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The key role for groundwater in urban water-supply security

Stephen Foster[a,b]
[a]University College London, Department of Geography, London WC1, UK
[b]IWA Groundwater Management Group Chair
E-mail: DrStephenFoster@aol.com

ABSTRACT

Groundwater provides nearly 50% of urban water supply, and probably a higher proportion at times of water stress. Groundwater systems generally exhibit exceptional resilience to drought and are well positioned to enhance water security for a wide range of users, provided they are adequately managed and protected to play the role sustainably. The serious urban water-supply crises of recent years, such as those experienced by Cape Town, São Paulo, and Chennai, have highlighted the vulnerability of major cities to surface water drought and a failure to incorporate groundwater as a key element to enhance water-supply security. But some progress has been made worldwide in adaptive sustainable management of groundwater for urban water supply, and this is illustrated by the cases of Hamburg, Lima, and Bangkok.

Key words: urban climate-change adaptation, urban groundwater resources, urban water-supply security

HIGHLIGHTS

- Role of groundwater in urban water supply.
- Public municipal versus private self-supply issues.
- Assessment of recent urban water-supply crises.
- Strengthening urban groundwater management.
- Profiles of water-supply status of key cities.

GROUNDWATER IN URBAN WATER SECURITY

During the 20th century, there was an enormous boom in waterwell construction for urban water supply, as well as for agricultural irrigation and industrial processing. Major advances in waterwell drilling, pumping technology, energy access and geological knowledge allowed deep boreholes to be drilled relatively quickly and extract large volumes. Shallow waterwells using affordable technology were developed for private users and community supplies. Groundwater thus became a key natural resource supporting human well-being and economic development – but still all too widely a resource misunderstood, undervalued, poorly managed and inadequately protected (IAH 2015, 2019).

Drivers of resource development

The groundwater dependence of innumerable urban areas appears to be intensifying, such that nearly 50% of the urban population today is believed to be supplied from waterwell sources (IAH 2015). In the cases of the EU and the USA, groundwater provides the public water supply for 310 and 105 million people, respectively. The present drivers of urban groundwater use are widely accelerating rates of urbanisation, increasing per capita water use, higher ambient temperatures and reduced river-intake security due to water pollution and climate change and the relatively low cost of waterwell construction and operation (Foster *et al.* 2010a). The social value of groundwater should not, however, be gauged solely by volumetric withdrawals. This is because groundwater use brings major economic and health benefits because of local availability, scaling to demand, high drought reliability and generally good quality requiring minimal treatment (Foster & Vairavamoorthy 2013).

Comprehensive national statistics on groundwater pumping for urban supply are not available, and recourse has to be made to data on selected cities to illustrate what are believed to be the most important global trends. Groundwater withdrawals are currently highest over large areas of India, China, Pakistan and Bangladesh, and in parts of North America, Southern Europe, North Africa and the Middle East. A list of major cities with major dependence on groundwater includes Europe

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(Copenhagen, Odense, Paris, Caen, Limoges, Hamburg, Berlin, Munich, Hannover, Budapest, Rome, Milan, Torino, Utrecht, Den Haag, Warsaw, Wroclaw, Krakow, Portsmouth, Hull, Cambridge and Brighton), Americas (Natal, Ribeirao Preto, Saō Luis Maranhăo, Santiago, Coquimbo, San Jose, Mexico DF, Merida, San Luis Potosi, Leon, Asuncion, Miami, Tampa and Phoenix), Africa (Addis Ababa, Abidjan, Mombasa, Dakar, Dodoma, Arusha, Lusaka and Kabwe), and Asia (Lucknow, Chennai, Indore, Islamabad, Lahore, Rawalpindi, Tianjin, Beijing, Handan, Shenyang, Jakarta, Semarang, Yogyakarta, Ho Chi Minh, Hanoi, Dhaka and Chittagong). South Asia and sub-Saharan Africa in particular are currently experiencing unprecedented rates of urban population expansion, with over 500 African cities growing at an annual rate of 3.9% or higher and 8 million new urban dwellers added annually.

Municipal water-supply provision

Groundwater exhibits numerous benefits for water-supply development by public utilities (Table 1). Its normally excellent natural quality, requiring only precautionary disinfection before supply into main distribution systems, has long made groundwater the preferred source. Urban centres underlain and/or surrounded by high-yielding aquifers usually have better water mains service levels and lower water prices because of the potential to expand water-supply production incrementally in response to rising demand at modest cost (Howard 2007; Taniguchi *et al.* 2009; Foster *et al.* 2010a).

Most urban areas located in favourable hydrogeological settings will initially have a significant dependence on groundwater for their water supply (Figure 1). Indirectly, groundwater contributes to urban poverty reduction by allowing water utilities to operate social 'pro-poor' tariffs. However, most urban poor live in peri-urban settlements, which are unplanned and lack legal

Table 1 | Benefits of groundwater sources to water service utilities

Groundwater assets	**Water-supply benefits**
• Widespread distribution, with direct access in many outlying districts	• Development usually involves low capital and recurrent costs (except in a few hydrogeological settings), which can be staged with rising demand
• Generally excellent natural quality, requiring minimal treatment (except where affected by anthropogenic pollution or by natural contamination)	
• Huge natural reservoirs that can be used for long-term water storage	• High level of water-supply security in drought and river pollution episodes
• Buffered against rainfall variability unlike surface-water sources	

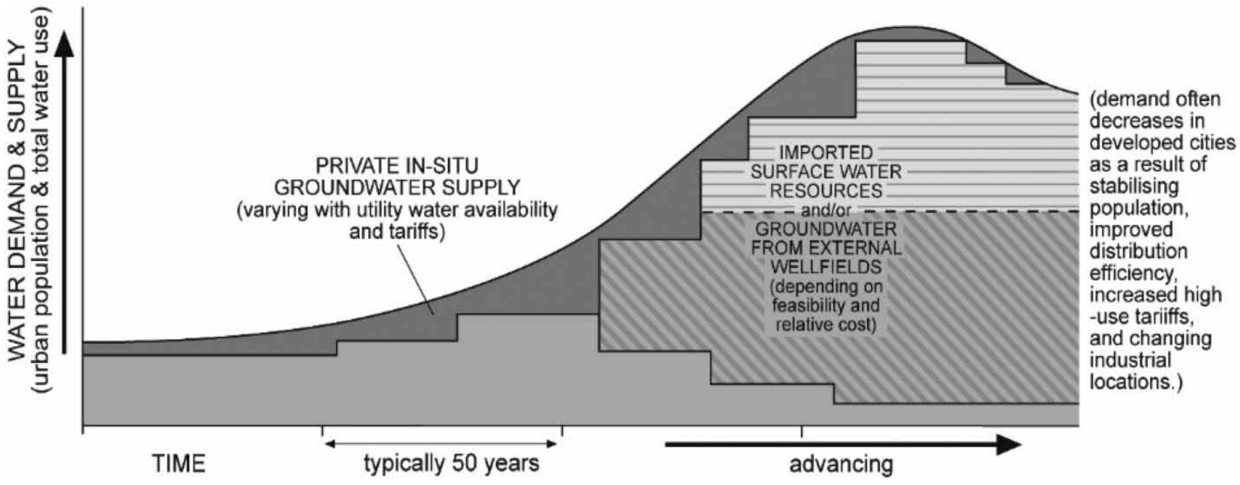

Figure 1 | Typical evolution of urban water supplies (after Foster *et al.* 2010a).

status, and city planners often impede the provision of public infrastructure services to such areas because of anticipated high capital costs and low revenue collection.

Normally, sufficient groundwater resources are not available within the limits of larger cities to meet fast-growing urban water demand sustainably (Figure 1). Where, high-yielding aquifers are present in the hinterland of cities, the development of 'external wellfields' is an attractive option compared to the long-distant import of surface-water resources. But groundwater also remains widely exploited by water utilities through individual waterwells scattered around urbanised areas, many without specific protection measures.

Looking to the future, groundwater resources should allow the rapid development of utility waterwells as the 'hub' of new decentralised systems of water service provision for the fast-developing outer urban districts with populations of 20,000–50,000, minimising infrastructure costs, energy use and water losses (Foster & Varaivamoorthy 2013). These would also value wastewater as a resource (with urine recovery as a fertiliser and faeces reuse for energy generation). But it will be necessary to put special efforts into on-the-ground control of other forms of groundwater contamination (such as petrol stations, small-scale motor shops, garages and dry-cleaning laundries) to reduce the risk of pollution of important waterwell sources.

Managed conjunctive use of groundwater and surface water (Figure 2) can greatly enhance water-supply security and has been successfully implemented in various cities. In essence, this involves a number of actions:

- constructing external wellfields with groundwater use and quality protection zones to provide the most secure component of urban water supply,
- reducing dependence on waterwells within city limits since these are more vulnerable to pollution,
- using treated river water preferentially for urban water supply moving progressively to groundwater at times of low river flow and
- collecting and treating urban wastewater to make it available for downstream agricultural irrigation.

In addition, in some instances (e.g. Lima – Peru and Delhi – India), construction work has been undertaken in the riverbed to enhance surface water recharge to groundwater or to direct excess monsoon river flow to groundwater recharge basins, which are other forms of conjunctive use.

Private and community self-supply

The term 'self-supply' refers to water-supply investments that are financed by users themselves (Oluwasanya *et al.* 2011). In developing economies, most self-suppliers use groundwater and share their supply with neighbours. Self-supply from

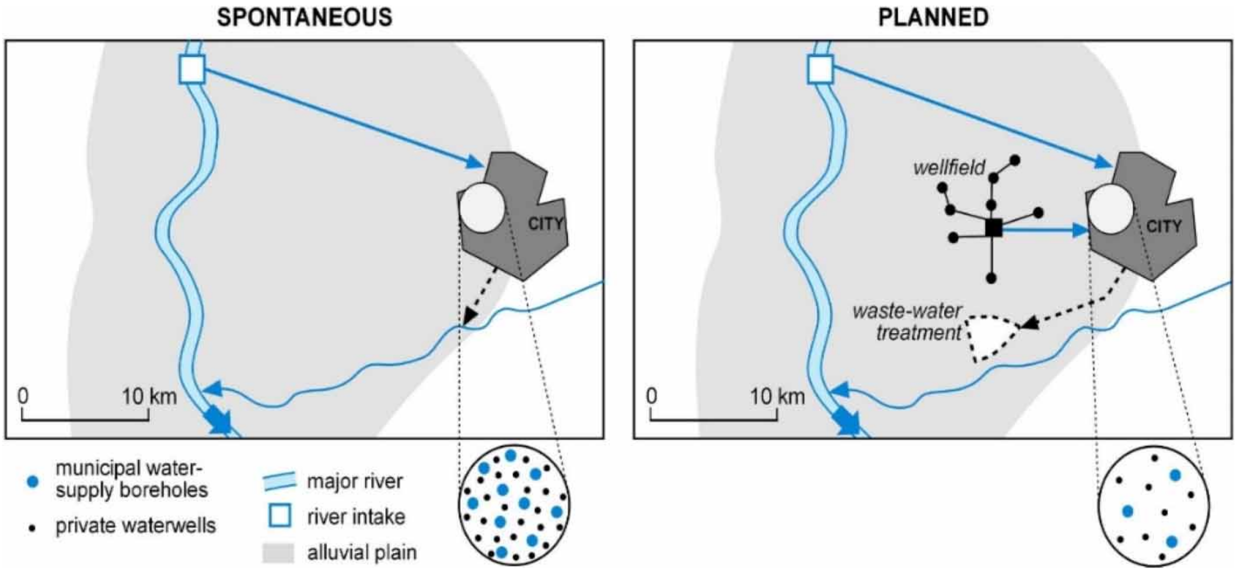

Figure 2 | General schemes of spontaneous and planned conjunctive use of groundwater and surface water for urban water supply (after Foster *et al.* 2010b).

groundwater provides a rapid solution in areas where it is technically feasible and affordable. The proximity to the home of a private waterwell, combined with low recurrent costs and, in some cases, low initial investment costs, makes private waterwells an attractive option. Such investments unlock significant finance for water-supply access and are a fast-growing phenomenon (Foster *et al.* 2010a; Grönwall *et al.* 2010). Nevertheless, private groundwater use tends to pass under the radar of official national water-supply statistics (Danert & Healey 2021) or the phenomenon is not recognised at all by the government (Foster & Hirata 2011).

The use of private waterwells for urban self-supply has 'mushroomed' in recent years, especially in South Asia, Latin America and sub-Saharan Africa (Foster *et al.* 2010a; Grönwall 2016). For example, some 125 million people in sub-Saharan Africa and 340 million in India depend primarily on this type of source. The practice usually commences as a 'coping strategy' for irregular or inadequate piped water supplies but then continues in perpetuity as a 'cost-reduction strategy' to avoid paying higher water tariffs.

Private waterwell construction costs in most hydrogeological settings will be in the range of US$2,000–20,000 but are considerably higher (US$30,000–45,000) where deep boreholes (of 200–300 m) are required. Private waterwell ownership will thus remain mainly the preserve of the wealthy, and it is not a 'pro-poor' phenomenon. While the practice reduces the pressure on water utility supplies, it can also have serious impacts on their cash flows and investment cycles (Foster *et al.* 2018, 2020a). There is obviously a clear need for some regulation of urban waterwell self-supply because, without regular quality monitoring (and if necessary, water treatment), it will be a 'risky business', especially from shallow aquifers as a result of the risk of their significant pollution.

Research into urban self-supply from groundwater has revealed the following:

- In India, an estimated 340 million dwellers depend primarily on self-supply sources, and many medium-sized cities are highly dependent on domestic self-supply from groundwater, which can amount to 40–60% of water-supply provision (Alam & Foster 2019).
- In Brazil, domestic self-supply from groundwater amounts to about 35% of the total drought water supply to São Paulo (despite the city not being underlain by a major aquifer) and nationally, there are at least 2.5 million private urban waterwells, which represent 6–7 times the annual investment in water supply by government agencies (Foster & Hirata 2011).
- In Nigeria, the level of dependency on private waterwells is extremely high, having reached some 38–43 million of the total urban population (75–80 million) by 2009 despite the coverage of public mains water supply having expanded, with only about 20% of the Lagos population (18–20 million) being served by piped utility water supply, 50% owning private boreholes and another 30% obtaining water from these sources.

WATER SECURITY AND WATER SCARCITY

In global climate circles, one hears the expression 'water security' used with ever-increasing frequency, together with declarations about the urgency to increase water security in these times of unprecedented global change. Global warming is likely to increase the frequency of serious droughts in many settings and create increased anthropogenic pressures that impact the water security landscape, resulting in aggressive political positioning and increased potential for local conflict or even violence. The water security concept has a very broad scope (Grey & Sadoff 2007; Cook & Bakker 2012) but at its heart is a societal issue and, thus, a political concern.

Issue of definitions

'Water security' was defined by UN-Water in 2013 as 'the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability'. The related concept of 'water scarcity' has evolved considerably since the definition of the 'Falkenmark (1989) water-stress index' in the 1980s, which led to 'absolute water scarcity' being defined as situations where local water resources are equivalent to less than 1,000 m^3/year/person of water availability.

In reality, the conceptualisation of water scarcity needs to consider not only the ratio of 'fresh water withdrawals to renewable resources' but also the local availability of natural groundwater storage, which can completely transform the water resource situation at times of surface-water stress. Another significant factor is the seasonality of the local rainfall regime. It is also most important to distinguish 'physical water scarcity' from 'economic water scarcity'. Nowhere is this more apparent than across the African continent (Dankaer & Taylor 2017), where only the northern and southern extremes exhibit physical water scarcity but much of the tropics currently suffer economic water scarcity due to a lack of investment in rational water development. There is also evidence of a direct correlation between drought proneness and persistent poverty in Sub-Saharan Africa (Grey & Sadoff 2007), further increasing pressure to find reliable water sources with sufficient storage to maintain supply through drought periods.

Water scarcity indicators need to define water resource availability levels below which serious allocation issues and environmental risks arise. These can have an impact at different levels – individuals, groups, states and countries – and relate to different geographic scales and socio-economic sectors, most notably the human population, environment conservation, food production and industrial activities. From a water resource perspective, the water security concept would be more rational if applied at the scale of a specific city and if it more clearly distinguished the differing impacts of drought, flood and pollution. However, to date, the concept has been principally applied at the national scale, using parameter indexation to arrive at a 'security score', whose primary objective is to provide an incentive for national governments to invest in water resource management measures.

'Groundwater vision' of water security

Globally, groundwater is the most abundant source of freshwater resources (representing 97% of non-frozen water), and one that can be accessed by waterwells and from springs. Aquifers hold very large volumes of freshwater naturally in storage, and their presence much improves local water security during prolonged droughts for all types of water users (Foster *et al.* 2018, 2020a). Groundwater storage plays such a fundamental role in shaping water security that it should be taken more prominently into account in water security evaluations, rather than considering only built reservoir infrastructure. The presence of major aquifers in the vicinity of cities can enhance urban water-supply resilience, because they provide a 'natural buffer' against the variability of river flows and surface-reservoir levels, as a result of the very large volume of groundwater held in storage. Aquifers have 'water retention times' ranging from decades to millennia (Foster & Vairavamoorthy 2013) and normally at least a few hundred years even for 'shallow groundwater systems' (with the notable exception of karstic limestones).

So what are the specific facets of groundwater systems that need to be taken systematically into consideration when evaluating urban water security? Research on groundwater and droughts (Villholth *et al.* 2013) can be helpful here. Incorporating groundwater considerations into the evaluation of water security will require indexation of the following:

- *groundwater storage availability*: an indicator of 'buffer capacity' to support water-supply abstraction in extended drought but one which will be constrained by current resource status (aquifer water level and salinisation trends) and connectivity to surface water;
- *groundwater supply productivity*: a measure of how easy it is to extract groundwater from an aquifer, which relates to its depth and the aquifer transmissivity, and any evidence of reducing productivity due to falling water levels;
- *groundwater pollution protection*: in terms of the interaction between aquifer pollution vulnerability (Foster *et al.* 2013), pollution pressure, the effectiveness of pollution control and aquifer protection measures, and any evidence of deteriorating quality trends.

The recent water-supply crises in São Paul – Brazil in 2016–2019 (Box 1), Cape Town – South Africa in 2016–2018 (Box 2) and Chennai – India in 2017–2019 (Box 3) have highlighted the vulnerability of major cities to surface-water drought and the critical importance of using (not ignoring) ground-water resources so as to provide a more secure water-supply element.

NEED FOR SUSTAINABLE MANAGEMENT

Groundwater systems, for the most part, exhibit exceptional resilience to drought impacts and are well positioned to enhance water security for a wide range of users. However, to perform this role sustainably, they require

- good hydrogeological data and understanding to guide groundwater management including the occurrence and use of non-renewable resources,
- careful administration of resource abstraction,
- effective protection against pollution.

Box 1 | São Paulo water-supply crisis during 2016–2019 (data from Foster *et al.* 2020b).

São Paulo – Brazil is the largest metropolitan region in South America, the home to 21.5 million people, occupies an area of 7,946 km^2 and has a GDP of US$ 237 billion/a. Public water supply is provided to about 95% of the population, mainly by a complex surface-water system producing 5,270 Ml/d of which only 1% is groundwater. However, there are more than 13,000 private waterwells extracting 950 Ml/d (18% of the public supply which increased to 25% during the last major water crisis), whose water-supply costs are generally 5–8 times less than that of the public utility.

Although private self-supply has increased water-supply security, large-scale uncontrolled waterwell drilling has caused problems with lowering of water-table levels with conflict among users and significant risk of pollution with many private sources not having regular chemical analysis. The failure to manage groundwater resources is primarily attributed to the lack of appreciation of their importance for water-supply security and the limited understanding of conflicts between users. Thus, little pressure is exerted on the water management agencies who have little incentive to try to regulate thousands of private waterwell owners.

Box 2 | Cape Town water-supply crisis during 2016–2018 (data from Olivier & Xu 2019).

Cape Town – South Africa has a population of about 3.8 million and a public water-supply demand of 900 Ml/d. The population faced an extreme water crisis in 2017–2018, with the WSD (Water & Sanitation Department) having to impose severe water-supply restrictions despite reducing distribution system leakage losses to only 14%. The crisis was provoked by the 2015–2017 drought with a total rainfall of less than 250 mm/a (compared to a 'long-term average' of over 600 mm/a). In June 2017, when the actual storage in its largest surface-water reservoirs fell to below 15%, the piped supply was reduced to 100 lpd/capita, with subsequent reductions to 80 and 50 lpd/capita in September 2017 and February 2018, and a warning of 'Day Zero' when all household taps would be shut off and people would have to queue for 25 lpd/capita from 150 collection points (equivalent to a total supply of just over 100 Ml/d). However, strong rains occurred in June 2018 and this was averted.

The Western Cape Province public water supply relies almost exclusively on surface-water reservoirs with a maximum capacity of about 900 Mm^3/a, 70% of which is held in the Theewaterskloof and Voelviel dams. Not pursuing greater water source diversity was a serious policy error, especially given that Western Cape groundwater systems (Cape Flats, Table Mountain and Atlantis Aquifers) have significant yield potential. Although adequate resource assessment and management are lacking, they would appear to offer the possibility of providing more than 200 Ml/d as a public water-supply reserve for drought.

Box 3 | Chennai water-supply crisis during 2017–2019 (data from Alam & Foster 2019).

Chennai is the fourth largest metropolitan area in India, and its 8.6 million populations faced an acute water crisis in 2019. Chennai's four main reservoirs and lakes almost dried-up as a result of persistent drought, and by June 2019, combined surface-water storage stood at only 0.1% of total storage with the water utility only being able to supply 525 Ml/d of the total demand of 830 Ml/d. Much of the city became totally dependent on groundwater, which is abstracted extensively both within and outside the city limits.

Within the city, there are about 420,000 private wells, but due to long-term overexploitation and limited recharge during poor monsoons the water table has fallen, causing wells to dry-up and groundwater quality to deteriorate through seawater intrusion. Thus, more than 5,000 tankers of 9,000 litre capacities have been doing 5–6 trips daily to supply groundwater from the surrounding rural areas for both the water utility and private operators at a total rate of 200–300 Ml/d. However, a history of inadequate groundwater management has led to conflicts at the urban–rural interface.

Undertaking adequate monitoring

It has to be appreciated that in the urban environment, the interactions affecting the availability and quality of groundwater are complex (Figure 3), and there is a need for much-improved field monitoring and data analysis to understand them and provide sound advice to those responsible for resource management and protection (Foster *et al.* 2010a). Such activities are well worth financing to obtain the anticipated benefit of avoiding potentially conflicting situations and averting water conflicts. The data generated and the understanding gained will serve as the basis to formulate rational policies to promote sustainable groundwater use. It is also important that the groundwater data collected are stored on recognised databases for future availability.

Given the numerous uncertainties and continuously evolving groundwater conditions in urban areas, it is wise for an 'adaptive approach' to groundwater resource management to be adopted – this should be based upon continuous monitoring of groundwater levels and quality trends (Box 4) and guided by transient numerical aquifer modelling (Foster 2020). This will permit the evaluation of future groundwater abstraction scenarios and lead to the definition of more robust and sustainable solutions to municipal water supply.

NEED FOR SUSTAINABLE MANAGEMENT

Avoiding excessive abstraction

Groundwater systems in urban areas usually have complex dynamics evolving with time because of the influence of various anthropogenic recharge sources, including water mains leakage and soakaways from road-and-roof drainage (both of good quality), and leakage from sewerage systems and infiltration from *in situ* sanitation (both of poor quality). This recharge usually more than compensates for the reduction of rainfall recharge due to land-surface impermeabilisation. However,

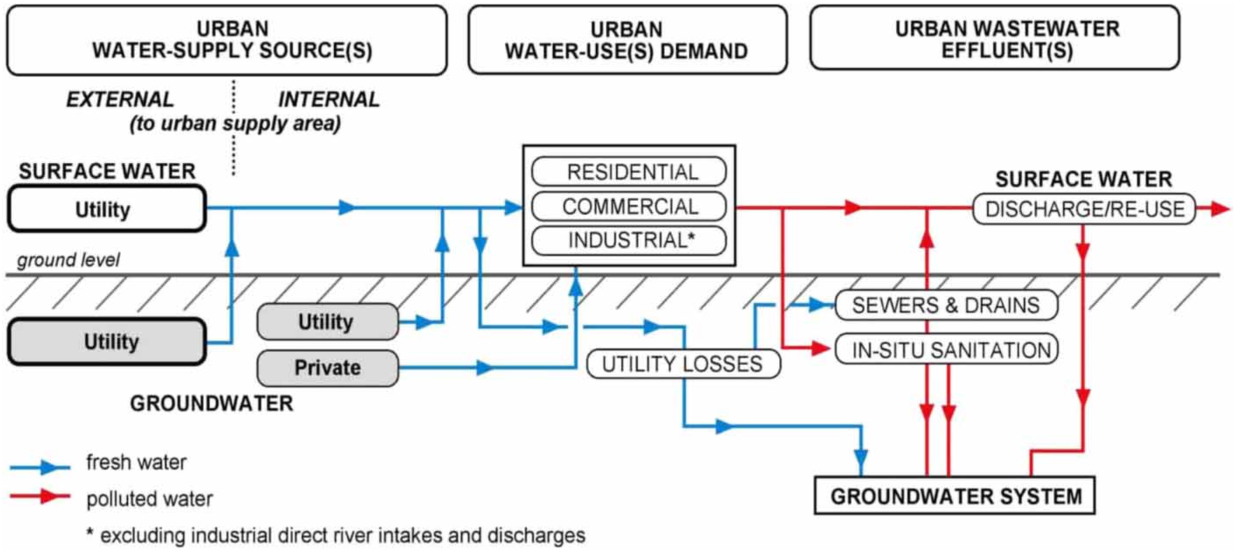

Figure 3 | Schematic overview of urban water-supply sources and their interactions (after Foster &Vairavamoorthy 2013).

Box 4 | Hamburg – an outstanding example of groundwater monitoring for adaptive management (data from Foster *et al.* 2020b).

An excellent example of comprehensive monitoring and adaptive management of groundwater for secure urban water supply is Hamburg – Germany, where a publically owned water utility and major groundwater abstractor have undertaken the greater part of the monitoring of both aquifer water-table levels and water quality (Foster *et al.* 2020b). Today, the utility operates about 470 waterwells pumping approximately 120 Mm^3/a and maintains its own monitoring network of about 1,400 boreholes, which provide a full and dynamic picture of groundwater flow and quality on which to base their abstraction strategy.

the total rate of groundwater recharge in urban areas is rarely sufficient to meet fast-growing water demand and resource over-exploitation with continuously falling water table occurs widely (Foster *et al.* 2010a).

This needs to be managed by both controls of private waterwell abstraction and redistribution of water utility withdrawals to allow the long-term use of groundwater. There are some recent examples from the developing world of successful management of urban groundwater abstraction, notably Lima – Peru (Box 5) and Bangkok – Thailand (Box 6).

The sustainability of urban groundwater use is strongly influenced by a complex array of local developmental decisions, which are rarely viewed in an integrated fashion because the production and distribution of water supplies is by water service utilities, urbanisation and land-use planning is by municipal government offices, and installation of sewered sanitation, and disposition of liquid effluents and solid wastes are by environmental authorities and public health departments. A more integrated approach is required to avoid costly problems, where local aquifers are providing an important component of municipal water supply (Foster 2020), which should include such measures as:

- defining areas with critical levels of resource exploitation as a basis for restricting further abstraction,
- providing clear criteria by area for issuing waterwell permits in terms of safe separation and maximum pumping rates,
- controlling municipal and private groundwater abstraction on the basis of the defined areas, including the relocation of municipal waterwells, and increased resource-use fees,
- pursuing opportunities to enhance aquifer recharge through rainwater harvesting and infiltration soakaways.

For most large cities, the long-term sustainable groundwater resource is limited by the aquifer geographical extension. In many such cases, it may prove more rational to use the large groundwater storage of nearby aquifers as a strategic reserve for

Box 5 | Conjunctive use to enhance water-supply security in Lima (data from Foster *et al.* 2010b).

Lima – Peru extends across the hyper-arid outwash fans of the Rimac and Chillon rivers, with groundwater recharge occurring through riverbed infiltration, irrigation canal seepage, excess irrigation to agricultural and amenity land, and leakage from water-supply mains and sewers. A waterworks on the Rimac River has a capacity of 860 Ml/d, although production is not possible at times of maximum suspended solids and also reduces in drought. Of the total water supply in 1997, 1,050 Ml/d was derived from groundwater (including 720 Ml/d from 380 utility waterwells) with a resultant water-table decline of 1–5 m/a. Major efforts were made to optimise conjunctive use through the reduction of groundwater abstraction in defined critical areas, an additional Andean surface-water transfer of up to 260 Ml/d, improved water distribution to allow most users to be supplied by either source and riverbed recharge enhancement over 6 km of the Rimac River. These measures were implemented through institutional arrangements that empowered the water utility to act on behalf of the government and led to a water-table recuperation of 5–30 m during 1997–2003, with water utility abstraction reducing to 135 Mm^3/a by 2009, but capacity for higher production in the short-term still exists.

Box 6 | Sustained effort to stabilise groundwater abstraction to limit land subsidence in Bangkok (data from Buapeng & Foster 2008).

Bangkok – Thailand occupies the lower part of the Chao Phrayh Basin, which is underlain by 500 m of interbedded alluvial and marine sediments that are recharged from the north and overlain by a confining Holocene Clay. Widespread exploitation of groundwater for urban water supply had reached a level of about 500 Ml/d by 1980 and caused water level lowering to 40 m bsl with the evidence of significant land subsidence. The initial approach to reducing groundwater abstraction was to require the Metropolitan Waterworks Authority to close its waterwells and substitute distant surface-water sources, but increased water tariffs had triggered a massive increase in private waterwell use amounting to over 2,000 Ml/d by the late 1990s, with a further 400 Ml/d abstraction by the Provincial Waterworks Authorities. This had resulted in drawdowns to 90 m bsl and land subsidence of 0.9 m by 1995. The increased seawater flooding risk was such as to prompt the government to provide increased powers and staff complement to the regulatory agency to reduce abstraction in the critical areas, which, through withdrawing waterwell licenses and increasing abstraction charges, had stabilised the position by 2000 with the total pumping reduced to 1,600 Ml/d.

conjunctive use with surface-water sources rather than for the traditional use of groundwater for base-load municipal water supply in selected districts (Foster *et al.* 2010b). But most conjunctive use presently encountered in the developing world amounts to a 'piecemeal coping strategy' in which waterwells have been drilled by water utilities on an *ad hoc* basis in newly constructed suburbs to meet their water demand at the lowest possible capital cost, and surface water has been recently imported from a major new distant source to reduce dependency on waterwells. The most common impediment to conjunctive use is the fact that urban engineers (usually pressed by day-to-day problems that require urgent attention) are forced to look for operationally simple set-ups, such as a major surface water source and large treatment works, rather than more secure and robust conjunctive use solutions (Foster 2020). Such impediments need to be confronted through capacity building and by water resource agencies engaging closely with water utilities on resource development strategy.

Promoting quality protection

In general terms, urbanisation has a direct interaction with shallow groundwater underlying cities through increasing contaminant load, as a result of *in situ* sanitation (especially important in the developing nation context) and to a lesser degree, sewer leakage, and also inadequate storage and handling of 'community' and industrial chemicals, and disposal of liquid effluents and solid wastes (Taniguchi *et al.* 2009; Foster *et al.* 2010a).

In situ sanitation of major urban areas presents a significant groundwater quality hazard, which needs to be recognised and managed. This problem is further accentuated by the fact that self-supply from groundwater is generally more intensive where access is easiest – namely in the presence of shallow unconfined aquifers, which are the more vulnerable to pollution. In most aquifer types, except the extremely vulnerable, there will be sufficient natural groundwater protection to eliminate faecal pathogens in percolating wastewater from *in situ* sanitation, but there are exceptions. However, elevated (and often troublesome) concentrations of N compounds (usually nitrate) and dissolved organic carbon (DOC) in groundwater will also be present and can penetrate to considerable depths (Taniguchi *et al.* 2009; Foster *et al.* 2010a; Lapworth *et al.* 2017). Such groundwater pollution can persist for years after the source of contamination is removed by the installation of main sewerage or other alternative sanitation. The most cost-effective way for water utilities to deal with excessive nitrate in groundwater is by dilution through mixing from a carefully protected source, such as an 'external well field'.

Groundwater pollution can be substantially reduced by deploying so-called dry or eco-sanitation units, in which urine is separated from faeces and not discharged to the ground. While such installations are highly recommended for new urban areas overlying significant shallow groundwater resources, their deployment as a universal solution to the groundwater contamination problem has absolute limitations since retro-installation in large numbers of existing properties is impractical, and it is unsuitable for certain cultural groups who use water for anal cleansing. It is thus usually more practical to prioritise recently urbanised areas for coverage by mains sewerage to protect good groundwater quality against progressive degradation, limit the density of new urbanisation with *in situ* sanitation to contain potential contamination and establish utility waterwell protection zones around all sources favourably located to take advantage of parkland or low-density housing areas.

A separate question is leakage from mains sewerage systems, which is always negative from the point of view of groundwater resource quality. It rarely receives attention from water service utilities since they do not see investment having any direct return by increasing water available for sale to consumers. Without adequate maintenance to reduce leakage losses, sewerage systems may not afford the protection to groundwater which is often assumed.

There are basically two institutional approaches to protect groundwater quality: specific regulatory codes and planning consultation (Table 2), but the challenge of implementation in the developing world is greater because of rapid population growth and limited public awareness.

The establishment of water utility wellfields outside cities, with their capture areas being declared as drinking water protection zones, must be promoted as 'best engineering practice' (Foster *et al.* 2010a; Grolleau & McCann 2012; Barataud *et al.* 2014; Thomsen *et al.* 2014). But in the developing world, their promotion often encounters administrative impediments related to fragmented powers over land use between the municipalities that comprise 'metropolitan areas'. Incentives need to be established for the groundwater resource interests of a given urban municipality to be assumed by a neighbouring rural municipality, such that adequate protection can be offered for the capture area of 'external municipal wellfields' providing water supply to the main urban area.

In many countries, there is a lack of clear incentive for water utilities to take action on groundwater quality protection through land-use controls because of uncertainty about the success of the approach and the time taken for the beneficial impacts of controls to be realised. It is often perceived by utilities as more secure to achieve drinking water quality goals

Table 2 | Institutional approaches to groundwater pollution protection

Main options	Planning consultation process	Specific regulatory code[a]
Procedures involved	• Regulatory agency is a formal consultee for all local government decisions and can request modifications to avoid/reduce potential groundwater pollution threat • In parallel, maps provided of APV assessment and SPA need to indicate spatial variation of concerns	• Regulatory agency has legal powers to enforce groundwater protection in priority areas • Delineation of SPAs and other vulnerable recharge zones, indicating land-use constraints as a basis for dialogue with stakeholders
Applicability and advantages	• Most hydrogeological conditions since APV mapping became universally applicable • Provides a clear basis for rational graduation of land-use constraints for groundwater protection	• Where water utility supply is from groundwater, and zones clearly defined where utility water-supply derived from aquifer of simple flow regime and high pollution vulnerability' • More readily understood by land owners and general public
Theoretical limitations	• Cautious interpretation needed in layered multi-aquifer systems • Some difficulties in covering risk of all types of potentially polluting activities	• Not readily applicable to semi-confined aquifers nor other groundwater systems for which the definition of SPAs is problematic
Implementation difficulties	• Potential social resistance because of land-use constraints over quite large areas and their impact on land prices • Does not address pre-existing potentially polluting activities and the difficulty of retrospective action	• Smaller land areas generally involved thus land acquisition or financial compensation feasible • BMPs for agricultural land-use not sufficient to provide the needed level of groundwater quality protection

[a] could be used to reinforce the planning consultation process.

APV, aquifer (groundwater) pollution vulnerability; SPA, source protection area for utility supply; BMP, best management practice for agricultural land use.

by complex water treatment, which is completely under water utility control and whose capital and operating costs can be charged to water users.

CONCLUSIONS

Groundwater is widely far more significant in urban water supply than is commonly appreciated and is also often the 'invisible link' between various facets of the urban infrastructure. It is a fundamental component of the urban water cycle, and there is always a need for groundwater to be integrated when making decisions on infrastructure planning and investment, whatever its use status.

In most developing cities, population growth precedes the construction of mains sewerage and wastewater treatment facilities, and in the meantime, shallow groundwater can become contaminated from inadequate *in situ* sanitation. It may be years before the full extent of pollution becomes apparent, and thus, it is critically important to recognise the incipient signs of pollution and put in place groundwater protection measures. Polluted groundwater not only has implications in terms of increased public health risk but also water-supply treatment costs. Advanced treatment of groundwater to achieve drinking water quality also greatly increases the carbon footprint of water-supply operations.

A major challenge as regards groundwater quality protection is promoting the acceptance of differential land management for important recharge areas in the interest of groundwater recharge quality. The impediments that have to be overcome include the often fragmented responsibility for land-use control and providing incentives for rural municipalities to protect the wellfields of neighbouring metropolitan areas.

Urban groundwater tends to affect everybody but is often the responsibility of 'nobody'. Municipal, provincial/state and national governments must find the political will and the practical means to constrain water demand and limit groundwater abstraction to avoid aquifer depletion; encourage water utilities to spread groundwater abstraction over larger areas and protect wellfield investments through the declaration of special protection areas, and plan urban sanitation and regulate the handling and storage of industrial chemicals and effluents adequately. For this to happen, it will be essential to appraise the roles of water resource/environment agencies, municipal water service utilities and municipal government offices, and the avenues of consultation between them.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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