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Urban water-supply security – making the best use of groundwater to meet the demands of expanding population under climate change

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Abstract In Sub-Saharan Africa the rate of urban population growth places heavy pressure on water-supply provision – a pressure that is likely to be exacerbated by reduced reliability of surface-water sources under most climate change scenarios. Where suitable aquifers are present, expansion of groundwater development is usually the preferred response, in terms of time taken, capital outlay and drought reliability. This is widely occurring, both by urban water utilities (at a variety of scales) and through the rapidly-growing phenomenon of "community and private self-supply". This paper provides an overview primarily from World Bank experience of the social benefits, economic implications and quality hazards of urban groundwater use, as a stimulus for discussion of the role of groundwater in improving urban water-supply security.

Key words urban water-supply; Sub-Saharan Africa; groundwater; climate-change adaptation

INTRODUCTION

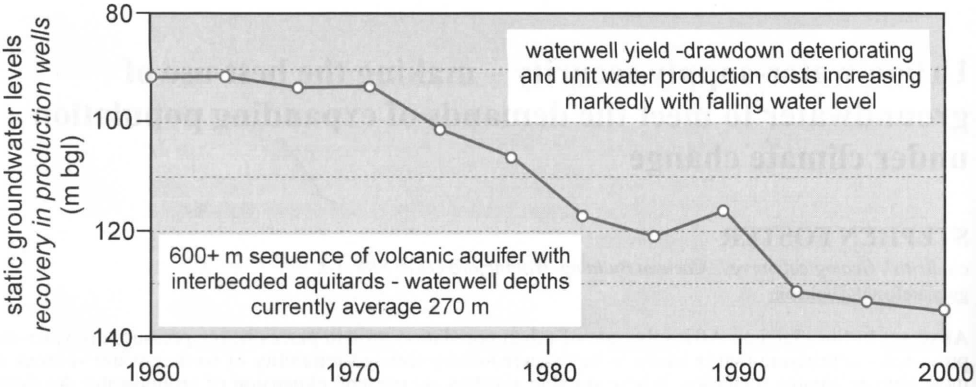
The rapid growth of urban populations (widely in the range 2–7% per annum) and water demand (at rates of up to 10% per annum) is a current reality in Sub-Saharan Africa – and is likely to be further aggravated by accelerated climatic change. These trends do not just affect megacities, where periurban areas in particular have extremely high population densities, but are even more pronounced in thousands of medium-sized towns (Foster *et al.*, 2006). Many climate-change scenarios imply increased frequency of surface-water drought, with potential impacts on the reliability of associated urban water-supply sources. This is likely to place greater demand on available groundwater resources as an integral part of climate-change adaptation since, inherently, they have better short-term security, being less directly and rapidly affected by climatic variability.

A good example from Sub-Saharan Africa of the role that groundwater is widely called to play in overall urban water-supply comes from Greater Nairobi (Kenya), which in the late-1980s developed major surface-water sources about 50 km distant and rated at 520 ML·day^{-1}. However, rapid urban expansion and large system losses has widely led to inadequate water utility service-levels, and the drilling or reactivation of many private waterwells to depths of 200–350 m into the underlying rift-valley volcanic deposits, despite questions about their long-term sustainability (Fig. 1). Moreover, in 2002 a flood-associated landslide caused loss of an external pipeline and reduced mains water availability to less than 300 ML·day^{-1} for many months, and further increased short-term dependence on private groundwater supplies (Foster & Tuinhof, 2005). The aquifers underlying Greater Nairobi merit much more investment in management measures in view of their proven character as a strategic reserve.

It should be noted that the processes of urbanisation have strong and evolving linkages with groundwater underlying cities (Fig. 2), and in general terms it can be said (Foster *et al.*, 1997) that:

- the urbanisation process impacts on groundwater through a tendency for increased contaminant load and recharge rates from water "imported to the city", as a result of *in situ* sanitation wastewater returns, sewer leakage and physical water-mains leakage;
- groundwater system changes impact on the urban infrastructure as a result of both falling water-table (land subsidence) and rising water-table (structural uplift and inundation).

Associated problems can be persistent and very costly, and all too often, where groundwater is concerned, without integrated vision and planning in the urban environment "one persons solution becomes another persons problem"!



data reflect expansion of public water-supply from groundwater during 1970–1980, but its abandonment in favour of surface-water sources in the late-1980s;
then major expansion of private groundwater production capacity to over 200 ML·day^{-1}, but normal use constrained to around 85 ML·day^{-1} due to increasing energy costs.

Fig. 1 Evolution of groundwater levels in Greater Nairobi (Kenya) during 1960–2000.

ANALYSIS OF URBAN WATER AND SANITATION PROVISION

Understanding the use of groundwater

Given the paucity and dispersion of reliable data, it is far from a trivial task to establish the present level and current trends in groundwater use in the rapidly urbanising areas of Sub-Saharan Africa. For the region as a whole, the most comprehensive information is contained in various reports of the World Bank Infrastructure Diagnostic (e.g. Banerjee *et al.*, 2008), which uses mainly the MACRO International Demographic & Health Survey Database of 2007 incorporating 63 large-scale surveys in 30 African countries. Some of these are time-sequential and complement the UNICEF/WHO Joint Monitoring Programme on household access to and cost of infrastructure services.

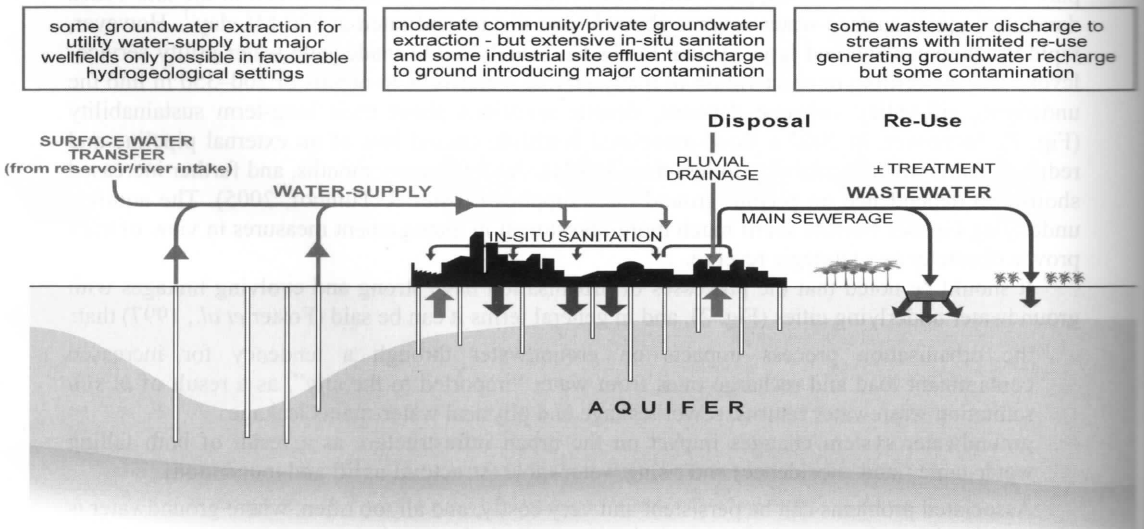


Fig. 2 Groundwater and the city – an intimate complex relationship.

From scaling-up these surveys it is estimated regionally that approaching 80% of the urban population have access to an "improved water source" although this proportion may actually be declining in recent years due to the very rapid rates of urban population growth. This "diagnostic study" showed substantial variation between more and less urbanised countries (Table 1) and areas, and major differences between different income groups within any country – but the following general conclusions could be reached (Banerjee *et al.*, 2008):

- on average only 38% of urban dwellers are served by mains water-supply piped to their dwelling place, but a further 29% do have access to a municipal stand-point within 500 m;
- 24% of urban water-supply is collected from waterwells (dugwells and boreholes but not all improved), constructed by the municipality, community or privately, and the balance is made-up by purchase from water vendors and collection from unsafe surface water.

Groundwater use figures in Table 1 reflect numbers of users but not volume of abstraction, and they do not consider other urban direct self-supply (commercial and industrial) users, most of which depend on groundwater. The available data in this respect are very incomplete and rather unreliable (Foster *et al.*, 2006) but those for three megacities (with population in the range 3.4–4.2 million) suggest the following approximate average levels in $ML \cdot day^{-1}$ of "surface water abstraction: municipal/utility groundwater abstraction: private groundwater use" – Addis Ababa = 180 : 50 : 90, Dar-es-Salaam = 300 : 30 : 80, and Nairobi = 520 : 10 : 90. Total groundwater abstraction exceeds 100 $ML \cdot day^{-1}$ in all cases and private groundwater use probably amounts to 15–30% of total urban water-supply.

Table 1 Sources of urban household water-supply in selected Sub-Saharan African countries.

Country	Population with piped supply	Standpost access	Collection from waterwells	Water vendors
Burkina Faso*	32%	52%	13%	1%
Ethiopia	52%	37%	6%	1%
Ghana*	34%	38%	21%	3%
Malawi	31%	42%	24%	1%
Nigeria*	15%	17%	48%	11%
South Africa	88%	10%	2%	0%
Tanzania	22%	45%	19%	8%
Uganda	14%	47%	35%	2%

* Countries with long-term tradition of groundwater use and dependency.

Sanitation realities and risks for groundwater

Other sections of the "diagnostic study" reveal the following situation regarding urban sanitation:

- an average of 33% of the urban population are served by waterborne sewerage systems – although the nominal proportion of the urban area with coverage is higher at over 50%
- 59% of the urban population are dependent upon *in situ* sanitation (mainly the basic pit latrine with a small proportion of septic tanks) and about 8% have no sanitation system whatsoever.

Contrary to operational guidelines, only a minor proportion of pit latrines in most African cities and towns are emptied (with most being connected subsequently to supplementary pits), and thus these data imply a very large wastewater-derived contaminant load to groundwater, especially in situations of highly-populated peri-urban areas underlain by shallow aquifers. This load will be augmented by sewer leakage, industrial effluent disposal, hydrocarbon spillage/leakage and leachates from solid-waste tipping. The former is clearly reflected in groundwater pollution case histories from a recent UNEP-UNESCO-funded programme (Table 2) – the problem of high nitrate concentrations (coupled with other chemical contamination) and faecal contamination hazards from pit latrines having first been identified in the small towns of eastern Botswana over

Table 2 Summary of recent urban groundwater pollution case profiles (derived from Xu & Usher, 2006)

City (population) country	Hydrogeological setting	Levels of groundwater pollution nitrate	faecal	other
Harare (1.4 M) Zimbabwe	weathered crystalline basement in seasonally humid climate	widely >100 mg/L in peri-urban areas	widely present and locally serious	low pH/local elevated heavy metals
Ougadougou (1.2M) Burkina Faso	weathered crystalline basement in semi-arid climate	50% borewells >50 mg/L and dugwells worse	implied for dugwells but no analysis	nothing major detected
Dakar (2.8M) Senegal	marine/aeolian sands with some basalt flows with moderate rainfall	widely >50 mg/L and >200 mg/L some areas	50% wells, because of poor completion	coastal saline intrusion also problem
Mombasa (0.7M) Kenya	marine/aeolian sands and limestones in humid tropical climate	30% wells >50 mg/L and few >100 mg/L	widespread and serious densely-populated areas	no other problems reported
Lusaka (1.2M) Zambia	dolomitic karst limestones with moderate rainfall	widely >50 mg/L, locally >100 mg/L dry season	widespread and serious, but seasonal variation	no other problems studied

25 years ago (Lewis *et al.*, 1980). The risk of faecal pollution of groundwater, however, could and should be limited to the most vulnerable hydrogeological conditions, but it currently remains a much more widespread problem because of inappropriate *in situ* sanitation unit design/operation and inadequate waterwell sanitary completion.

Future trends in urban infrastructure development

The World Bank Infrastructure Diagnostic raises the critical question of "how to provide safe urban water-supply at affordable cost whilst ensuring the financial viability of the urban water-sector utilities?" – making the point that most urban households in Sub-Saharan Africa survive on a very small budget (averaging just above US$100/month) of which 50–65% is used to purchase food. Groundwater resource development (in one shape or another) will quite widely represent the lowest-cost option and thus must always be considered as a potentially important component of the solution. But the appropriate type of waterwell, their yield potential, pumping lift and the corresponding capital cost (for completed well with pump) will vary widely (by more than an order-of-magnitude) with hydrogeological setting, and further variation may be introduced as a result of local market factors and equipment import levies – and it will be such economic considerations that determine the drivers and actors involved.

The limited available collated data suggest the following as regards typical waterwell costs:

- small-diameter shallow tubewells (20–30 m), with simple plastic support casing (not purpose-manufactured wellscreen) and equipped with a handpump, cost US$ 3000–5000 equivalent – such waterwells are feasible in shallow aquifers (weathered crystalline basement and coastal alluvium) for which yields of 0.2 $L \cdot s^{-1}$ (say 10 000 $L \cdot day^{-1}$) are widely obtained and capable of supplying 200 people at a capital cost of US$15/capita (yields sufficient for motorised pumping require significant local field investigation for successful siting);
- deeper tubewells or borewells (100–200 m) equipped with small-capacity electric pumps are capable of producing 1–10 $L \cdot s^{-1}$ (depending on aquifer conditions) and cost US$15 000–25 000 equivalent; such waterwells would be required for sedimentary, volcanic and some alluvial aquifers (in which the permeable horizons are located at depth and/or natural static water-levels are below 30 m depth) and where feasible with a motorised pump yielding 2 $L \cdot s^{-1}$ (say 100 000 $L \cdot day^{-1}$) could supply around 2000 people at a capital cost of US$10/capita.

It is evident that (for the most part) even the cost of shallow waterwell drilling in the urban environment would need to be shared across a substantial number of dwellings, and thus it is likely (in the immediate future given average family incomes) that the majority of urban waterwell construction will be using national, state or municipal funding, together with the financial resources of international donors and charities. The policy of these types of organisation as regards groundwater use in the urban environment is likely to be dictated by:

- the prospects, relative cost and hydrological security of groundwater sources,
- whether the yield and quality of the more accessible aquifers is adequate to support local reticulation to standposts (or even use as mains supply) or more suited to providing a local community source for water collection.

The expansion of low-cost facilities, such as boreholes/dugwells, with limited reticulation to standposts where feasible and coupled with improved pit latrines for sanitation, is the most probable future scenario.

The economic situation has incidentally tended to reduce pressure on available groundwater resources (limited in some hydrogeological settings) from private waterwell construction. This situation could, however, change relatively rapidly if policy decisions are made, and financial support secured, to stimulate the waterwell drilling. Current waterwell construction costs in Sub-Saharan Africa are significantly higher than those in Latin America and South Asia (Foster *et al.*, 2006) – where the unit cost of small-diameter waterwells with low-capacity electric pumps currently averages around US$2000 and US$500, respectively, and private direct supply from groundwater has mushroomed with users invariably counted in many thousands (even in medium-sized cities).

POLICY IMPLICATIONS FOR GROUNDWATER USE

The availability of groundwater resources is constrained by hydrogeological setting and this shows wide spatial variation. These resources tend therefore to play a different range of roles and offer different prospects in urban water-supply according to conditions:

- a few megacities are underlain by major aquifers which provide the principal source of both utility and private urban water-supply (e.g. Lusaka, Abidijan, Dakar);
- some megacities have deep aquifers in their vicinity which offer potential to become a major source of urban utility water-supply (e.g. Dar-es-Salaam, Addis Ababa);
- most megacities are underlain by relatively low-yielding aquifers, but these have become increasingly developed for water-supply by a range of users in response to past failures in the utility mains water-supply system (e.g. Nairobi, Harare);
- the vast majority of small-to-medium sized towns depend on groundwater (springs, boreholes) for their municipal water-supply but are encountering difficulties in expanding their systems to cope with increased demand – many having developed their initial groundwater sources without significant hydrogeological investigation or subsequent systematic monitoring.

Expansion of small–medium town supplies

In small- to medium-sized towns the rate of urban population growth and the vulnerability of shallow aquifers to pollution are widely leading to a need for the siting and development of waterwells with sufficiently large yields and assured quality to support continuous pumping and reticulation to urban standposts. Concomitantly a very high priority needs to be put on improved groundwater resource and vulnerability appraisal, efficient waterwell design, local aquifer recharge area and wellhead protection – together with much improved water source and aquifer monitoring which will provide a logical basis for the design of the inevitable expansion of municipal water-supply sources and services in years to come.

Potential growth of *in situ* self-supply

Sooner or later in most countries, it is likely with urban economic development that the demand for direct self-supply from groundwater by residential, commercial and industrial users will grow substantially, even in hydrogeological settings which offer prospects of only relatively small waterwell yields. Looking further afield at medium-sized cities (Fortaleza-Brasil/2.2 million and Aurangabad-India/1.2 million) (www.worldbank.org/gwmate), it can be predicted with some confidence that large-scale private groundwater self-supply is usually initiated by individual private urbanisations as a "coping strategy" at times of inadequate municipal utility water-service provision (and in the presence of modest underlying aquifers and relatively inexpensive drilling services). But private waterwells tend to continue in use by the same users as a "cost-reduction strategy" (given their "sunk capital") to avoid paying the higher tariffs of municipal utility services when these are augmented with new more costly water sources – this almost regardless of quality considerations and the potential presence of significant contamination.

In reality, pragmatic ways need to be identified locally of living with urban groundwater quality deterioration problems – and there is thus a need to:

- facilitate and provide incentives for rational private urban groundwater use (such as domestic toilet flushing, laundry, amenity irrigation, non-sensitive industries, cooling water, etc.);
- be aware of potential long-term operational and financial problems created by large-scale residential *in situ* self-supply for municipal water-supply planning and the potential public health hazard in highly vulnerable urban aquifers.

In the longer run, it will be beneficial to register the multi-residential private waterwells, to improve urban waterwell sanitary completion and wellhead protection, and to consider measures to reduce subsurface contaminant load (especially regular emptying of existing *in situ* sanitation facilities, introducing eco-sanitation units, prioritising mains sewerage in areas of high aquifer pollution vulnerability and/or industrial effluent generation) and to enhance aquifer recharge by rainwater harvesting from roof-top and paved areas. A number of tools can and should be developed to facilitate the ordered development of groundwater resources in urban areas and (where appropriate) to reduce the risk associated with private investment in groundwater development:

- maps of waterwell yield potential and reliability, depth to main aquifer horizons, static groundwater levels, groundwater pollution vulnerability and natural quality hazards;
- protocols for waterwell design, construction and operation, and design and operation of *in situ* sanitation (septic tanks and improved latrines);
- assessments of approximate status of groundwater resource abstraction, levels of sustainability and seriousness of risks associated with persistent excessive abstraction;
- guidelines on groundwater use precautions in relation to quality considerations and risks;
- procedures for rainwater harvesting and aquifer recharge enhancement techniques at individual urban plot level.

Controlling operations of water vendors

In some cities within Sub-Saharan Africa, the distribution of water by private-sector vendors (at differing scales from bottles to trucks) plays a significant role in urban areas, in terms of bulk-supply and/or the potable component – and as such has a special significance in the public-health sense. It is virtually impossible for local public-health authorities to inspect such operations on the basis of "product quality control" and a much more pragmatic approach ought to be taken involving regular inspections of the suitability and level of wellhead protection of the groundwater sources used, and of the process of handling and distribution. Those that do not meet adequate sanitary standards must be banned from operation and the unacceptability of their product publicised, since otherwise they will represent a major public health hazard.

Development of major new municipal groundwater sources

Where hydrogeological settings are favourable (albeit a minority of cases) there may be potential for significant new groundwater resources to be developed by wellfields in the hinterland of cities and large towns. This will have the major benefit of providing access to large natural storage reserves to act as a "buffer" for climate-change adaptation. The development of such groundwater resources will require substantial investment – with a systematic approach including stepwise investigation, phased monitored development and concomitant action to preserve recharge areas and protect dependent ecosystems.

A good example in Sub-Saharan Africa comes from Dar-es-Salaam, where the water-services utility (DAWASA) is responsible for municipal water-supply to a conurbation of over 3.0 million population. Its major water-supply source is an intake about 35 km distant on the Ruvu River rated at almost 300 ML·day^{-1}, but this is threatened by baseflow reduction and sediment load (Kalugendo, this volume). At present the supply deficit is partially met from municipal and private boreholes in the urban area (Fig 3), but a major Tertiary-Neogene "coastal terrace" sedimentary aquifer has been explored in an essentially rural area of low population density 30–60 km south and southeast of the city. Its successful development will require systematically-staged and carefully-monitored development together with land protection to avoid urban invasion and degradation of the aquifer recharge area.

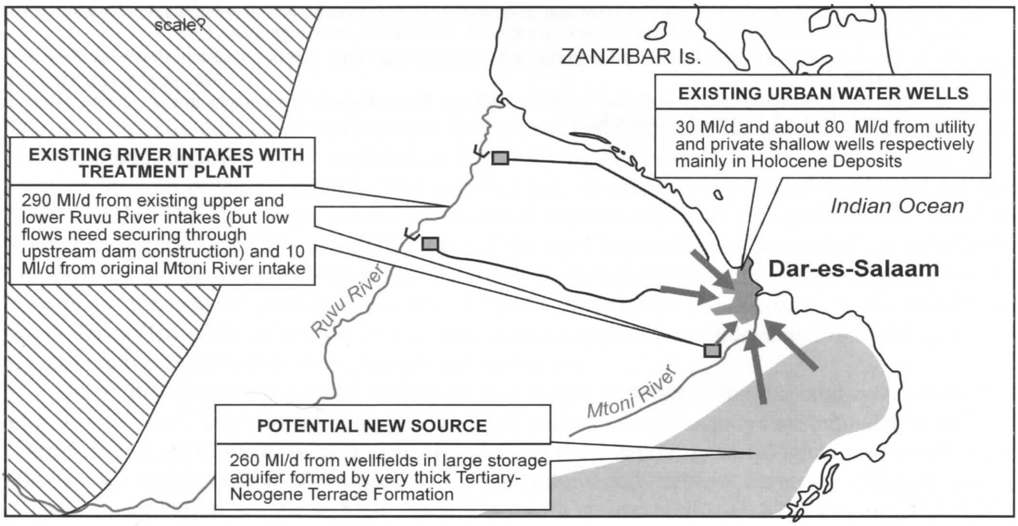


Fig. 3 Existing and potential new water-supply sources for Dar-es-Salaam (Tanzania).

INSTITUTIONAL ARRANGEMENTS FOR URBAN GROUNDWATER

It is evident that in virtually all cases more effort needs to go into the development of appropriate policies for urban groundwater use and on evaluating, managing, conserving and protecting groundwater resources. Given the special conditions in fast-growing urban centres this will normally require an integrated effort involving empowered representatives from the water resource regulator (where such exists), the water utility, the public-health authority and the municipal land-use planning agency, and a standing committee of such representatives would benefit from a mechanism for community consultation and the work of a technical support group to investigate and report back on specific issues and potential conflicts. Professional expertise on how to evaluate, develop, manage and protect groundwater resources has declined in some parts of Sub-Saharan Africa since the 1980s (especially in government offices) (Foster *et al.*, 2006). This has been due to lack of appropriate training, poor recognition of groundwater professionals, reductions in public spending, disbanding of some national centres, etc. and the human resource dimensions of addressing the issue of "making better use of urban groundwater resources" cannot be overlooked.

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