Los edificios, carreteras y otras infraestructuras superficiales se combinan con las obras antrópicas de drenaje para modificar las vías de infiltración. Una parte de la recarga directa se pierde, pero puede haber contribuciones adicionales a partir de los sistemas de drenaje de aguas pluviales. Se importa grandes volúmenes de agua a la mayoría de las ciudades para abastecimiento, siendo distribuida por medio de tuberías subterráneas, y recogida de nuevo en alcantarillas o fosas sépticas. Las pérdidas en las redes de distribución a menudo aportan una recarga substancial. Las fuentes de recarga en zonas urbanas se identifican mediante la piezometría, trazadores químicos y balances de agua, pero los tres métodos presentan problemas. La recarga se cuantifica bien por sus componentes individuales (recarga directa, goteo en tuberías, fosas sépticas, etc.) o bien de forma holística. La primera opción requiere muchos datos, a menudo inciertos, y es probable que se obtengan enormes incertidumbres en el resultado final. Los enfoques holísticos recomendados abarcan el uso de modelos de aguas subterráneas y de balance de soluto, los cuales integran varios ti-

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pos de datos. La investigación de la recarga en zonas urbanas continua siendo secundaria, disponiéndose de pocas referencias a estudios aplicados de alta calidad.

**Keywords** Groundwater recharge · Urban groundwater · Rainfall/runoff · Unsaturated zone · General hydrogeology

## Introduction

Hydrologists once believed that cities reduced the amount of recharge to the underlying groundwater because of impermeabilisation of surfaces. This myth has been widely discredited since a mainly British group of hydrogeologists began to present research from various cities around the world (e.g. Lerner 1986a, 1990; Brassington and Rushton 1987; Rushton et al. 1988; Price and Reed 1989; Foster 1990). Now most hydrogeologists accept that the infrastructure for water supply and storm drainage generates large amounts of recharge through leaks. In almost all environments, urbanisation leads to an increase in recharge (Fig. 1). Urban recharge is variable in time, responding to changes in land use and subsurface infrastructure as well as to climatic changes. Unfortunately, estimating urban recharge is difficult, and little research has been done on methodologies or on individual cities over the last decade. This paper reviews the issues of urban recharge, identifies difficulties and typical approaches adopted, and makes some suggestions for the benefit of practitioners who need to make recharge estimates and cannot afford to carry out a research study.

## Sources of Urban Recharge

### *Pathways for Precipitation to Groundwater*

The routes that rainwater takes from the sky to rural aquifers are well described by de Vries and Simmers (2002, this volume). They discuss a conceptual division into three types of spatial distribution: direct, localised, and indirect. Direct recharge is an areally distributed process that happens below the point of impact of the precipitation by vertical movement through the unsaturated zone. This process differs from the line or point processes of localised recharge, where water moves short distances laterally before infiltration, perhaps from rivulets or into fractures. Indirect recharge describes the pro-

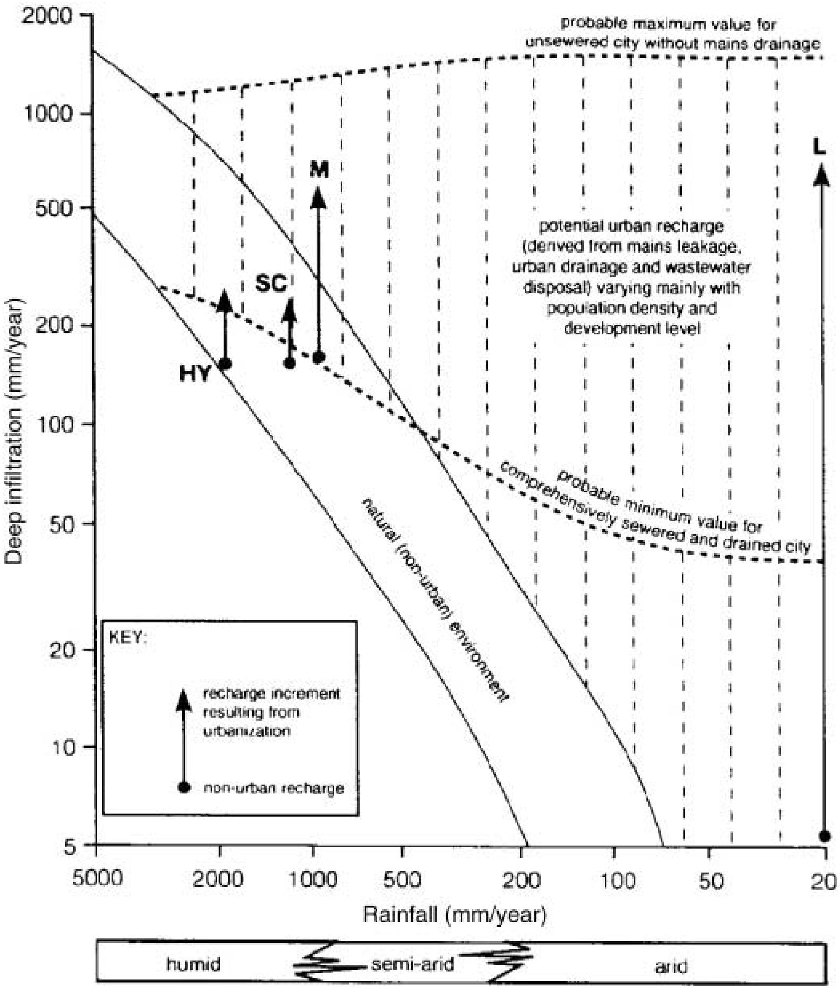


**Fig. 1** Potential increase in deep infiltration to unconfined aquifers due to urbanisation. *L* Lima; *M* Merida; *SC* Santa Cruz; *HY* Hat Yai. (Modified from Foster et al. 1999)

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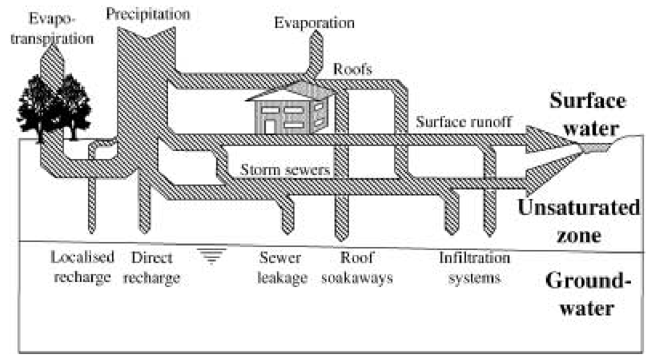


**Fig. 2** Pathways for precipitation to recharge groundwater in urban areas

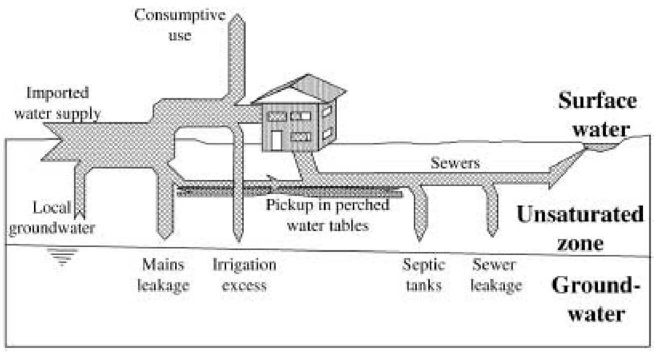


**Fig. 3** Routes for water supply and sewage to recharge urban groundwater

cesses where recharge occurs from runoff into mappable features, such as rivers and sinkholes.

The brief discussion of recharge above hints at the complexity of the surface and subsurface processes that occur in rural situations. However, the urban environment is even more complex. Not only do many impermeable areas exist, such as roads, but a dense network of drainage channels and drains is present to carry away storm water, at least in developed countries. Figure 2 illustrates schematically some of the many routes by which precipitation recharges groundwater in urban areas. In addition to direct recharge in parks and gardens, localised recharge often occurs along the edges of paths and roads where no formal storm drainage exists. This case is likely to occur in arid and semi-arid areas and in many rapidly urbanising cities, where little storm-drainage infrastructure exists. Roof runoff infiltrates through soakaways, and infiltration basins and boreholes are used to dispose of some storm runoff (Price 1994). Thus, many more routes exist for urban than for rural recharge. In addition, Fig. 2 does not represent the multiplicity of locations where each route occurs, caused by the high variability of land use and the complexity of the water-carrying infrastructure.

### Imported Water Pathways

The ideas underlying Fig. 2 show that identifying and quantifying urban recharge are complex and difficult when considering precipitation as a source. In addition, another source of water is available for recharge which is as large or larger than the direct recharge. Virtually all cities import water in order to satisfy the demand for public and industrial water. Lerner (1990) gives some specific examples to compare water-supply rates with rainfall. For temperate European cities, the rates are very similar: for example, in Birmingham, UK, both are 650–750 mm/year. In arid climates, in very densely developed cities, and in city centres such as Hong Kong, water-supply rates are commonly an order of magnitude larger than rainfall.

With such large amounts of water being imported in cities, many opportunities exist for extra recharge to occur. Figure 3 summarises the main routes. If no sewers are present to take wastewater away, the most important recharge route would be the infiltration of wastewater from large numbers of septic tanks, latrines, and soakaways. In such cities, most of the imported water recharges the aquifer. In cases where sewers are used to remove effluents, much of the imported water is re-exported and does not become recharge. A potential exists for leakage from sewers, and Lerner et al. (1994) and Misstear and Bishop (1997) provide evidence that such leakage does occur in Britain and Ireland.

The fact that the water mains leak is more important than the effects of sewers in sewered cities. Rates of leakage of 20–25% are common, and rates up to 50% have been observed (Lerner 1986a), causing large amounts of recharge. In Tomsk, Russia, 4–11 leaks develop every year per kilometer of water main, leading to leakage rates of 15–30% (Pokrovsky et al. 1999). A leakage rate of 26% is reported for Göteborg, Sweden (Norin et al. 1999).

Another problem that has been observed in high-income arid climates is over-irrigation of parks and gardens, with the excess water becoming groundwater recharge. One example is Riyadh, Saudi Arabia, where the excess recharge has caused groundwater flooding in road underpasses and the death of many ornamental plants (Rushton and Alothman 1994).

As with precipitation recharge, the overriding characteristic of recharge from water-supply systems is the complexity of the infrastructure. Locating this infrastructure and then determining losses from it is a daunting task in any city.

### Identifying Recharge Sources

Prior to quantifying urban recharge, the hydrogeologist should identify whether the various sources discussed above are present. This effort could be at a local scale for a pollution study or at a city-wide scale for a water-resources study. At a local scale, the process involves identifying every water main and sewer, storm drain, soakaway, septic tank, area of irrigation, and impermeable surface, and then finding all the recharge points associat-


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ed with them. Based on an analysis of maps for Nottingham, UK, about 50 km of water-carrying pipes (water mains, sewers, and drains) exist per square kilometer of urban area in the UK. Göteborg has 16 km of water main per square kilometer of urban area (Norin et al. 1999). One can imagine consulting records and conducting surveys on the surface, perhaps using remote sensing, aerial photography, and geophysics, to obtain information on this infrastructure and its condition. The complexity of the urban environment means that a very large amount of data would be needed to identify every possible recharge source, and the cost is likely to be prohibitive for the value of the data collected. In some cities, the water utility and the municipal authority have developed a GIS system that shows all the water infrastructure; this is standard practice in the UK. Without the availability of such a database, probably the only realistic operations would be to positively identify a few examples of the sources. These examples may be of value in convincing city engineers and water-resource planners that there are issues to be addressed. Some value may result in studying a few examples in detail to determine whether any general characteristics could be applied to the whole city. For example, Eiswirth et al. (1995) were able to demonstrate by a variety of techniques that specific sewers were leaking into groundwater. Groundwater-based methods for detecting recharge at a local scale include the use of piezometry and chemical signatures, as discussed below.

When studying urban recharge at a regional scale, the interest is no longer in identifying individual points of recharge. Rather, the objective is to show that sufficient individual sources of, say, water-main leakage exist to have an impact on overall urban recharge. The use of chemical signatures and water balances is probably the only viable method at this scale.

### Piezometry

Continuously flowing point sources of recharge, such as leaking mains, cause local, steady mounding of the water table. Intermittent recharge sources, such as storm-water infiltration systems, cause transient, often short-lived, responses in piezometric levels. Both types of signature are detected by a sufficient density of measurements. The difficulty lies in knowing where to put the piezometers, because the locations of the recharge points are not usually known in advance. In addition, access for piezometer installation is difficult in urban areas; such access requires the goodwill of land owners and a detailed knowledge of the subsurface infrastructure in order to avoid damage.

An example of the successful use of piezometry to detect some urban-recharge sources is a geotechnical study of the heavily built-up Mid-Levels area of Hong Kong Island (Lerner 1986b). The main objective of the study was to understand the mechanisms of failure of the steep slopes; these mechanisms were partially governed by piezometric levels and recharge sources. More than 400 piezometers, many with continuous recording of heads, were installed. Lerner (1986b) gives two examples where leakage from the water-supply system could be identified by unexpectedly high water-table levels. He also discusses the transient response of piezometers. In these steep slopes, several possible causes of rapid transients after heavy rainfall exist, including rapid vertical recharge, downslope throughflow along preferential pathways, soakaway drainage, and leaking storm drains. These multiple causes of transient responses make it difficult to interpret the Hong Kong data. Transient responses are easier to interpret in ordinary aquifers, where vertical recharge responses can be separated, and rapid downslope flow is not present.

### Chemical Signatures

The concentrations of various solutes in a water, or the ratios between solute concentrations, define the chemical signature of that water. Such signatures are widely used in hydrogeology to identify waters and their origins (Lloyd and Heathcote 1985), and potential exists for using such markers for identifying various sources of urban recharge. Barrett et al. (1999) argue that an ideal recharge marker is an easily analysed solute that is unique to one source and to one pathway, at a constant concentration in the source, and non-reactive in all conditions. They point out that such solutes are rare. They summarise the potential marker solutes into four categories, as follows:

1. *Inorganic*, which are further grouped into major cations (Ca, Mg, K, and Na) and anions ($HCO_3$, $SO_4$, and Cl), nitrogen species ($NO_3$ and $NH_4$), metals (Fe, Mn, and trace metals), and other minor ions (B, $PO_4$, Sr, F, Br, and CN).
2. *Organic*, of which the most relevant are chlorofluorocarbons (CFCs); trihalomethanes (THMs); faecal compounds, such as coprostanol and 1-aminopropanone; detergent-related compounds, such as optical brighteners and EDTA; and industrial chemicals, including chlorinated solvents and many hydrocarbons.
3. *Particulate*, including faecal microbiological species and various colloidal particles.
4. *Isotopic*, particularly the stable isotopes ($^{2}H$, $^{15}N$, $^{18}O$, and $^{35}S$).

Table 1 summarises the potential sources of these solutes in groundwater and shows that multiple sources exist for most potential tracers. For example, B is a component of domestic detergent but is found in industrial processes and also has a geochemical origin (Barth 1998). Therefore, its presence in groundwater is not in itself proof of leaking sewers or infiltration from septic tanks. The same difficulty applies to virtually all other tracers in Table 1, and no universally applicable tracers are known for identifying recharge sources.

Occasionally, the use of a tracer, particularly isotopes, identifies a source of urban recharge. An example is given by Seiler and Alvarado Rivas (1999) for Caracas,

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**Table 1** Sources of possible marker species. Numerous environmental tracers are available to identify the sources of recharge, but most of the tracers can enter groundwater from multiple sources, as shown in the table

| Group of marker species | Potential sources of solutes | | | | | |
|---|---|---|---|---|---|---|
| | Atmosphere | Geological materials | Agriculture | Mains water | Sewage | Industrial and commercial sites |
| Major cations and anions | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| N species ($NO_3$, $NH_4$) | ✓ | | ✓ | ✓ | ✓ | ✓ |
| B and P | | ✓ | | | ✓ | ✓ |
| Other minor ions | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Heavy metals | | ✓ | | | ✓ | ✓ |
| Chlorofluorocarbons (CFCs) | ✓ | | | ✓ | ✓ | ✓ |
| Trihalomethanes (THMs) | | | | ✓ | ✓ | ✓ |
| Faecal organic compounds | | | | | ✓ | |
| Organics in detergents | | | | | ✓ | ✓ |
| Industrial organic chemicals | | | | | ✓ | ✓ |
| Microbiological species | | | | | ✓ | |
| Colloidal particles | | | | | ✓ | ✓ |

Venezuela. The water supply comes from surface water in neighbouring catchments and, once treated and supplied to the city, has a distinct $^2H$–$^{18}O$ signature from the local natural recharge. Groundwater from under the city has $^2H$–$^{18}O$ ratios that lie on a mixing line between the water supply and meteoric water, demonstrating that a significant proportion of recharge is treated water from water mains or sewers.

In other cases, combining the evidence from multiple tracers has greatly increased confidence in the outcome, despite the uncertainties involved in determining the origin of each individual tracer. An example is given by Barrett et al. (1999) for a 1-km$^2$ study area in Nottingham. They convincingly argue that leakage from sewers could be detected in 8 out of 10 boreholes by combining the evidence of microbiological tracers (faecal bacteria), nitrogen-isotope ratios, and the presence of limonene, a component of some detergents.

### Water Balances

In some cases, the existence of a source of recharge is confirmed by a water balance on the source water. For example, leakage rates of 25% from water mains would be a noticeable item in the water balance of the water supply. However, such an approach does not work when the recharge is a small proportion of the water balance, when the data have high uncertainty, or when alternative destinations exist for the water. For example, Lerner et al. (1993) attempted a water balance on the Coventry, UK, wastewater network. They compared estimated inflows to the sewer network, based on water-supply data, with the measured flow entering the sewage-treatment works. The results are inconclusive, because almost certainly both inflow and outflow occur between the sewers and groundwater, and the difference between inflow and outflow is well within the margin of error that results from differencing two large numbers.

## Quantifying Urban Recharge

### Complexity of the Problem

Estimates of recharge at a point or over a small area can always be made, even in urban areas, using any of the classical techniques (Lerner 1997; other papers in this volume). However, water-resources and regional pollution studies require areal totals of recharge, which are difficult to obtain in an urban setting. The discussions above highlight just how complex the urban environment is, and that it is not realistic to quantify each individual point source or subarea of recharge. This paper deals exclusively with areal recharge estimates.

In most cases, urban recharge estimates are made for zones, as is usually done for rural water-resource studies. The zones are chosen to be reasonably uniform in land use (industry, city centre, or residential), soil type, and water infrastructure (type of sewers and storm drainage). They may be delineated on the basis of age of property, because plot sizes, ratio of paving to garden, and water infrastructure are often reasonably uniform for a particular age of development.

The following two sections describe how to estimate the individual components of precipitation and water-supply recharge. However, each component is complex, little research is available to support such estimations, and the uncertainties are high. The third section suggests that the practitioner should consider taking an approach in which the entire recharge amount is estimated as a whole instead of as complex components.

### Precipitation Recharge

At its simplest level, the water-balance equation for urban precipitation is:

$$\text{Precipitation} = \text{Evapo(transpi)ration} + \text{Runoff} + \text{Recharge} \quad (1)$$

A useful estimate of recharge cannot probably be obtained by applying Eq. (1) at the city-wide scale. The

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problem of looking for small differences between large numbers is alluded to above. When one considers the errors in measuring the total volume of storm flow from a city, or in getting a good estimate of actual evapotranspiration, Eq. (1) probably is not an accurate enough method to estimate recharge, or even to distinguish between the results of rural and urban analyses. This situation suggests that an analysis of each of the recharge components is more likely to be satisfactory. However, as shown below, this approach has as many problems as an integrated approach.

Figure 2 identifies the urban recharges arising from precipitation as direct, localised, leaking sewers, and storm-water infiltration systems; the last combines several different recharge routes. These sources are considered individually below.

The conventional method to estimate *direct recharge* in humid climates is a soil-moisture balance (SMB). Separate SMBs may be developed for each vegetation and soil type, or a factoring scheme may be used with a standard SMB result. These methods apply equally as well to urban settings as they do to agricultural and natural settings. In an urban setting, different land uses and plant types exist. Extensive parks often exist; heavy usage (sports, car parks) acts to overcompact the soils, whereas extensive cultivation (gardens) increases infiltration rates. Irrigation is often an important part of the urban SMB. Irrigation protocols are very different in urban settings compared to agricultural areas, with significantly higher application rates for amenity land uses such as golf courses and gardens.

No research is known on the significance of *localised recharge* in urban areas. Most cities have many paths, car parks, compacted soils, driveways, and other low-permeability surfaces that do not have any storm drainage associated with them. Very likely significant localised recharge occurs, but little or no evidence exists for this, and no data are available to quantify the amounts. A practical but unproven suggestion is as follows. If such localised recharge occurs, it passes through the soil zone and so plays some part in the SMB. Hence, a proportion of the impermeable area should be treated as permeable (perhaps 50%), particularly in residential areas. Sudicky et al. (2000) have developed a fully integrated, high-resolution, surface–unsaturated zone–groundwater numerical model. They are currently attempting to quantify the direct and localised recharge processes in an urban area by modelling about 10 $km^2$ at a 5- to 10-m horizontal resolution (Ed Sudicky, University of Waterloo, personal communication, March 2001). If successful, this exercise would provide valuable insights into urban recharge and runoff processes.

*Storm-water recharge* is also difficult to estimate. This source consists of localised recharge, as discussed above; recharge through soakaways on individual properties; leaks from storm sewers, drains, and ditches; infiltration from storm-retention ponds; and deliberate artificial recharge through infiltration boreholes and basins. To make good estimates, the practitioner needs information describing the storm drainage network and giving its condition, namely, where are all the drains and are they leak-proof? Then comes the problem of estimating leakage rates, given that leakage occurs mainly in transient conditions at high-flow times, when measurement is difficult. In cities where all road runoff is diverted to infiltration basins, such as Perth, Australia, measurements of inflows to representative basins provide a good estimate of recharge, but these cases are the exception. In most cases, the practitioner should adopt a simple empirical approach, either by assuming that a proportion of storm flow (or rainfall) becomes recharge, or by ignoring the effects of impermeabilisation for part of the land surface (as suggested above for localised recharge).

### Water Supply and Wastewater

Figure 3 identifies the principal routes of imported water to groundwater as leaking water mains and sewers, infiltration from septic tanks (and similar wastewater facilities), and over-irrigation. Any water infrastructure is likely to leak and thus may result in recharge. Thus, a complete urban water balance should take account of fountains, lakes, and other amenity systems; canals, which are often above the water table; fresh- and wastewater lagoons; and other structures.

In unsewered cities, an overall water balance of the water supply and disposal system is probably the most practical method of estimating recharge. This approach requires only a measurement of the total imported water supply and an estimate of consumptive use. The latter includes the small amounts of water evaporated by respiration, cooking, and washing; and the potentially larger amounts of evapotranspiration from irrigation water and evaporation and export in industrial processes. In sewered cities, this overall water balance may also be feasible if the outflow of sewage is measured. However, sewer systems are rarely completely isolated from storm-water and groundwater infiltration (into sewers), and so the measured outflow is often much larger than the amount of wastewater discharged to the sewers. An overall water balance is unlikely to be useful in these cases.

If wastewater is exported through sewers, then the major contribution of recharge from water supply is leaking *water mains*. Water balances on the water-supply network are the usual way to estimate losses and are routinely carried out by many water-supply utilities. The conventional approach is to measure the minimum night flow (MNF; Lerner 1988). A zone of the city is isolated so that all water supply flows through one pipe in which the flow is measured during the night-time, between 2 and 4 a.m. Because legitimate uses of water are very small at such times, the inflow to the zone is often taken to be the rate of leakage. Some legitimate uses may occur, such as automatically flushing toilets or 24-h operations in factories, restaurants, and other commercial enterprises. A proportion of the leakage takes place on consumers' premises through leaking taps, and this loss is likely to end up in the sewer rather than as recharge. Provided caution is used and such effects are discounted, MNFs provide useful estimates of recharge from leakage.

Leaking *sewers* are less significant as a recharge source than water mains, although they may be very important sources of pollution. The depth of sewers relative to the water table is probably the major control on leakage rates. Sewers below the water table tend to collect groundwater, and only those above the water table leak outwardly. Yang et al. (1999) observe that only 5% of the recharge in Nottingham is from leaking sewers. Eiswirth and Hotzl (1997) suggest that the total leakage from sewers in Germany is 100 $Mm^3$/year and is the main source of pollution in various cities. As discussed earlier, water balances on sewer systems are very difficult to achieve, because of storm-water ingress and groundwater infiltration. However, no other satisfactory methods are known, and practitioners should continue to estimate the proportion of sewer leakage by empirical and water-balance methods.

*Over-irrigation* commonly occurs in climates with dry seasons that adversely affect gardens. Over-irrigation occurs when the cost of water is low relative to incomes and the amenity value of water. Thus it is common in arid and semi-arid climates, in the oil-rich states of the Middle East, and where water is free or economically priced. For example, Perth, Australia, has 135,000 well points used for irrigating gardens (S.J. Appleyard, Rivers and Waters Commission, personal communication, 2000). Such water is free, except for electricity costs. The soil is very permeable and has low organic-carbon content. At least 25% of the irrigation water applied to gardens is estimated to recharge the aquifer; most of this water has already been recharged to the aquifer within the urban area, so the net effect of irrigation is to reduce the amount of urban groundwater. The situation in Perth is complicated by the use of imported water from the mains for irrigation; this practice gives a mixed signature in the aquifer. In other countries, Foster (1990) points out that the labourers employed to irrigate gardens are inclined to over-water rather than under-water to avoid any stress on plants and possible disciplinary action that could result. No general method is available to estimate the effects of over-irrigation, except to include it in the SMBs for direct recharge. This approach requires information on irrigation amounts, perhaps from surveys of sample areas or from metering records.

## Holistic Approaches

The complexity of urban-recharge processes and the lack of data on many aspects make it difficult to reliably estimate all the components of urban recharge. An alternative approach is to use methods that estimate the total recharge and thereby neglect the subdivisions. These methods have their own uncertainties, but, because they use many fewer data than the component methods, the final error range is probably similar in the two cases. In a textbook on recharge estimation, Lerner et al. (1990) proposes some very simple rules of thumb to estimate urban recharge in different environments. A recent literature search revealed no evidence that these suggestions have been used or commented upon. These rules of thumb are for rapid "engineering" estimates of recharge. This section describes three more sophisticated methods; two, groundwater modelling and solute balances, are recommended, and a third, piezometry, is not.

### Groundwater modelling

Numerical models of groundwater flow solve an equation such as (for unconfined aquifers):

$$S_y \frac{\partial h}{\partial t} = K\left[\frac{\partial}{\partial x}h\left(\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}h\left(\frac{\partial h}{\partial y}\right)\right] - Q(x,y,t) + R(x,y,t) \quad (2)$$

where $S_y$ is specific storage, $h$ is groundwater head, $t$ is time, $K$ is hydraulic conductivity, $x$ and $y$ are co-ordinates, $Q$ is discharge and is a function of location and time, and $R$ is recharge, which is also a function of location and time. Normally the equation is solved for $h$, with $Q$ and $R$ being known and $S$ and $K$ being data or parameters that are calibrated.

$R$ can be a calibration parameter. That is, available data on all other parameters and state variables can be used to estimate recharge by calibrating a groundwater flow model. The calibration can be by manual trial and error, or can be semi-automated. The automated process has become easier in recent years with the advent of inverse modelling codes such as UCODE (Poeter and Hill 1999).

A strong inverse correlation usually exists between recharge $R$ and hydraulic conductivity $K$ when calibrating a flow model against groundwater heads. Thus the calibration process generally provides an estimate of $R/K$ rather than an estimate of $R$ alone. Separation of these parameters requires additional information, such as calibration data on the water balance or on the movement of tracers in the aquifer. This issue is discussed in more detail by Sanford (2002, this volume).

An example of a trial-and-error calibration of an urban groundwater model is that of Birmingham, UK, in a study of rising groundwater (Greswell et al. 1994). Some empirical formulae were used to obtain a first estimate of recharge. A model was then calibrated for 1850–1990, with recharge as one of the changeable parameters. Nottingham is an urban modelling case study in which solute data were used to constrain the calibration, as outlined in the next section (Yang et al. 1999).

### Solute balances

Information on solute loadings to an aquifer and concentrations in groundwater are used to analyse the subdivi-

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sion of recharge into some of its components. If the solute is conservative and loadings and concentrations are in steady state, the concentration of a solute in groundwater is given by:

$$C_i = \frac{1}{R}\sum R_j C_j \tag{3}$$

where $C_i$ is the average concentration of solute $i$ in groundwater, $R$ is total recharge, $R_j$ is the recharge rate from component $j$ (e.g., rainfall, water mains), and $C_j$ is the solute concentration in recharge component $j$.

If total recharge $R$ is independently estimated, for example by calibrating a groundwater model, and $C_i$, $C_j$ are known by measurement, then the $R_j$ is estimated by Eq. (3). One solute balance is required for each recharge component $j$. This type of analysis can be applied at the aquifer scale (see below) or over the catchment of a single borehole.

Yang et al. (1999) present such an analysis for Nottingham. In their case, the turnover time of the aquifer was long, and a non-steady version of Eq. (3) was used. They calibrated a groundwater flow model for 1850–1996, with 13 stress periods and the land surface divided into 6 recharge zones. The model shows that total recharge had remained about constant at 220–240 mm/year. They had data for three solutes (Cl, $SO_4$, and total N) and so were able to subdivide recharge into three components (water mains, sewers, precipitation) by calibrating three solute-transport models for the aquifer. This is probably the most comprehensive analysis of urban recharge to date, and it shows that the three components contributed in the following proportions: precipitation, 30%; water mains, 65%; and sewers, 5%. High uncertainties remain for these estimates, because of the lack of historical data.

### *Piezometry*

Water-table rise is widely used to estimate the recharge resulting from an event, whether it is a storm or a wet season, by applying Eq. (4):

$$R = S\Delta h + Q\Delta t \tag{4}$$

where $R$ is total recharge over an event of duration $\Delta t$, $S$ is specific yield, $\Delta h$ is the rise in water table as a result of the recharge event, and $Q$ is the discharge (e.g., pumping, spring discharge) that occurs during the event. Sometimes $Q$ is omitted from the calculation, but this is only valid if it is small in relation to $R$. Some of the problems in using this method are discussed by Scanlon et al. (2002, this volume). The particular problem that applies to urban groundwater is that the method only works for non-continuous recharge, whereas much of the recharge is not episodic or seasonal. All the recharge associated with water supply and sewage is continuous, and so does not cause episodic fluctuations in the water table. Because these components of recharge are often the largest in an urban area, the method gives completely erroneous estimates of recharge and should not be used for urban groundwater.

## Case Studies

Relatively few case studies of urban recharge estimation have been reported in the research literature, with a particular shortage of cases where estimates have been validated, for example by numerical modelling. Some examples are:

- Seiler and Alvarado Rivas (1999) report recharge and discharge calculations for Caracas, Venezuela. They suggest that the losses from water mains are ~5% of supply, which is surprisingly small, particularly in view of the high rate of water supply of 375 l/person/day. However, they state that this source of recharge is 40% of the total recharge to the aquifer.
- An aquifer water balance for Aquascalientes, a city of 560,000 in Mexico, is provided by Fernando and Gerardo (1999). No details of the calculations are provided, although a numerical model was calibrated and gives some credence to the values. Water-mains leakage is 25 $Mm^3$/year (≡300 mm/year in the urban area) and wastewater infiltration is 1 $Mm^3$/year (≡12 mm/year). These amount to 30% of the recharge for the whole aquifer. Abstraction is double the recharge, and groundwater levels are declining by 3.2 m/year.
- In Wolverhampton, UK, total recharge is reported to have increased from pre-urban rates of 120–250 mm/year to current rates of 220–300 mm/year, with the spatial differences caused by variations in the superficial geology (Hooker et al. 1999).
- The sandy aquifer underlying Perth, Australia, is probably the most extensively studied urban aquifer (Appleyard 1995; Davidson 1995). Appleyard (1995) provides data and citations to indicate that recharge in non-urban parts of Perth is 15–25% of the annual average rainfall (860 mm). By contrast, urban recharge, based on water balances, tritium, and CFC measurements, is as much as 37% of average annual rainfall. This approximate doubling of recharge by urban development is attributed to the clearing of native vegetation, imports of water, and infiltration of storm water (Appleyard et al. 1999).
- The city of Hat Yai, Thailand, was studied in detail by Lawrence et al. (1994). They subdivide the urban recharge of 240 mm/year between rainfall on non-paved areas (46 mm/year), leaking water mains (97 mm/year), seepage from cesspits (39 mm/year), and wastewater disposal in areas without sewerage (58 mm/year). In addition, another 420 mm/year of recharge is induced from canals by groundwater pumping, making this the largest item in the water balance.

These examples show that many hydrogeologists now recognise the role of water-supply and disposal systems in urban recharge. Most of the recharge estimates are made by analysis of components. Regrettably, only a few of the published cases include a validation of the estimated recharge by an independent method, such as groundwater modelling.

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## Conclusions

Recharge in urban areas is now widely recognised to be usually as high or higher than in equivalent rural areas. The main source of the additional recharge is the imported water supply, through leaking water mains and septic tanks (if present). Unfortunately, the complexity of the land surface and the water-carrying infrastructure in cities makes it difficult to estimate urban recharge accurately.

The usual methods of estimating recharge are available for use in urban areas. However, the complexities of the city and the paucity of data lead to high uncertainties. On the basis of this review, holistic approaches are recommended for use whenever possible, for example by investigating the overall water balance or calibrating a groundwater flow model. Solute data provide additional valuable information both to identify and quantify recharges.

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