PERSPECTIVES PAPER

Global Water Partnership

Urban Groundwater

– Policies and Institutions for Integrated Management

Urbanisation is the predominant global phenomenon of our time. Groundwater is a critical, but unappreciated, resource for urban water supply. It is also a serious and costly hazard to urban infrastructure, and the 'invisible link' between many facets of the urbanisation process. Many important cities are located in 'landscape lows', and their underlying groundwater systems in reality represent both the 'last reserve' in terms of water resource and also the 'ultimate sink' for persistent urban pollutants.

In this paper we present an overview of the benefits of urban groundwater use, together with some insidious and persistent problems that groundwater can present for urban development. Spontaneous piecemeal approaches invariably mean that 'one person's solution becomes another person's problem'. We press the case for groundwater to be integrated within a more holistic approach to urban infrastructure planning and management and as an essential component of integrated water resources management in an urban setting. But this is not a simple task because of the widespread vacuum of institutional responsibility and accountability for groundwater in urban areas and their immediate hinterland. Pragmatic approaches to confronting this situation are discussed and some successful experiences highlighted.

A GWP Perspectives Paper is intended to galvanise discussion within the network and the larger water and development community. Feedback will contribute to future GWP Technical Committee publications on related issues.

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Urban Groundwater

– Policies and Institutions for Integrated Management

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The Global Water Partnership's vision is for a water secure world. Its mission is to support the sustainable development and management of water resources at all levels.

GWP is a global network of 13 Regional Water Partnerships, 84 Country Water Partnerships and more than 2,800 Partner organisations in 167 countries.

GWP was founded in 1996 by the World Bank, the United Nations Development Programme (UNDP), and the Swedish International Development Cooperation Agency (SIDA) to foster integrated water resource management (IWRM).

IWRM is the coordinated development and management of water, land and related resources in order to maximise economic and social welfare without compromising the sustainability of eco-systems and the environment.

The network is open to all organisations involved in water resources management: developed and developing country government institutions, agencies of the United Nations, bi- and multi-lateral development banks, professional associations, research institutions, non-governmental organisations, and the private sector.

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1.1 The challenge of urbanisation

Urbanisation is a major global challenge for water management. Global urban population is expected to nearly double to 6.4 billion by 2050, with about 90% of the growth in low-income countries. Urban populations are not only growing but also 'growing-up', which is disproportionately increasing both domestic and industrial water demand, and also generating more wastewater. Of similar concern is the predicted increase in the number of urban slum dwellers to 2.0 billion in the next 30 years. Unless adequately managed these trends are likely to impact negatively on groundwater resources. To assess the implications for management policy, groundwater resources must be seen within an integrated framework that includes other components of the urban water system, such as surface water, wastewater, and storm water, their relationships, and positive and negative interactions (Foster et al., 2010a; Jacobsen et al., 2012).

1.2 Groundwater use for urban water supply

1.2.1 Drivers and modes of urban groundwater use

Groundwater has been a vital source of water supply since the first urban settlements, when water was captured at springheads and in shallow dug waterwells. Recent times have seen significant growth in urban groundwater use, with municipal water utilities deploying deep waterwell technology and private abstractors in some instances constructing large numbers of low-cost shallow waterwells (Foster et al., 1998 and 2010a). Urban centres surrounded by high-yielding aquifers, with sufficient potential to expand water supply incrementally with demand, are often found to have better utility water services and lower average water production costs.

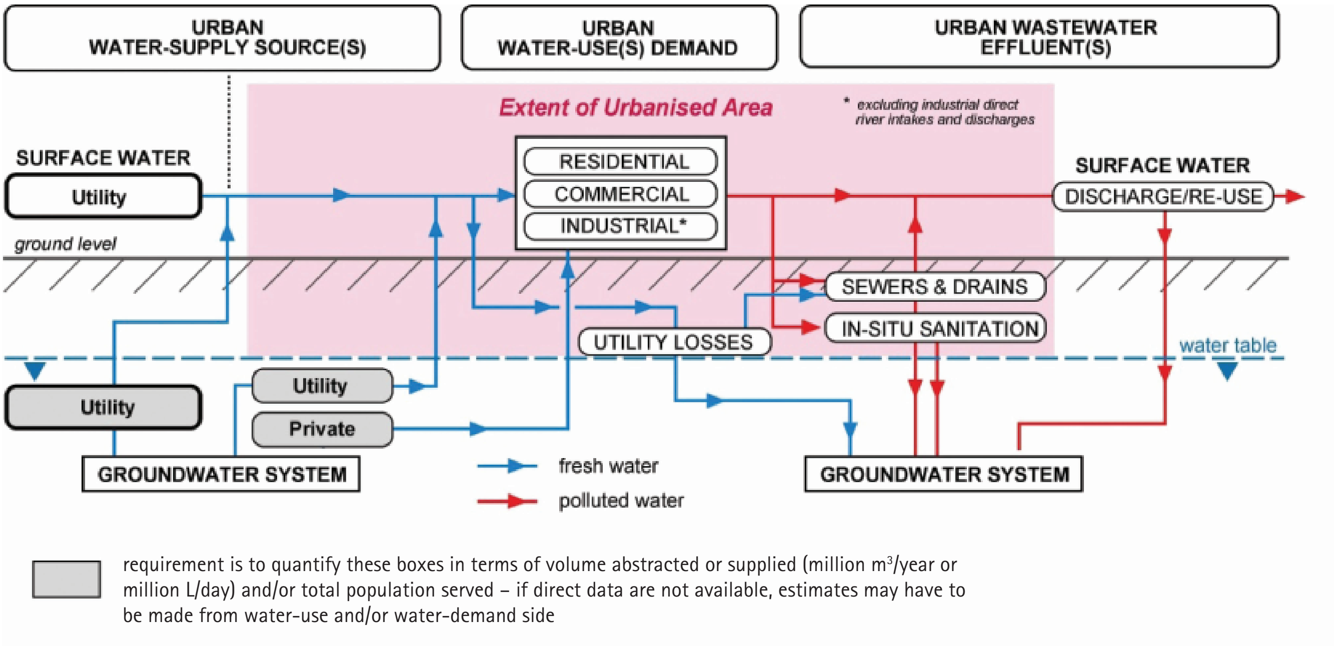
The current drivers of urban groundwater use are accelerating rates of urbanisation, increasing per capita water use, higher ambient temperatures, reduced river-intake security under climate change,

and decreasing costs of waterwell construction. While there are significant regional and local variations in the evolution of urban water supply provision and of dependence upon groundwater, the key considerations are resource reliability for municipal utility use and resource accessibility for private self-supply (Foster et al., 1998 and 2010a).

Utility groundwater use fits into the broader dynamic of urban water supply (Figure 1). Groundwater may be sourced from waterwells within the urbanised area and also from designed and protected 'external well fields or springheads'. Both sources may be used conjunctively with surface water sources rather than in parallel as base-load supply to different urban districts.

Urban groundwater use includes not only utility supplies, but also private in-situ self-supply (Figure 1). This now extends far beyond (traditional) industrial and commercial users to large-scale residential use in some cities, which is a growing phenomenon in those

Figure 1 Sources of urban water supply and their relation with wastewater (excluding direct reuse)



developing nations where the municipal water supply service is inadequate (Foster et al., 2010a; Gronwall et al., 2010). This is not restricted to cities with high-yielding aquifers. Private supplies from groundwater represent a significant proportion of the total urban water supply 'actually received by users' and their presence has major implications for planning and investment in municipal water utilities.

1.2.2 Global statistics on groundwater dependency

It might be imagined that information on waterwell and springhead capacity of urban utilities would be publically available, since it is required for water resource planning, assessing water supply security, and for water utility 'asset management' inventories and investment strategies. But a GEF-2012 rapid appraisal in developing nations concluded that such data are at best patchy and at worst deficient. More generally international organisations, such as UN-Habitat, through an International Benchmarking Network for Water and Sanitation Utilities (IBNET), and International Union for the Scientific Study of Population (IUSSP) through Demographic and Health Surveys (DHS), have compiled little or no groundwater use data for water service utilities. Developing a pilot inventory of urban utility groundwater use required working with 'key professional contacts', such as the International Association of Hydrogeologists (IAH), International Water Association (IWA), and Global Water Partnership (GWP) networks, on a city-by-city basis. This yielded reasonable estimates of the 'groundwater-dependent urban population' for a number of countries (Table 1). If further resourced this approach would go some way to filling this serious gap in global knowledge.

Most towns and smaller cities located in favourable hydrogeological settings will initially be heavily dependent upon groundwater. The available data suggest a broad generic relationship between the size of urban areas and the groundwater dependency of their water utilities, albeit with some exceptions. Private, in-situ residential self-supply from groundwater widely represents an important component of total urban water supply, either as a sole or supplementary source. For many developing nations rough estimates can be made from DHS campaigns quantifying dependence on 'non-reticulated waterwells'. Aggregating these data implies huge numbers in terms of population served: 62-82 million in Sub-Saharan Africa (about 40 million in Nigeria alone) and 154 million in a sub-set of seven South Asian countries.

But a note of caution is needed when using this information:

- There is no standardisation of what constitutes an urban area. Towns normally ranging from 10,000-100,000 population, smaller cities 0.1-1 million,

Table 1 Assessment of groundwater use in urban water supply provision for selected countries

Country (main cities)	Year(s)	Urban utility water supply		Urban private water supply (popln equiv/M)
		Total (Ml/d)	Groundwater part (popln equiv/M)	
PAKISTAN (> 1.00 million) (Lahore, Faisalbad, Rawalpindi and Multan)	2007-09	6,720	48% (11.0)	15.8
BANGLADESH* (Dhaka)	2007-09	1,840*	85% (12.0)*	6.0+*
BRAZIL (> 0.25 million) (Ribeirao Preto, San Luis, Natal, Belem, Manaus, Recife, Uberaba, Maceio)	2009	13,510	15% (6.4)**	major in some cities
PERU (> 0.10 million) (Lima, Piura, Chimbote, Ica and Trujillo)	2007-11	2,850	37% (5.0)	limited
ZAMBIA (> 0.05 million) (Lusaka, Ndola and Kabwe)	2007-10	960	45% (1.9)	1.0 approx

* data refer only to Dhaka, which is the dominant urban centre with 20+ million population
** very much higher proportion and equivalent population (popln equiv) if innumerable smaller cities (of 0.05-0.25 million population) are considered, since these are highly groundwater-dependent

large cities 1-10 million, and mega-cities >10 million. There is little consistency in accounting for urban boundaries and data may refer to an urban municipality, metropolitan area of the same name, or an urbanised area served by the corresponding water utility.

- Many urban water utilities have very high levels of 'unaccounted for' water – often above 30% and in some cases up to 50% of total supply. This includes physical losses from the distribution system and so the net supply to users, whether registered or illegally connected, is much less.
- Reported groundwater use may be in the form of dependent population or of volumetric abstraction with empirical conversion factors. Water source dependency under drought conditions is not generally reported, although groundwater sources are generally the more resilient at such times.
- National surveys and statistics on household water supply record the main source of supply; although in many cases households use two or more sources for different purposes and/or at different times of year.

1.3 Urbanisation and groundwater – an intimate fragile relationship

1.3.1 Urban modifications to groundwater cycle

Urbanisation greatly modifies the 'groundwater cycle', with some benefits but many threats (Foster et al., 1994). Urbanisation and associated industrialisation usually have a marked impact on aquifers underlying cities and in turn man-made modifications to the groundwater regime can have equally serious impacts on urban infrastructure (Foster et al., 1998; Howard, 2007). These modifications show systematic variation with hydrogeological setting, for example:

- Unconfined (oxygenated) aquifers allow free vertical movement of water and pollutants to the water-table and direct interaction with the built infrastructure.
- More confined aquifers greatly impede vertical water movement, often contain anoxic groundwater, are less prone to pollution but more readily over-exploited.

The hydrogeological setting also tends to determine the extent of the 'urban groundwater footprint' into the rural hinterland. The precise form of the 'groundwater capture zone' is determined by the presence of major cones of pumping depression from external water utility well fields, natural aquifer recharge areas, and zones of 'incidental recharge' from urban wastewater irrigation. Coastal cities need to be treated as a special case, because of the risk of saline groundwater intrusion and groundwater abstraction inducing land subsidence and aggravating tidal-flooding.

In general terms, urbanisation interacts with groundwater by:

- Modifying recharge mechanisms and generally increasing recharge rates, with reductions in natural rainfall recharge being compensated by leakage from water mains, infiltrating pluvial drainage, and/or wastewater 'returns' via in-situ sanitation and leaking sewers (Figure 2).
- Increasing contaminant load resulting from in-situ sanitation, sewer leakage, and wastewater irrigation reuse.
- Draining shallow unconfined aquifers by introducing deep drains to protect underground infrastructure such as road tunnels (Wolf et al., 2006).

1.3.2 Unstable groundwater regimes – an infra-structure hazard

There are rarely sufficient groundwater resources within an urban area to satisfy the full water demand of larger cities and so resource sustainability often becomes an issue (Foster et al., 1998; Taniguchi et al., 2009). Serious localised aquifer depletion can induce seepage of contaminated water or coastal saline intrusion in unconfined aquifers. Land subsidence associated with settlement of inter-bedded aquitards in semi-confined aquifers (e.g. in Jakarta-Indonesia, Bangkok-Thailand, and Mexico City) can also have serious consequences for urban infrastructure (Table 2).

As major conurbations evolve there can be a 'sting-in-the-tail' in central districts as water-tables rebound, rather than continuing to fall. This occurs when waterwell pumping is abandoned because of declining 'heavy industry', if high-density residential areas convert to commercial use, or where there are fears of groundwater pollution and major new water supplies are imported from elsewhere. This can seriously impact urban infrastructure (Table 2), especially where it is designed and constructed on the geotechnical assumption of 'drained soil conditions'.

Figure 2 Typical modifications of the urban groundwater regime in downtown areas with sewerage (without waterwell abstraction)

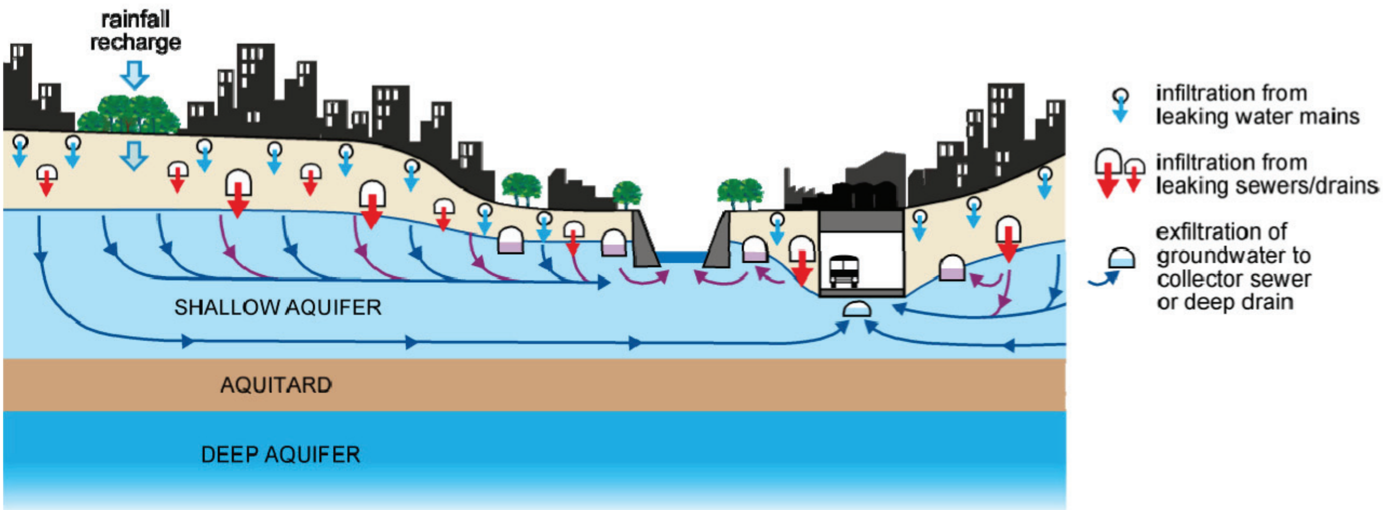


Table 2 Major causes and consequences of unstable urban groundwater regimes

Groundwater system status	Fundamental cause	Major potential side effects
Long-term water-table or piezometric pressure decline	Excessive localised abstraction compared to net recharge in urban environment or inflow capacity to semi-confined aquifer systems	Improved urban drainage, but sometimes also induced infiltration of polluted or saline surface water, in unconfined groundwater systems Aquitard settlement and land subsidence (sometimes differential) causing serious damage to built infrastructure, subsurface tunnels and sewerage system
Water-table rebound to shallow depth	Cessation or reduction of groundwater abstraction coupled with increased net rate of groundwater recharge in urbanised area	Structural uplift damage or flooding in basements, tanks and tunnels Seepage to deep collector sewers causing damage and flow excess Septic tank malfunction Mobilisation of water pollutants/toxic gases from contaminated land Decrease in effective soil stress reducing foundation bearing-capacity and engineered slope-stability Corrosion of buried structures where groundwater has high salinity

More subtle water-table rise may also occur in shallow groundwater systems. This may be the result of increased urban groundwater recharge rates and/or sealing natural drainage routes when local watercourses are canalised and sealed, or sub-surface cut-off walls are constructed. This can cause persistent 'groundwater flooding' problems that affect the operation of main sewerage collectors and septic tanks (Table 2). Such problems were witnessed over the past 15 years in Buenos Aires in Argentina (Foster et al., 2010a), Riyadh in Saudi Arabia, and Bucharest in Romania.

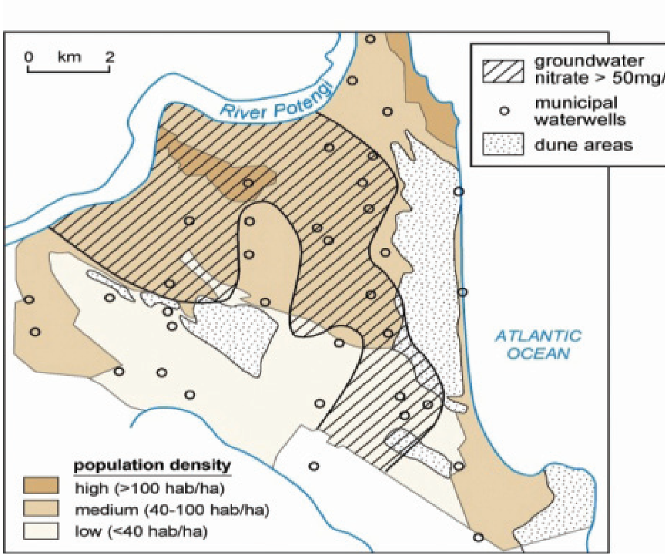
1.3.3 Impacts of urbanisation on groundwater quality

The link between groundwater and sanitation is especially important in developing nations because of the high proportion of urban population (and high population densities) served by in-situ sanitation, which can result in substantial subsurface contamination and a hazard to groundwater quality (Foster et al., 1998; Barrett and Howard, 2002). In most aquifer types, except the most vulnerable, there is sufficient natural groundwater protection to eliminate faecal pathogens in percolating wastewater from in-situ sanitation. But hazards increase markedly with sub-standard waterwell construction and/or informal or illegal sanitation and waste disposal practices (e.g. Lewis et al., 1980). However, troublesome levels of nitrogen compounds (usually nitrate and sometimes ammonium) and dissolved organic carbon (including increasing numbers of community chemicals such as pharmaceuticals, disinfectants, and detergents) also occur to varying degrees, according to the population density served by in-situ sanitation (Figure 3). Such pollution can penetrate to considerable depths and persist after the contamination source is removed (Foster et al., 2010a).

There are many other contaminant sources in urban areas that potentially can impact groundwater quality:

- Infiltration of urban runoff from streets, roofs, gardens, and industrial sites with heavy metals and persistent micro-pollutants.
- Intensive urban horticulture, resulting in nutrient and pesticide leaching.
- Inadequate chemical storage or handling and/or improper urban and industrial liquid-effluent and solid waste disposal can generate a subsurface load of potentially mobile, persistent, and toxic compounds.

Figure 3 Groundwater nitrate concentrations and their relation with population density in an unconfined sand-dune aquifer – the example of Natal-Brazil (the urbanised area is served by in-situ sanitation except for a limited river waterfront zone)



1.4 *Lack of integrated vision among fragmented urban institutions*

Groundwater is far more significant in the water supply of developing cities than is commonly appreciated. It is also the 'invisible link' between various facets of urban infrastructure. Most urban groundwater problems are insidious, persistent, and costly. They affect everybody, but all too often they are the responsibility of 'nobody'. While many problems are 'predictable', few are actually 'predicted' because of the vacuum of responsibility and accountability.

Thus when making decisions about urban infrastructure planning and investment it is important to give appropriate, and often detailed, consideration to groundwater, whatever the status of waterwell use. But this is not so simple to achieve because institutional responsibility is split between various organisations, none of which take the lead. Regretfully in the developing world, water resource agencies do not have the capacity to cope with urban development, urban water service utilities have a tendency to be rather 'water resource illiterate', and land use and environmental agencies have little understanding of groundwater.

River basin stakeholder committees (where these exist) should be conscious of the usual need to incorporate groundwater as part of watershed planning and be aware of the special problems that arise in major urban areas. Unfortunately, it is rare for members of such committees to have sufficient knowledge of groundwater system behaviour to be able to provide an early warning of potentially hazardous problems.

2 How can we improve management?

2.1 *Effective resource governance – filling the institutional vacuum*

Every urban area is unique, as a result of its different hydrogeological setting, socio-economic evolution, and institutional provisions. Thus no simple universal model for urban groundwater governance and management is applicable. But there is a pressing need to pursue an integrated approach which includes systematic groundwater management plans in order to improve urban water service efficiency and security and avoids costly impacts on urban built infrastructure and the environment.

Groundwater resources in and around urban areas are influenced by a complex array of local decisions, which are rarely viewed in an integrated fashion. These include:

- Waterwell drilling and use authorisation – usually by water resource agencies.
- Producing and distributing water supplies – mainly by water service utilities.
- Land use change and industrial development by municipal government.
- Installing in-situ sanitation and handling wastewater by public health departments and water service utilities.
- Handling industrial and community chemicals, and disposing of liquid effluents and solid wastes by environmental authorities.

The importance of groundwater for urban water supply is not yet reflected by sufficient investment to manage and protect the resource base. Government, at all levels from national to local, must establish realistic policies and effective institutional arrangements to address these issues. This will require support from political leaders, improved communication with and participation of stakeholders, and all informed by sound hydrogeological science.

Most cities need to establish an 'urban trans-sector groundwater consortium' or 'standing management group', comprising regulatory department/agency and all major stakeholders. This needs to be empowered and financed in the common interest to improve urban groundwater monitoring and evaluation, and define and implement a 'priority action plan'. The consortium could be constituted as a sub-committee of a more general integrated stakeholder platform. It would also need sound technical advice and diagnostics provided by a recognised groundwater institute. A major challenge is likely to be the acceptance that different municipal land management practices are needed in areas where there is significant groundwater recharge taking place in order to protect groundwater quality. This will often be further constrained by the fragmented nature of land ownership, land use jurisdiction, and environmental controls.

2.2 *Controlling exploitation of major urban aquifer systems*

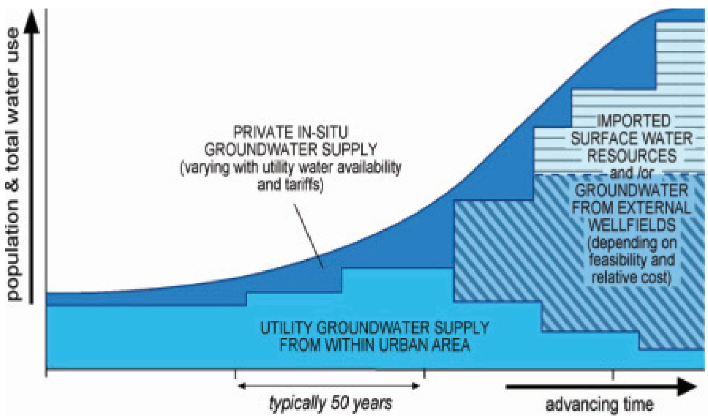
2.2.1 More sustainable deployment of utility groundwater sources

Water service utilities, which abstract groundwater solely within urban municipal boundaries, are likely at some point to confront concerns about sustainability (Foster et al., 1998). They must also consider the broader issue of community interest in stabilising the water-table as part of an integrated strategy that recognises all the components of the urban water system and sits within an organisational framework that includes institutional, financial, and policy structures (Jacobsen et al., 2012).

The first priority must be to critically appraise perspectives on urban water management and water use practices, and to develop a strategy that maximises the benefits of water services whilst minimising water usage. If this alone is not sufficient, then a groundwater management plan will be needed which takes into account such measures as:

- Declaring 'critical areas' where large-scale groundwater abstraction must be constrained or reduced, variously through waterwell closures and/or specific bans on new or replacement waterwells.
- Establishing municipal well fields outside cities with capture areas declared as drinking-water protection zones (Figure 4), and introducing procedures and incentives so that neighbouring rural municipalities are fully aware of the groundwater resource interests of the urban municipality.
- Importing additional surface water supplies from distant sources, usually at high associated capital and revenue cost (Figure 4).

Figure 4 Typical temporal evolution of water supply sources with large-scale urban development (for areas surrounded by high-yielding aquifers)



These measures must form part of an integrated water resources strategy that thinks creatively and considers a portfolio of water source options (including mains leakage reduction, storm water capture and rainwater harvesting), promotes multiple water use (in sequence from higher to lower quality needs), looks critically at reducing water wastage, and uses innovative storage (through exploring the options for managed aquifer recharge, storage, and recovery). This presents not only a challenge in terms of raising the necessary financial investment, but also of overcoming conceptual, institutional, and administrative constraints such

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as fragmented powers over land use and pollution control, and a lack of incentives for cooperation among municipalities within and around 'metropolitan areas' (Foster et al., 2010b).

2.2.2 Taking an adaptive approach to groundwater management

Given the evolutionary nature of urban groundwater systems and significant hydrogeological uncertainty in predicting their precise behaviour, an adaptive management approach is strongly recommended. Such an approach offers greater long-term water supply security, but needs to be founded on sound information (Box 1).

The core tools for adaptive groundwater management are a transient numerical aquifer model, calibrated with historic groundwater abstraction and drawdown data, and an adequate groundwater level and water quality monitoring network. By regularly updating the model, it can be used to evaluate future groundwater abstraction scenarios, such as increased abstraction rates during drought, and thus help to define more robust and sustainable solutions for municipal water supply.

Box 1: Adaptive management of urban groundwater – investigation requirements

- Hydrogeological survey to establish aquifer recharge mechanisms/rates (including man-made sources), the evidence for natural aquifer discharge, the position of any saline-water interfaces and/or overlying patches of polluted or saline groundwater.
- Detailed inventory of current municipal, industrial, and commercial waterwells (including up-dating the administrative status of their use rights and socio-economic profile of users).
- Economic assessment of the cost of improving interconnectivity within parts of the municipal water supply system to allow various areas to be supplied for different sources.
- Evaluation of surface water availability for municipal water supply within various time frames, the seasonal variability of their yield, and other vulnerabilities.

2.3 Private groundwater use – reducing risks and improving benefits

2.3.1 Rational assessment of private waterwells

The initial capital investment for private waterwells is usually triggered during periods when utility water supplies are highly inadequate in service continuity and/or aerial coverage. Private self-supply is essentially a 'coping strategy' for households, commercial establishments, and industrial enterprises (Foster et al., 2010a). Although the economy of scale can be poor, the cost of private self-supply usually compares favourably with the utility tariff when it is based on full cost recovery for new surface water supply schemes. For this reason private waterwell use often continues as a 'cost-reduction tactic' to avoid paying higher tariff levels. The well researched cases of Aurangabad in India and Fortaleza in Brazil clearly reveal this user behaviour and show that residential and commercial/industrial users tend to take water from multiple sources according to temporal availability and relative cost (Foster et al., 2010a).

Public administrations need to undertake a broad assessment of private waterwell use practices in order to formulate a balanced policy on groundwater resource use (Table 3). Intensive private groundwater use does not necessarily cause serious resource over-exploitation since aquifers are often replenished from water-main leakage and seepage from in-situ sanitation. But private users are at risk from anthropogenic pollution or natural contamination. Private waterwell use also reduces demand on municipal resources for non-sensitive uses, such as garden irrigation, cooling systems, and recreational facilities. It also guards against the possibility of groundwater-table rebound and urban drainage problems should utility abstraction radically reduce.

However, when large numbers of more affluent dwellers opt for private waterwell use the knock-on effects can be complex. They can 'free-up' utility water production capacity to meet the needs of low-income

Table 3 A public-administration overview of private in-situ urban water supply from groundwater

PROS	CONTRAS
• greatly improves access and reduces costs for some groups of users (but not generally for the poorest because without help they cannot afford the cost of waterwell construction except in very shallow water-table areas)	• interactions with in-situ sanitation can cause public health hazard and could make any waterborne epidemic more difficult to control, and also potentially hazardous where serious natural groundwater contamination present
• especially appropriate for 'non quality-sensitive' uses – could be stimulated in this regard to reduce pressure on stretched municipal water-supplies	• may encounter sustainability problems in cities or towns where principal aquifer is significantly confined and/or mains water-supply leakage is relatively low
• reduces pressure on municipal water-utility supply and can be used to meet demands whose location or temporal peaks present difficulty	• can distort the technical and economic basis for municipal water utility operations with major implications for utility finance, tariffs and investments
• incidentally can recover a significant proportion of mains water-supply leakage	

neighbourhoods but they simultaneously reduce utility revenue collection and make it more difficult to maintain highly subsidised 'social tariffs' for minimal use. Where a municipal water utility has excess resources and is subject to commercial incentives, it may market mains water supply as a substitute for private supply and distort the policy dialogue on rational urban water provision.

2.3.2 Regularising private waterwell use

Private waterwells can pose a major challenge for water resource agencies. Modern waterwell drilling techniques provide rapid access to groundwater for modest capital investment, making it possible for large numbers of users to invest in 'hardware' which is soon hidden from view. This can lead to unregulated and illegal abstraction. Managing this situation is often beyond the capacity of public administrations. This situation is counter-productive from both the private and public standpoints, and also impedes rational policy design and integrated planning for urban water supply. But it can be 'regularised' by taking advantage of modern technologies, such as geographical positioning and data-capture systems. Some strengthening of the professional capacity and political mandate of water resource agencies will be required, but the emphasis must also be on gaining civil society commitment, using participatory mechanisms with incentives for 'self-registration' and 'self-monitoring'.

If systematic assessments indicate a serious hazard from groundwater pollution or over-exploitation the following management actions could be considered:

- Registering all multi-residential, commercial, and industrial users, and charging (directly or indirectly) for abstraction to constrain use.
- Issuing water quality advice and/or health warnings to private waterwell operators, and in severe situations declaring sources unsuitable for potable and sensitive uses.

An important emerging policy question is – What circumstances might justify completely banning private residential waterwells in an urban setting? Historically, private waterwell use bans, or severe constraints, were introduced to help control water-borne disease outbreaks. Examples include cholera in 19th Century London and in seaports in the Caribbean in the 1980s. Restrictions were also introduced in Bangkok and Jakarta in the 1990s to limit land subsidence and flood risk. But bans or restrictions usually have high transaction costs and may only be partially successful. In Brazil, abstraction constraints are currently in place in parts of Ribeirão Preto and São José do Rio Preto in São Paulo State to address problems of local over-exploitation, with restrictions applying to all classes of groundwater user. In São Paulo City abstraction limits are in place for zones of proven industrial groundwater contamination, but complete replacement is simply not possible (Foster and Hirata, 2012).

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There are also some promising examples of attempts to regularise private use of urban groundwater. In Bangkok in Thailand an approach using time-limited licensing for all larger multi-residential, industrial, and commercial groundwater abstractors was adopted to constrain private waterwell use in critical areas. This is coupled with a progressive charging plan and has successfully stabilised groundwater levels and curtailed serious land subsidence (Buapeng and Foster, 2008). In Recife and Fortaleza (Brazil), municipal utilities argued for levying a volumetric water charge on private waterwell users who make use of mains sewerage. A comprehensive inventory of private waterwells on multi-residential, commercial, and industrial properties was drawn-up and charges made based on sewer use by type/size of property or by metering private waterwell use (Foster et al., 2010a).

2.4 Mitigating the groundwater pollution hazard

2.4.1 Managing the link between in-situ sanitation and groundwater

The link between groundwater and sanitation is especially relevant in developing nations since it presents the greatest hazard for groundwater quality (Foster et al., 1998). Poor in-situ sanitation systems, such as pit latrines and/or dysfunctional septic tanks, have widely been responsible for microbiological contamination of groundwater sources. Where piped sewerage systems exist, there is the risk of leakage into groundwater.

A more integrated approach to urban water supply, mains sewerage provision, and urban land use is required to avoid persistent and costly problems, especially where local aquifers are providing the municipal water supply. Public administrations and water service providers can employ a number of simple measures to improve groundwater sustainability (Drangert and Cronin, 2004; Foster et al., 2010a). These include:

- Prioritising recently urbanised districts for sewer coverage to protect good quality groundwater and/or limiting the density of new urbanisation served by in-situ sanitation to contain groundwater nitrate contamination.
- Establishing groundwater source protection zones around all utility waterwells that are favourably located to take advantage of parkland or low-density housing areas.

- Ensuring availability of 'nitrate-dilution capacity' by securing a stable source of high quality supply for blending.
- Involving residents in wastewater quality improvement by seeking cooperation on not discarding unwanted chemical products to toilets or sinks, and avoiding the use of particularly hazardous community chemicals.

Much more effort is needed to change attitudes towards wastewater reuse and associated energy and nutrient recovery, which can contribute positively to urban groundwater management. New technologies that promote wastewater as a resource need to be tailored to conditions in low-income countries, including low-cost membrane systems, and hybrid natural and constructed wetlands. Another promising technology is eco-sanitation, which separates urine from faeces and recovers both for reuse. This reduces the subsurface contaminant load. But large-scale retro-installation in existing dwellings is not straightforward and it is not well suited for cultural groups who use water for anal cleansing.

2.4.2 Pragmatic ways of addressing industrial pollution threats

Where there is significant industrial activity interspersed with public utility and private domestic waterwells, it is essential to carry out groundwater pollution surveys and risk assessments. Fuel storage facilities, chemical plants, paint factories, metallic and electronic industries, dry-cleaning establishments, leather tanneries, timber treatment, and waste tips can all discharge mobile, persistent, and toxic chemicals with potential to contaminate groundwater and thus need to be closely monitored. The intensity of subsurface contamination is not necessarily a function of the size of industrial activity. Often small, widely-distributed enterprises use considerable quantities of toxic chemicals and pose a major threat since they operate outside the formal registers and environmental controls.

Groundwater pollution surveys and risk assessments should be commissioned by the public health, environmental, or water resource agencies, in close liaison with water service utilities, using recommended protocols (Foster et al., 2002/2007). A typical survey would involve the following steps:

- A systematic survey of existing and past industrial activity to assess the probability of different pollutant types contributing to subsurface contaminant load.
- A groundwater pollution hazard assessment considering the interaction between the subsurface contaminant load and local aquifer pollution vulnerability.
- A detailed groundwater sampling and analysis programme with the analytical parameters being guided by the above survey.

The results of such scientific survey and assessment work should guide policy by:

- Introducing pollution control measures including better constraints on handling and disposal of industrial effluents to reduce groundwater pollution risk.
- Increasing quality surveillance for selected utility waterwells and/or progressive investment to replace waterwells considered at greatest risk of serious pollution.
- Advising and warning private domestic waterwell users of potential pollution risks, imposing use constraints, and in extreme cases forcing closure of waterwells.
- Designing a long-term focused groundwater monitoring programme to improve water quality surveillance and security.

2.4.3 Downstream of downtown – spatial planning of wastewater reuse

Many developing cities have to invest in expanding mains sewerage, and in one sense urban wastewater is the only 'natural resource' whose global availability is steadily increasing. Wastewater reuse within and downstream of cities for agricultural and amenity irrigation often results in major recharge to alluvial aquifers because of a general tendency to over-irrigate. This 'accidental' groundwater recharge often ends up being the predominant reuse in volumetric terms (Foster and Chilton, 2004). Urban wastewater must be regarded as both a useful resource but also a pollution hazard because its nitrogen content generally exceeds crop requirements and it contains elevated dissolved organic carbon (DOC) concentrations. This can lead to a trihalomethane hazard on water supply disinfection and/or the possible presence of hazardous synthetic organic compounds in waterwells.

The impact of wastewater irrigation reuse on groundwater quality can be reduced and managed by a combination of measures:

- A proactive approach to spatial planning controls over wastewater to avoid irrigation in municipal waterwell protection areas.
- Reducing the ingress of saline water and toxic compounds into the main sewerage system.
- Urging constraints on the use of shallow private domestic waterwells in wastewater irrigation areas, but encouraging pumping from shallow aquifers for irrigation.
- Improving wastewater treatment and reducing over-irrigation.
- Increasing the intake depths and sanitary sealing of utility waterwells.
- Intensifying groundwater monitoring for pathogens and synthetic organic compounds.

Box 2: Key Components of an Urban Groundwater Management Plan

Groundwater Status and Services

- Current resource and quality status and trends
- Future services required from groundwater body or aquifer system

Current Management Arrangements

- Institutional provision, capacity and effectiveness
- Water allocation arrangements and use regime
- Adequacy of monitoring networks

Future Management Measures and Programme

- Economic cost-benefit analysis for management options
- Feasibility of introducing economic incentives to reduce demand
- Identification of key tasks, their financial and institutional needs
- Definition of strategy for stakeholder participation
- Development of an adaptive management strategy

3 What is the future outlook?

3.1 Urban groundwater resource management planning

Groundwater planning should be an essential component of integrated water resources management in an urban setting. An 'urban groundwater management plan' will have several components (Box 2). But the first requirement is to delineate a 'groundwater management unit or body'. This will normally be centred around the area of urban abstraction and take into account the groundwater flow regime and any major surface water interactions defined by hydrogeological criteria. The boundaries of the unit should be adapted as far as possible to local political land divisions, since these are the units in which the public administration of urban municipalities must work.

Management unit boundaries always need to be sensitively located, even where an urban area does not exert strong influence on the subsurface flow regime, because of the diverse impacts and complex interactions with underlying groundwater. Critically a groundwater management plan must coordinate effectively with various 'external interfaces' such as sanitation, drainage, infrastructure function and/or stability. This requires effective coordination with the corresponding authorities for public health, environment, infrastructure, water supply, drainage, and sometimes also with power utilities. Similarly, groundwater will also have an intimate relationship with metropolitan and municipal land use planning.

A sound groundwater management plan will need to be in place before large-scale water supply transfers are introduced into an urban area previously dependent on local groundwater. There are many examples globally of very costly problems arising where inadequate planning has resulted in unexpected rapid water-table rebound and/or increased groundwater pollution when groundwater abstraction is significantly reduced.

Implementing a plan requires a staged process including structured interaction with stakeholders, preferably federated into a 'permanent consultation mechanism'. Successful implementation may also require strengthening institutional arrangements and linkages, raising substantial capital investment, improving groundwater use and aquifer response monitoring, organising an effective public-information campaign, and promoting capacity building programmes.

3.2 Conjunctive groundwater and surface water management

Groundwater needs to be used effectively and can play a key role in adaptation strategies to climate change in many developing countries. For this the large groundwater storage of many aquifers should be managed strategically, and in some cases used conjunctively with surface water (Figure 5) to improve water supply security (Foster et al., 2010b) in preference to use for 'base-load municipal supply'. But most present conjunctive use in developing countries amounts to a 'piecemeal coping strategy'. One example is Lucknow in India where over several decades utility waterwells were drilled ad-hoc in newly constructed suburbs to meet water demand at lowest possible capital cost (Foster et al., 2010b). Surface water was recently imported from a new distant source to reduce dependency on waterwells because of groundwater over-abstraction and pollution fears rather than for conjunctive management.

There are, however, some good examples of optimised resource use, such as Lima in Peru and Bangkok in Thailand, where the normal constraints to promoting managed conjunctive use were overcome and the related capital investment mobilised (Foster et al., 2010b). However, urban water engineers, pressed by day-to-day problems, more often look for operationally simple set-ups, such as a single major surface water source and large treatment works, rather than more secure and robust conjunctive solutions. There can also be vested interests in constructing large capital works. A 'resource culture' needs to be fostered within water utilities of developing cities in order to promote a more balanced view between long-term security and short-term considerations of operational efficiency and cost.

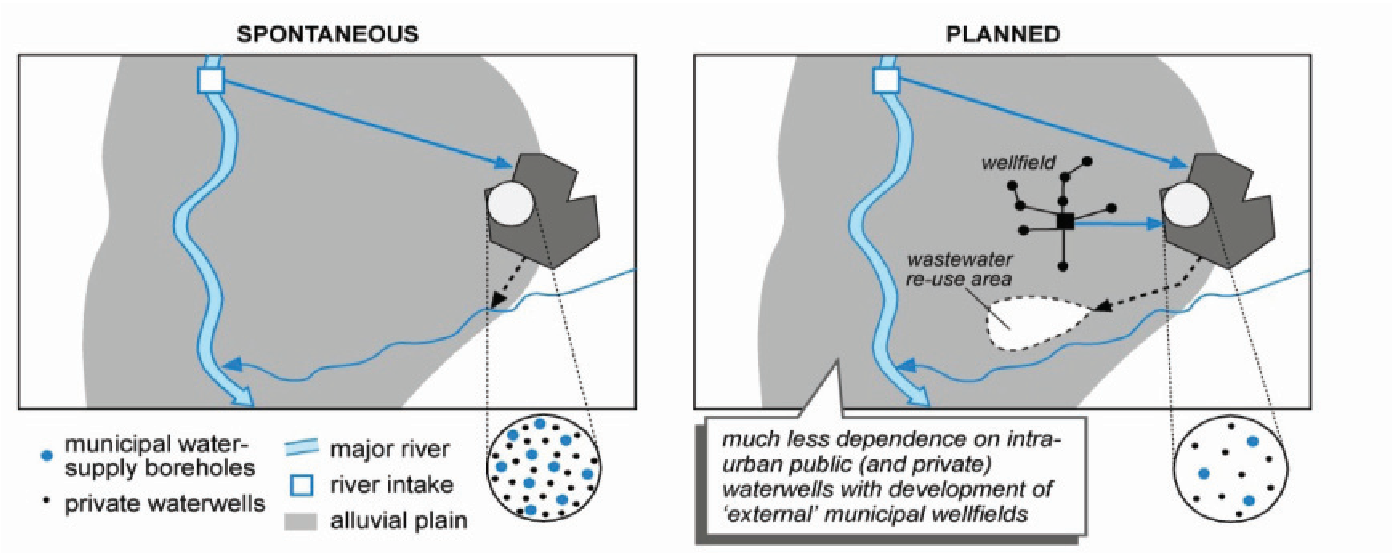
3.3 Groundwater in decentralised urban water service paradigms

In the future, and especially given the escalating global rate of urbanisation, urban water service systems will probably need to be both more decentralised and planned as 'closed-loop' operational cells. This is particularly relevant for servicing populations in the range 10,000–50,000. Such systems can be operated to minimise infrastructure costs, energy use, and water losses, since they reduce the distance between household use and water treatment (Vairavamoorthy et al., 2011). They can also promote energy and nutrient recovery by converting current liabilities, such as energy required for wastewater treatment, into assets, such as energy recovery from wastewater treatment, and facilitating local wastewater reuse. Decentralisation can increase adaptive potential if clusters are added in stages to meet growing demand.

The natural drought resilience and quality protection of many aquifers and deep waterwells means that they are well suited to be the water supply source for decentralised closed-loop water service systems. Since these systems treat wastewater nutrient content as a resource by separating urine from faeces and recovering it for sale as fertiliser, their installation should substantially reduce the urban subsurface contaminant load for in-situ sanitation, and thus one major groundwater pollution threat. Nevertheless, it will also be necessary to put more local attention and effort into on-the-ground inspection and control of other forms of urban land and groundwater contamination, such as gasoline stations, small-scale motor shops, dry-cleaning laundries, etc., to prevent the loss of important waterwell sources.

The 'future vision' of urban water services in developing countries recognises that decentralised sanitation will be essential on grounds of cost and reliability to achieve much-needed major improvements in coverage for existing urban areas (Howard and Bartram, 2010), although more centralised solutions for potable water supply may in some cases be more appropriate for such areas (on grounds of quality).

Figure 5 Illustration of planned (as opposed to spontaneous) conjunctive urban use of groundwater and surface-water sources



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