

Addressing urban water scarcity: reduce, treat and reuse – the third generation of management to avoid local resources boundaries

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Abstract

Urban growth leads to geographically concentrated demand for water and food – and to growing volumes of wastewater and organic waste. Left unattended by city authorities, both local and planetary resources boundaries for water and nutrients will be transgressed. A novel partly dynamic ‘flexible water balance’ is developed to explore ways to address a looming water crisis. A systems-based flow chart shows how rainwater, groundwater and recycled water interact. Measures from supply-, demand-, and reuse management are combined to manipulate the water flows.

Water management in Bangalore, India, focused on supply management over the period 1964 to 2015, tapping distant rivers. This mind-set was challenged by a Water Disputes Tribunal and international financiers. Residents and industry were losing faith in the erratic water supply, and met part or all their water needs by digging or drilling wells. The ‘flexible water balance’ is tested on Bangalore for the year 2050 when the population has increased from 8 to 20 million. New housing complexes can provide opportunities for effective arrangements to recycle water and nutrients, save energy, and reduce water pollution and air emissions. The ‘flexible water balance’ indicates that Bangaloreans can get enough household water without tapping river water and still recharge groundwater.

Keywords: Bangalore; Demand management; Groundwater abstraction; Rainwater harvesting; Recycling wastewater; Supply management; Sustainable sanitation; Urban eco-houses; Urban water balance; Water scarcity

1. Introduction

World population will increase from six to more than ten billion (10^9) in this century, and it is estimated that 8.5 billion will live in urban areas, up from 3 billion in the year 2000 ([Organisation for](#)

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Economic Co-operation and Development (OECD), 2013) – and tens of millions of them are already born. The additional 5.5 billion urban people will need housing, and the number of urban dwellings has to almost triple. This increases the stress on limited resources and the environment, among them scarcity of water and plant nutrients. The present systems-based study develops local management options for cities to help avoid transgressing such global boundaries without compromising comfort, human health, climate or the environment.

Life-supporting water flows through our communities, and most efforts to meet demand have gone into supplying sufficient water of good quality. Three policy phases have evolved to address challenges to manage limited water resources. The first, supply management, presupposes that if users *ask for more* water it should be supplied by withdrawing more water from previously untapped sources. The rapid population increase in many urban areas implies that this supply management entails chasing a moving target. Therefore, it becomes necessary to also manage the demand to control and reduce the per capita use of water. The questions asked from the demand management perspective are *what do users do* with the water they already have at their disposal, and whether they can reduce this amount without compromising, e.g., comfort and health. Demand management comprises a number of soft instruments to modify user behaviour with rather short notice, as well as medium-term installation of water-saving technical devices.

With mounting water scarcity, supply and demand management measures are not likely to deliver enough water to meet future demands. A more proactive and systems-based approach is needed which asks different questions: What do *users add* to the water while using it? Where does the effluent and sludge end up after treatment? If not polluted unnecessarily, this used water could be treated and used again. This recycled source of water is seemingly limitless.

The fast-growing city of Bangalore in southern India is an example of how this emerging third generation of water management, here called reuse management, can utilise recently used water as a resource (Drangert & Cronin, 2004). The study analyses earlier and present water management practices in Bangalore and explores anticipated sustainable strategies and measures to secure future water supply as well as the availability of nutrients for food production while protecting human health and the environment.

2. Bangalore's water challenges

Bangalore is the capital of Karnataka State, and dubbed the Silicon Valley of India thanks to its software industry being a prime mover of today's economy. The city is expanding rapidly, both in population and size, and counts over eight million inhabitants after its jurisdiction tripled in size in 2007 by adding 550 km² and incorporating more than 1.2 million people who lived in neighbouring municipalities and villages (Figure 1).

The area is drought-prone because of its location in the rain shadow of the Western Ghats mountain range, which blocks the south-western monsoon. The yearly rainfall is about 900 mm, and mostly within a range of 830–970 mm. The city used to be famous for being a lush 'Garden City' as well as for having hundreds of water tanks. In an early integrated water management initiative, lakes and man-made ponds were joined in chains to harvest rain for irrigation, serve as freshwater reservoirs, and at the same time recharge the groundwater. But, both tanks and parks have been diminishing in number and size for a long time. A High Court Report on Bangalore Lakes (High Court, 2011) describes the situation as

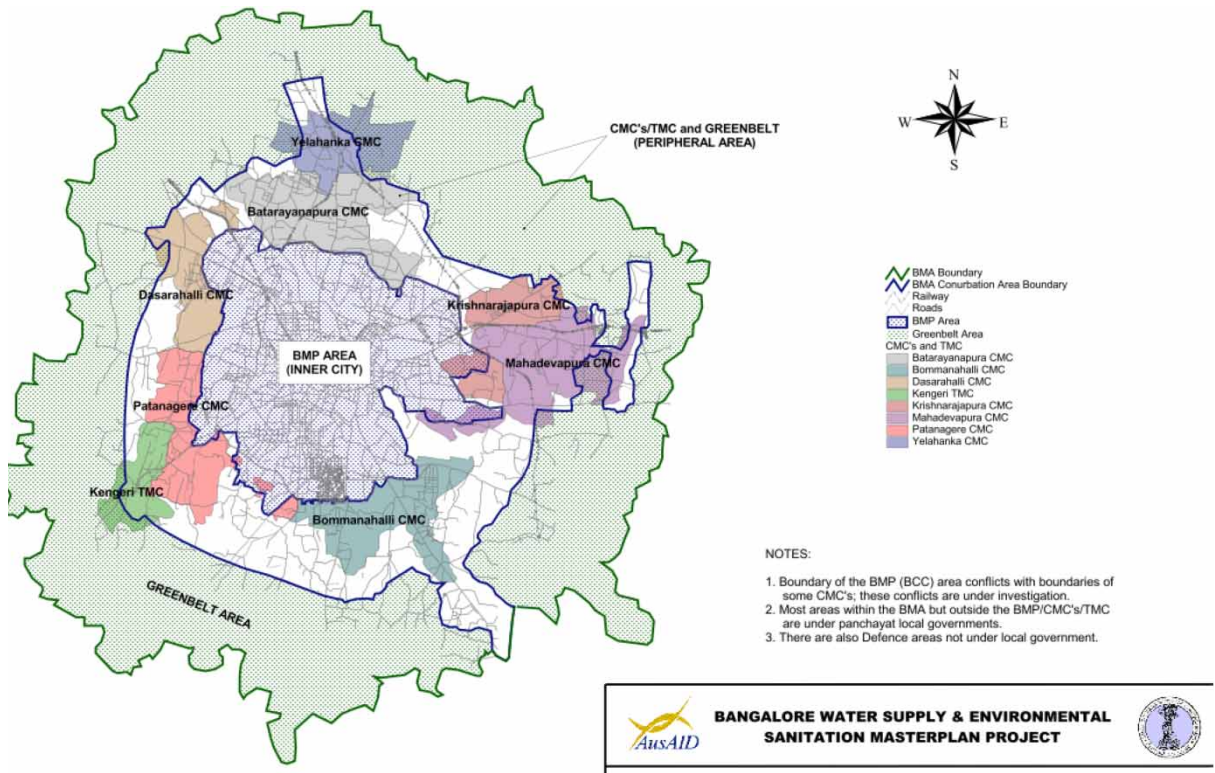


Fig. 1. Map of Greater Bangalore with the core city, municipalities and villages added in 2007 and including a 200 km² greenbelt peripheral area (AusAid, 2002). BMA = Bangalore Municipal Authority, BMP = Bangalore Municipal Corporation, CMC = City Municipal Corporation (seven), TMC = Town Municipal Council (one).

follows. Tanks, being seasonal by nature, have been encroached upon by new infrastructure and residential layouts, including slum areas. Others vanish due to the spread of the water hyacinth or because the flow to them has been inhibited. Surface water bodies are hence disappearing and the rejuvenation of groundwater is severely affected. Also, heavy rains cause flooding and damage due to the lack of drainage routes and retention sites. These problems are aggravated by indiscriminate disposal of solid waste in drains. The small streams that flow through the undulating city terrain are used as drains for untreated sewage and stormwater, and some tanks have become perennial due to inflow of wastewater from these drains.

A Water Board (Bangalore Water Supply and Sewerage Board, BWSSB) was set up in 1964 with essentially technical staff, like in most utilities in the world at that time. Their work was centred on water supply schemes, and huge investments were made to impound Cauvery River water and to pump it through 100 km long conveyor pipes to the city. Strong evidence of ‘supply thinking’ is the Board’s request to the Disputes Tribunal in 1990 to be allocated as much as 2,350 MLD (Million Litres per Day) (30 TMC [Thousand Million Cubic Feet]) of Cauvery River water, while the [Disputes Tribunal \(2007\)](#) allowed 12.75 TMC. The Board was empowered to plan, operate, and maintain public water supply and sanitation services, a kind of city monopoly since no other agency was allowed to compete.

Few attempts have been made over the years to understand the entire water balance of the city. The planning authorities have focused on drawing ‘virgin’ water from the Cauvery River (Metha *et al.*, 2013). Apart from some legislation, little if any attention was paid to groundwater sources or run-off water. Agricultural and city interests were not reconciled and inter- and intra-state interests delayed proactive responses. Recently, two groundwater experts (Hegde & Chandra, 2012) proposed the water balance in Figure 2 for Bangalore city. They estimate that a quarter of normal annual rainfall over Greater Bangalore, recalculated to 1,800 MLD, becomes run-off (466 MLD), while 71% (1,288 MLD) is taken up by plants and evapotranspired to air, and a tiny 2% and 6% infiltrate to the groundwater in built-up areas and open areas, respectively. The total recharge of groundwater amounts to 90 MLD of which 58 MLD comes from rain, 25 MLD from perennial tanks, and 7 MLD from wastewater (1% of the total volume of wastewater). The water balance shows a heavy dependence on Cauvery River water and a serious 378% (341 MLD) overdraft of groundwater (Hegde & Chandra, 2012). The data are analysed further in the following sections with the purpose of designing a systems-based water balance.

Gross river supply is claimed to vary between 110 and 150 litres per capita per day (lpcd) over the last few decades, including domestic and non-domestic water and wastage (BWSSB, 2008). Metha *et al.* (2013) claim that on average residents receive less than 40 lpcd in rapidly expanding parts of the city and 60–80 lpcd in slowly expanding core areas. But, the supply is erratic and in large areas, residents receive tap water for a few hours every second day, and numerous customers receive tap water only twice a week or every ten days (Sastri, 2006; Metha *et al.*, 2013). Bangaloreans are therefore aware of the increasingly grave shortage facing them and the city. Yet, the City reported full coverage of water supply to the Millennium Development Goal database in 2005 (Central Public Health and Environmental Engineering Organisation (CPHEEO), 2005).

3. Water supply management measures in the past

Three main water sources are presently used in Bangalore, i.e. rivers and lakes, groundwater and directly collected rainwater. The water flows are described with the aim to formulate a revised water balance for 2050, and all volumes are given in MLD for comparison purposes.

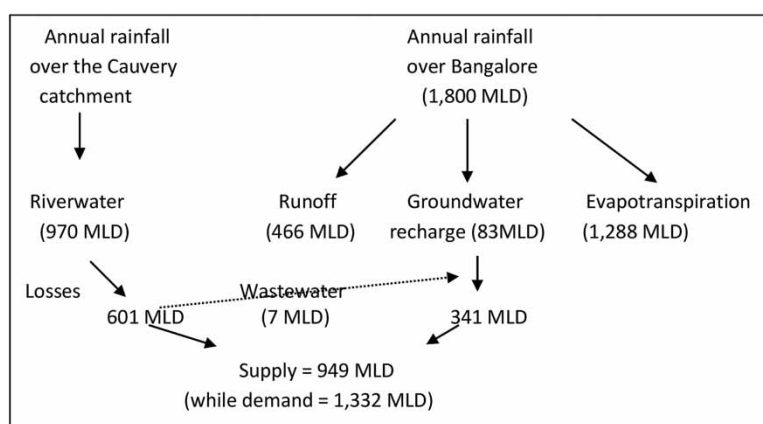


Fig. 2. A water balance for Greater Bangalore (revised from Hegde & Chandra, 2012).

3.1. Surface water sources

Greater Bangalore has no major river, and the city was self-sufficient in terms of water only until around the second half of the nineteenth century. Later, the city became more and more dependent on pumping surface water from afar. Since the inauguration of the first conveyance of water from the Cauvery River in 1974, a major extension has been added each decade. The Water Board reserved the 2013 extension of Cauvery water supply (510 MLD) to residents in areas incorporated in Greater Bangalore in 2007, where earlier only 8% in the municipalities and 6% in the villages were connected to the city supply (Sastry, 2008).

The withdrawal volume from the Cauvery River has been negotiated through a Disputes Tribunal set up in 1990 with the States of Karnataka, Kerala, Tamil Nadu and the Union Territory of Pondicherry. In 2013 the Supreme Court confirmed the Tribunal's decision of 2007 to allocate 8.75 TMC per year, the equivalent of 685 MLD, to Bangalore households (equals 1.75 TMC at the rate of 20% consumptive use) and 4 TMC, or 310 MLD, to industries (equals 0.1 TMC with 2.5% consumptive use), which adds up to about 5% of the total river flow (Metha *et al.*, 2013). This allocated amount to Bangalore is about half of what most cited papers report. The Supreme Court decision assumes 150 lpcd for Bangalore residents and 70 lpcd for rural dwellers, and also assumes that only half of the drinking water requirement is met by river supply (including transit losses). Furthermore, two-thirds of Bangalore city is located outside the Cauvery River basin, and therefore only a third of the metropolitan area is eligible to access this water. This court decision blocks all further expansion of withdrawal from the Cauvery River, and even the present withdrawal is likely to be challenged by farmers in Karnataka State (Metha *et al.*, 2013).

Apart from being subject to strong competition, water from the Cauvery River must be pumped against a head of 500 m over a distance of almost 100 km to reach the city at a mean altitude of 920 m. Some 60 MW of electricity is required per day to lift 910 MLD and the cost amounts to 70% of the total revenue (BWSSB, 2012b). Any interruption of electricity contributes to making the supply of river water unstable.

3.2. Groundwater resources

Some 40% of the residents are estimated to depend on groundwater to some extent (Raju *et al.*, 2008). The Water Board had some 7,000 bore wells in 2005 and a decade later, they had 12,000 wells out of which 3,000 were constructed over the four-year period 2007/08–2010/11 (BWSSB, 2011c). However, about 4,000 wells have become dry at a rate of 300 per month (BWSSB, 2013). This has resulted in public frustration and moreover it may cast doubts on actual depths of public wells. The Board's groundwater withdrawal is estimated to be 66–70 MLD by Banerjee & Chaudhuri (2012) and Raju *et al.* (2008) whereas the '2030 Water Resources Group' made up of local water experts claims it to be 500 MLD (Deloitte, 2014).

Bangalore has experienced a phenomenal growth of private tube wells from about 5,000 to more than 300,000, possibly 400,000, over the last two decades which shows that – in practice – not only river water has been in focus for the residents (Hegde & Chandra, 2012; Deloitte, 2014). Rithesh (2010) estimated that one out of every five buildings with a BWSSB water connection also has a bore well. This proportion has risen substantially due to the increase in the number of wells. Studies indicate that private wells yield 261–306 MLD (Banerjee & Chaudhuri, 2012; Hegde & Chandra, 2012). In addition, some

3,000 private tankers sold about 8.5 MLD to new housing estates in the incorporated municipalities, originating from private wells in villages (Central Ground Water Board (CGWB), 2008). Raju *et al.* (2008) estimated a total of 750 MLD to be extracted from private and public wells every day in Bangalore. The range of available data calls for more comprehensive and reliable estimates.

Groundwater is found in streaks and pockets, and many Bangaloreans utilise open wells that are dug in the weathered zone to a depth of only 5–10 metres (CGWB, 2008). Most of the yield is found down at a depth of 60 metres (Radakrishna, 2006). The rock formations below 280 m lack primary porosity and fractures and thus have low water-holding capacity (Hegde & Chandra, 2012). Expanding hardened city surfaces and vanishing infiltration areas has contributed to a serious 200% overdraft of groundwater and rapidly sinking groundwater levels (CGWB, 2008). Monitoring data from the Department of Mines and Geology (2011) show that the water table has fallen in the peripheral area due to urban growth. Leaking mains and a move of industries out from the core city resulted in an increase of the groundwater table there by a few metres (BWSSB, 2008). The ‘2030 Water Resources Group’ reported lowered levels by up to 1,000 feet (Deloitte, 2014).

The Karnataka Ground Water Bill (2009) provides wide-ranging authority to protect groundwater quality and yields. The enforcement of this Bill is weak, however, as evidenced by the large number of new unregistered private wells, a serious overdraft, and the drying up of public wells. Not only groundwater quantity but also quality becomes an issue for the many who rely on groundwater. Infiltration of chemicals, microorganisms and organics in wastewater from households and industry is dominating (CGWB, 2008). There are only a few regular groundwater-sampling points in Bangalore, and the information on quality is contradictory. A recent survey by the Department of Mines and Geology (2011) showed that out of 2,209 analysed samples, 29% exceeded the allowed level of nitrate, and 31% did not comply with the drinking water standard, but 50% of the groundwater was considered potable without treatment. However, the Karnataka State Pollution Control Board (KSPCB) (2007) monitored 171 tube wells and found *Escherichia coli* contamination in most samples to be above the limit for drinking water. A few wells showed an elevated nitrate level. Again, there is a need for more data.

3.3. Rainwater

Bangalore has an average precipitation of about 900 mm and some 60 rainy days in a year spread over five months. If a good fraction of the average 1,800 MLD rainfall over Greater Bangalore was harvested, it could replace most of the present river water supply. If purposely infiltrated, it would counteract the mining of groundwater. Yet, BWSSB has not seen rainwater as part of water supply in Bangalore until recently. In 2003, the Karnataka State Government made rainwater harvesting mandatory for new buildings with a plot area exceeding 120 m² and an amendment made it compulsory also for existing buildings with a plot area of 240 m² or more (BWSSB, 2011a). In 2003, the Water Board also made it mandatory to provide 10 litres of storage capacity for every square metre of plot area to recharge groundwater with rain- and stormwater (BWSSB, 2011a). The potential harvest of rain on roofs is estimated at 235 MLD (Deloitte, 2014). The BWSSB chairman reported that some 23,000 households harvested rainwater at that time (BWSSB, 2011b). By 2011, a mere 3% of the 2,523 government buildings in Bangalore harvested rainwater (Times of India, 2011). The government has repeatedly extended the deadline for compliance.

In a drive to empower house owners, contractors, non-governmental organisations (NGOs) and others, the Board disseminated a practical manual on how to collect rainwater and recharge wells and aquifers

(BWSSB, 2012c). A 100 m² roof potentially collects 90,000 litres annually, and provides a family of four with 100 litres of water each, every day for 200 days. If the collected water were to last the whole year, the daily use would be 60 lpcd. However, this would require sizeable investment in storage capacity that would exceed the financial resources among poorer sections of society. But, if the richer echelon and industry were to invest in storage capacity, the saved piped water could be allocated to the poor.

4. Water management efficiency and costing

At best, the Water Board could only provide 60% of urban residents with erratic tap water despite all its supply efforts. Gradually, residents, both rich and poor, and industry lost faith in the piped system and invested in tanks on roof-tops, or dug or drilled wells while others relied on water trucks or vendors. Despite its ineffective and inefficient supply management, the Water Board managed to avoid serious discussions about improved maintenance and development of alternative sources (rainwater, reclaimed wastewater, and groundwater). It is worth noting that the BWSSB statistics up to 2007 pay no attention to either rainwater harvesting or well water, but occasionally mention reuse of treated wastewater. The Water Board still viewed wastewater and stormwater as problems and not as resources.

Equally serious is the scant interest in maintenance – despite rising losses due to leakages. An estimated 48% of the water is unaccounted for due to physical and commercial losses (Deloitte, 2014). External financing institutions were the ones pressing for measures to reduce unaccounted-for water, assisted by the Supreme Court cap on additional withdrawal of river water. The Board was slowly forced into rethinking in the new century and seemed to have fully accepted that distant virgin water sources will not provide the solution to potential future water shortages (Narayana *et al.*, 2013). But, recently, the idea of tapping distant rivers has been revived (Deloitte, 2014).

For water projects with multiple sources of finance, it is notoriously difficult to identify comparable investment costs. Keeping that in mind, Table 1 roughly indicates the cost per additional MLD of water supply. The calculations have been grouped according to year, in order to make comparisons independent of inflation and exchange rate variations. For example, a study in 2004 found that reduced losses in district

Table 1. Investment costs for extending the supply of water to Bangalore.

Kind of additional MLD and year	Project MLDs	Total investment cost in		Investment cost per MLD	
		USD (M)	INR (crore)	USD (M)	INR (crore)
Cauvery (2002) ^a	270	250	1,072	0.93	4.0
Repair (2004) ^b	276	96	400	0.35	1.45
Cauvery (2013) ^c	500	546	3,384	1.1	6.8
Reuse (2013) ^d	200	50	300	0.25	1.5
Reuse (2012) ^e	0.5	1	6.2	2	12.4

1 crore = 10 million.

Sources:

^aBWSSB (2008).

^bBWSSB (2004).

^cBWSSB (2008).

^dNarayana *et al.* (2013).

^eAkme Symphony, (2010).

pipes and removal of illegal connections had the potential to make 276 MLD of lost water available to paying customers at a cost of Rs. 4,000 million or some 96 million USD (BWSSB, 2004). This amount of water equalled the second last extension (2002) of the Cauvery scheme, which had required a two and a half times higher investment of about 250 million USD or Rs. 10,720 million (BWSSB, 2004). The last extension provided 500 MLD for Rs. 33,840 million. This cost is four times higher than the life-cycle cost of Rs. 3,000 million that Narayana *et al.* (2013) estimated for reclaiming 200 MLD of wastewater. Recycling is markedly less costly per MLD than transferring Cauvery water (Hingorani, 2011).

Investment in infrastructure is often small compared to operation and maintenance (O&M) cost over its lifetime. For instance, the purchase value of a bus or lorry makes up only 5–10% of the total cost for running the vehicle. Similarly, in the case of Bangalore water supply, the total investment is about one million USD for 1 MLD of Cauvery water, while at an O&M cost of Rs. 40 per m³ it takes four years to reach the same one million USD. If the structure lasts for, say, 40 years the initial investment makes up some 9% of the lifetime cost for the supplied water. Therefore, the selection of a water system should not only consider the cheapest investment, but should also weigh in O&M costs.

The ‘2030 Water Resources Group’ estimated present life-cycle costs for various water sources and volumes that could be made available by 2030: rainwater harvesting costs Rs. 4 per m³ and the potential volume is 235 MLD; reduction of losses costs Rs. 4.6 per m³ and the volume is 313 MLD in the core city while in outlying areas the cost is Rs. 6.2 per m³ and the volume is 313 MLD; reuse costs Rs. 8.4 per m³ and the volume is 501 MLD; Cauvery V project costs Rs. 20 per m³ and the volume is 626 MLD; and lastly lake rejuvenation costs Rs. 27 per m³ and the volume is 305 MLD (Deloitte, 2014). Only the reuse alternatives include costs for proper treatment of wastewater. Table 1 and the life-cycle cost show that BWSSB focused on the most expensive solutions for its first half-century activities.

5. Demand management

Supply management is at its limit, and the Cauvery River is protected by the Supreme Court decision described earlier – therefore demand itself has to be managed. An unintended but strong measure to curb water use is that the Water Board supplies water only part of the day or not every day. Intentional demand management measures were introduced only in 2005 with a modestly progressive water tariff. Most non-slum consumers can be targeted since all single houses and apartment buildings are metered, but rarely individual apartments. However, many meters are known not to work correctly and may have been tampered with (Praj, 2010). Also, over 40% of the respondents in a 2004 household survey indicated that they had given more than one small bribe in the previous six months for the Water Board staff to falsify their water meter readings in order to lower their bills (Davis, 2004). However, this loophole is being reduced as more of the billing is computerised and faulty meters are being replaced (Praj, 2010).

The domestic sector is the Board’s major consumer group and was allocated 89% of the river supply in 2006; 62% in private taps and 27% in public stand posts (BWSSB, 2008). Most of Bangalore’s slum dwellers – who are estimated to make up some 20% of all inhabitants – had access to public water mainly from the 7,000 stand posts (Karnataka Slum Clearance Board, 2005). The Water Board has continued to reduce water supply via public taps and to industries.

The previous flat rate of Rs. 115 per month for any household usage between 0 and 15,000 litres was split in two in 2005, and reduced to Rs. 48 for the first 8,000 litres. One objective was to help

slum-dwellers to afford individual connections and to discourage them from using free public stand posts. The first 8 m³ per month cost less than a US dollar and requires only 1% of the income of residents on the poverty line of 2 US dollars a day (Water and Sanitation Programme (WSP), 2011). This tariff allows each member of a family of four, rich or poor, to receive 66 litres every day for only Rs. 0.35 or about half a US cent. Yet, poor customers are particularly sensitive to the step from free water to any charge (Bognäs, 2011).

The best estimate of actual water use is presented in Table 2 where the billed consumption is recorded. In 2006, the total amount of paid-for water was 112 M m³ which translates into 307 MLD. BWSSB (2008) reported a water production of 961 MLD this year, of which 10% was for non-domestic uses. With an assumed non-revenue level of 48%, including losses and free stand post water, the revenue volume should be 450 MLD. The ‘missing’ 143 MLD need to be traced. A likely explanation is a combination of underreporting of non-revenue water, leakages, and embezzlement.

Progressive water rates are generally believed to lower demand, but the present tariff structure, which has remained unchanged since 2005, is unlikely to lower demand as much as erratic supply does. Table 2 allows a discussion on how effective the tariff is in reducing water use. The new tariff gives incentive to move upwards from the lowest bracket to the next. For example, if a family uses 10 m³ instead of, say, 5 m³ the bill goes up from Rs. 48 to only Rs. 66 per month and therefore they are likely to use the higher volume. Rs. 18 or 33 US cents for the extra 5 m³ is far below its life-cycle cost of at least Rs. 100 (Deloitte, 2014), and thus strains the BWSSB budget further.

The 85,000 households with the lowest water use represent 22% of all connections, but this bracket uses only 4% of the total supplied water. Surprisingly, they demand only half of the guaranteed 8 m³ per month they have paid for. This may reflect the fact that supply is erratic and poor families are short of storage vessels and water sumps. Low-income earners are therefore likely to desire free public stand posts and wells. The Water Board, however, maintains that this is not the case (BWSSB, 2011d).

In 2011, the chairman announced that BWSSB will provide water and sewage connections free of charge for 362 core slum areas as part of the final extension of the Cauvery supply (BWSSB, 2011b), and only charge Rs. 250 for the water meter (BWSSB, 2012b). A likely reason for this policy revision is that BWSSB can close down stand posts, and thereby get rid of a number of illegal connections. Also, public taps account for 18% of unaccounted losses of river water as compared to 38% for the mains and 33% for service pipes (Sastry, 2006). This revision is likely to speed up the

Table 2. Paid-for domestic water from BWSSB river water supply, 2006–07 (BWSSB, 2008).

Water usage bracket m ³ /month	Tariff Rs/m ³	Proportion of total volume	No. of connec- tions	Average volume per year/ connection	Litre/day/ connection	Household size (estimated)	lpcd
0–8	Rs. 6	4%	85,000	56 m ³	153	7	22
8.1–25	Rs. 9	31%	174,000	200 m ³	548	10 ^a	55
25.1–50	Rs. 15	44%	115,000	381 m ³	1,043	10 ^a	104
50.1–75	Rs. 30	15%	23,000	631 m ³	1,728	incl. flats	n.a.
75.1–100	Rs. 36	3%	3,700	1,135 m ³	3,102	incl. flats	n.a.
>100	Rs. 36	3%	1,250	2,711 m ³	7,430	incl. flats	n.a.
Total		100%	401,950	112 M m ³			

Source: Calculations using data in Table 11 in Water Handbook (BWSSB, 2008).

^a400,000 connections service some 4 M residents, i.e. average 10 people per connection.

ongoing gentrification of core slum areas, and most likely the poorest section will gradually move away (interview with Renu Makunda, Water & Sanitation for the Urban Poor (WSUP) in Bangalore, 12 April, 2008) and be replaced by paying customers.

Due to the low tariff, most households (46%) belong to the next bracket, and they withdraw on average 20 m³ per month of the available 25 m³, indicating that the group is price-sensitive not to cross into the next bracket, or unable to cope with the erratic supply. A 10-member household would enjoy 45 lpcd which is likely to include water to flush toilets. The bracket 25.1 to 50 m³ has a surprisingly high number of connections (30%) and a likely reason for this is that households are big, but also that the cost of water is low. Twenty persons sharing the meter would use on average 60 lpcd. This and the three brackets above 50 m³ may include flats in apartment buildings, which makes it impossible to interpret the figures in terms of lpcd.

The first steps have been taken to introduce two important new components in the tariffs: a progressive tariff and a sanitation/treatment charge. A general experience is that it takes a number of years to perfect this instrument. In the meantime, the financial contributions required by BWSSB come from cheap (subsidised) loans and through levies. The Water Board has also received grants from Bangalore Development Authority (BDA) towards the Cauvery River project (BDA, 2007).

Other demand management measures, such as promoting water-saving household devices, and informing users on how to conserve water, are not yet common. For instance, there is no policy on low-flush toilets or on water-conserving shower heads and faucets, despite the fact that the regulation allows the Water Board to stipulate the kind of equipment to be installed (BWSSB, 2012b). The Karnataka State Pollution Control Board (KSPCB) has made some efforts to move the city towards water conservation in industries and public places. Incorporation of waterless urinals was made part of the consent condition for large hotels, shopping malls and the new airport. However, due to non-availability of low-cost urinals at the time this was not implemented.

6. Reuse management – the budding third generation of the water strategy

New apartment buildings and entire residential areas are regularly added to the Water Board's list of responsibilities. This not only calls for water but, more importantly, for treatment of wastewater and management of sludge. Treatment and handling of increasing volumes of wastewater is mandatory to prevent untreated wastewater from flowing by gravity beyond the city border. Most water sources under the reuse paradigm are close to sites of use and likely to be managed by communities, housing companies, individual house-owners, and industries themselves. Reuse of used water requires dual piping in the houses, decentralised treatment and return pipes to users, but rarely long conveyor pipes. Thus, energy costs for pumping and unaccounted-for losses become comparatively small for condominiums and single households.

6.1. Conventional wastewater approaches

Partial treatment of wastewater has a short history in Bangalore. Presently, the total treatment capacity is on a par with the maximum piped water supplied by the Water Board. BWSSB concedes, however, that 'in many areas, the sewerage system is incomplete. Hence sewage is either simply let into the storm-water drains (meant to carry only rainwater) or lakes' (BWSSB, 2011b). The BWSSB chairman stated

that out of 750 MLD of wastewater, about 350 MLD flows in stormwater drains (Prajna, 2010). The grave impact of untreated wastewater manifests itself as inferior quality of groundwater and pollution of old water tanks as well as of streams in- and outside the city (Jawaharal Nehru National Urban Renewal Mission (JNNURM), 2006). The situation worsens as additional untreated wastewater from houses with private wells is disposed of into municipal sewers and drains. In order to cater for volumes from private wells and rainwater harvesting, another 11 Sewage Treatment Plants (STPs) with a capacity of 349 MLD are being built (BWSSB, 2011b).

A rule-of-thumb is that proper treatment of wastewater makes up two-thirds of a water bill. The sewage treatment charge for households is a mere Rs. 15 (25 US cents) flat rate up to 25,000 litres which is totally inadequate and results in, for example, improper treatment and postponed maintenance of the networks for long periods. Today, frequent overflows of manholes and backflows to house connections occur from the 230 km trunk sewer network and 5,000 km of connection pipes.

In areas without sewer lines, a septic tank for at least toilet water is the mode of disposal of wastewater while greywater flows to stormwater drains. The Water Board does not provide vacuum tankers for emptying the tanks and house-owners rely on private entrepreneurs. However, emptying services are poor and leaking and overflowing septic tanks contribute to groundwater pollution. Only in April 2011, were guidelines introduced to prevent indiscriminate and illegal dumping by regulating discharges of industrial and trade effluents and domestic wastewater from soak pits and mobile toilets into Board sewers. Implementation of these guidelines remains a challenge.

6.2. Proactive measures for reuse – reuse management

Alternative ways to manage liquid wastes such as source control and treatment of effluent to reuse quality is just about to begin. The Water Board has begun selling treated wastewater from recycling plants at Yelahanka (60 MLD) and V. Valley (10 MLD). It is sold for Rs. 15 at site to industries, while the production cost is estimated to a mere Rs. 10–12 per m³ (Hingorani, 2011). The industrial tariff is a flat rate of Rs. 60 per m³ or 0.9 USD plus a treatment charge of only 20%. The Department of Horticulture STP treats all wastewater (1.5 MLD) in the central Cubbon Park area by using membranes and the effluent is recycled in the park. Similarly, the Lalbagh Park STP treats 1.5 MLD of wastewater with UV-radiation and recycles the effluent in the large park.

KSPCB is requesting on-site treatment to prescribed standard and reuse of wastewater in order to grant establishment rights for industries, commercial and residential areas. The new Bangalore International Airport has a modern treatment plant where the entire volume of wastewater is treated and then reused. In 2006, KSPCB made it mandatory for large apartment complexes with more than 100 apartments to have a mini-STP and dual piping system in order to use treated water for secondary uses, mainly for toilet flushing and gardening. In the last few years several hundreds of such on-site mini-STPs have been installed. Many large apartment complexes are now going for tertiary treatment options including chlorination, UV-radiation, and filtration – before reusing the water.

An extreme case of recycling is a complex of apartments (1,250 flats), a hotel, hospital and commercial centre in a core area of Bangalore which treats all its wastewater in an ultra-filtration system followed by chlorination before recycling the entire volume (2,630 m³ per day) within the complex (Brigade Group, 2012). Similarly, a condominium of one hundred flats and 19 individual houses treats 40 m³ of wastewater in its STP, including reverse osmosis, mixes this with 20 m³ of rainwater and groundwater, and uses the mix for all purposes including drinking (study visit to ZED colony in

Whitefield, 2014-08-28). Likewise, BWSSB tried to treat used water conventionally, blending it with fresh water from the T.G. Halli reservoir, and finally ultra-filtrating the mix before supplying it to the city (BWSSB, 2012a). However, due to public concern the development of recycled water to households was put on hold.

6.3. Risk factors for recycling effluent and sludge

Authorities fight an uphill battle to control all the chemical products and compounds that households purchase and dispose of in the sewer. Authorities (can) do little to prevent chemicals from entering the sewers, while wastewater-treating utilities could become whistle blowers in addition to reducing the nutrient content. Since residents and industries know that the treated wastewater comes back to them in the taps, they are likely to be more careful with what they mix into the water while using it. Residents are also encouraged to segregate solid waste, including organic waste for composting. Through such measures, the quality of the raw wastewater entering the mini-STP is likely to be better than that received at a municipal wastewater treatment plant.

The accumulation of pollutants from frequent reuse is taken care of by diluting the effluent with some rain- or groundwater, polishing it in a wetland where pollutants bond with soil particles and roots while percolating through the soil and, finally, by hygienising in a drinking water treatment unit.

Effective monitoring of mini-STPs is crucial for the treatment result. The operator knows that he cannot provide smelly or discoloured water for toilet flushing on any occasion, since the affluent residents would object. This is very different from the situation for staff at big treatment plants where there are no immediately-affected residents – and nature has no voice. Regular testing of the quality of effluent from mini-STPs shows that biological oxygen demand, chemical oxygen demand and suspended solid levels are within prescribed limits, and often lower than those of effluent from the large treatment plants (Kodavasal, 2011). Decentralised mini-STP systems are competitive concerning standard tests for treated wastewater. The chemical quality is likely to be better because residents know their wastewater is recycled and also because the household wastewater is not mixed with any hazardous industrial or hospital wastewater.

The better wastewater treatment is, the more sludge is produced. Nutrients make up a large part of sludge, but chemical contaminants often make the sludge unfit for application on farm land (European Union (EU), 2008). Therefore, sludge management improves if the nutrient-rich toilet water and urine from urine-diverting toilets is collected separately, treated and applied in the garden or on nearby farmland (Drangert *et al.*, 2017). At the same time, this makes it easier to secure better greywater quality.

7. A ‘flexible water balance’ for 2050 – a discussion

A potential water deficit in the decades ahead can be addressed with a systems approach which employs supply, demand, and reuse management of the four kinds of water sources: rainwater, surface water, groundwater and recycled water. Solutions require both improved technical installations and attitude changes, not least among professionals.

The city is expected to have at least 20 million residents by 2050. The potential to gradually build water-, sanitation-, and nutrient-smart houses is substantial since the city adds tens of thousands of new flats every year. The principles developed by BWSSB and KSPCB can be combined to create

an elaborated closed water loop. Progressive tariffs and water-saving gadgets such as low-flush toilets and water-efficient showers, faucets and washing machines can reduce demand while retaining comfort. Demand can be brought down by 30–40% compared to today's installations, to an average usage of 85 lpcd, down from the standard value of 130 lpcd, reducing total demand for household water to 1,700 MLD in 2050. The required water-saving gadgets should be compulsory in new buildings and gradually installed in old houses and flats when refurbished. If a few per cent of the housing stock are upgraded each year, all dwellings and offices will have these gadgets by 2050.

Residents and industries are eager to ensure 24/7 water supply, but they may feel less comfortable with treating the wastewater. Therefore, BWSSB is likely to be engaged in treating wastewater and providing recycled water. Its service level and tariff structure will influence to what extent industries and households will connect their valuable discharged wastewater to the communal system. Users are likely to accept higher water charges if they receive improved service (Asian Development Bank (ADB), 2010).

7.1. A 'flexible water balance' shows the way forward towards 2050

The design of a 'flexible water balance' takes into account primarily rainfall on the Greater Bangalore catchment area, groundwater recharge and recycled water, while the external water from the Cauvery River serves only as a complement in 2050, but leaking conveyor pipes should be repaired as soon as possible. Figure 3 shows the tentative amounts of water in the various flows. These are commented on below and related to reported data.

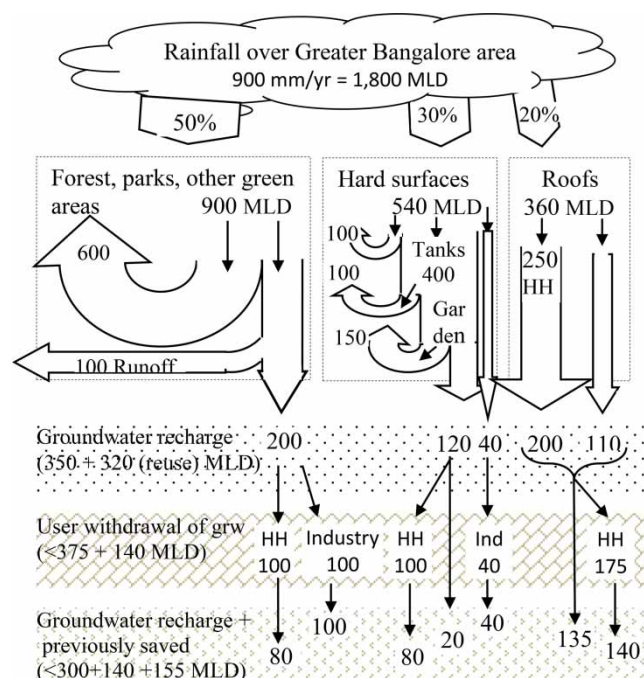


Fig. 3. A 'flexible water balance' for Greater Bangalore for the year 2050.

7.1.1. Rainfall. The annual rainfall averages some 1,800 MLD and falls on roofs (20%), hard surfaces (30%) and forests, parks/gardens and other green areas (50%). Due to an anticipated expansion of the built city to 20 million inhabitants in the year 2050, this tentative distribution is somewhat different from the one presented by Hegde & Chandra (2012).

The following assumptions are made. The 900 MLD of rain falling over green areas is split into infiltration/groundwater recharge (200 MLD), run-off (100 MLD), and 600 MLD of water sucked up by vegetation and returned to the atmosphere. The fairly high rate of infiltration may require revitalisation of tanks and construction of scattered impoundments in forests.

The 540 MLD of rain falling on hard surfaces such as streets and parking lots will partly evaporate (100 MLD), and partly infiltrate to groundwater through cracks in the hard surfaces and through compulsory infiltration (40 MLD). Of the 400 MLD run-off to rejuvenated tanks/dams, a quarter of this tank water (100 MLD) is likely to evaporate, leaving 300 MLD available for household use. The quality is good enough to flush toilets, fill washing machines, and water gardens if modestly treated. It may be recycled n_1 times in the houses, and eventually some 150 MLD will have evapotranspired and (150–30) MLD will have recharged the groundwater (20% consumptive usage).

Rainwater harvesting is mandatory. Of the 360 MLD falling on roofs, 110 MLD recharges the groundwater directly through mandatory infiltration. The bulk, 250 MLD, can be economically feasible for storage in sumps and be used by households. The produced wastewater can – after treatment – be recycled once or more times (n_2). Eventually, some (250–50) MLD are piped to recharge wells (20% consumptive usage).

Altogether, $n_1 \cdot 300 \text{ MLD} + n_2 \cdot 250 \text{ MLD}$ of recycled rainwater is made readily available for household usage from man-made structures (tanks and sumps). The full-scale reuse projects mentioned earlier show that this is possible.

7.1.2. Groundwater. The assumption is that 350 MLD (200 + 40 + 110) of rain is directly recharging groundwater under the city and together with the 320 MLD from treated wastewater, a total of 670 MLD of fair-quality water is *added* to the groundwater. Conveniently, the groundwater serves as a big reservoir that can be used to even out seasonal differences in water abstraction and this allows drawing of more water during the dry part of the year and less during the wet season.

7.1.3. Recycling. Households and industries can catch water after first use and recycle it again and again if and when required. This can be done directly, as in the upper part of Figure 3, as well as after a phase in the groundwater as shown in the lower part of the figure. A user could initially withdraw up to 670 MLD of this *added* groundwater without lowering the level. However, in this example only 515 MLD (375 + 140) are withdrawn by households and industry. Again, this fair-quality water may be recycled once or more after use and treatment: n_3 times by households and n_4 times by industry. After deducting for consumptive use, another 440 MLD (300 + 140) is recharging groundwater. In the whole process 595 MLD (670 – 515 + 440) have been *added* to the groundwater.

This is the essence of a ‘flexible water balance’ in which various water sources are interacting. In this case, urban water users have access to altogether:

$$(1 + n_1) \cdot 300 \text{ MLD} + (1 + n_2) \cdot 250 \text{ MLD} + (1 + n_3) \cdot 375 \text{ MLD} + (1 + n_4) \cdot 140 \text{ MLD}$$

This situation offers policy-makers several options to combine the management tools at their disposal. For instance, a low-rate of recycling where $n_1 = 0.5$, $n_2 = 1$, $n_3 = 1$, and $n_4 = 2.5$ provides 1,700 MLD for households and 640 MLD for industries. This amount is enough to meet demands in the year 2050 of 1,700 MLD. Cauvery water has not been utilised in this example and a non-use of river water would ease political tensions. Groundwater has, instead of being mined as is presently the case, been substantially recharged and represents a huge unconfined storage potentially available for additional uses.

7.2. A green scenario: sustainable water management in new housing complexes

The city-wide water balance combines man-made flows and flows in nature. How does this translate to individual apartment complexes? The objective is to secure 24/7 access to water and to leave almost no environmental footprints. Instead of importing 130 lpcd of river water, losing 65 lpcd of them along the leaking conveyor pipeline, and exporting 50 lpcd of wastewater (less 20% consumptive use) plus contaminated sludge, the proposed system for the city imports zero lpcd and exports zero lpcd while providing life-supporting nutrients from high-quality sludge. This is achieved with only small changes in residents' routines.

Figure 4 shows how wastewater from several hundred flats is treated in a mini-STP to produce a high quality effluent with no odour or colour. The size of the plant in the cellar can be made smaller and the effluent quality improved if the nutrient-rich toilet water or only urine from urine-diverting toilets is collected separately, treated and applied in the garden or on nearby farmland (Cordell *et al.*, 2009; Drangert *et al.*, 2010).

We assume the same water use as today's 70 lpcd, and that all wastewater is treated conventionally in the mini-STP. A total of 10 lpcd of treated wastewater are recycled for each of the three purposes, to

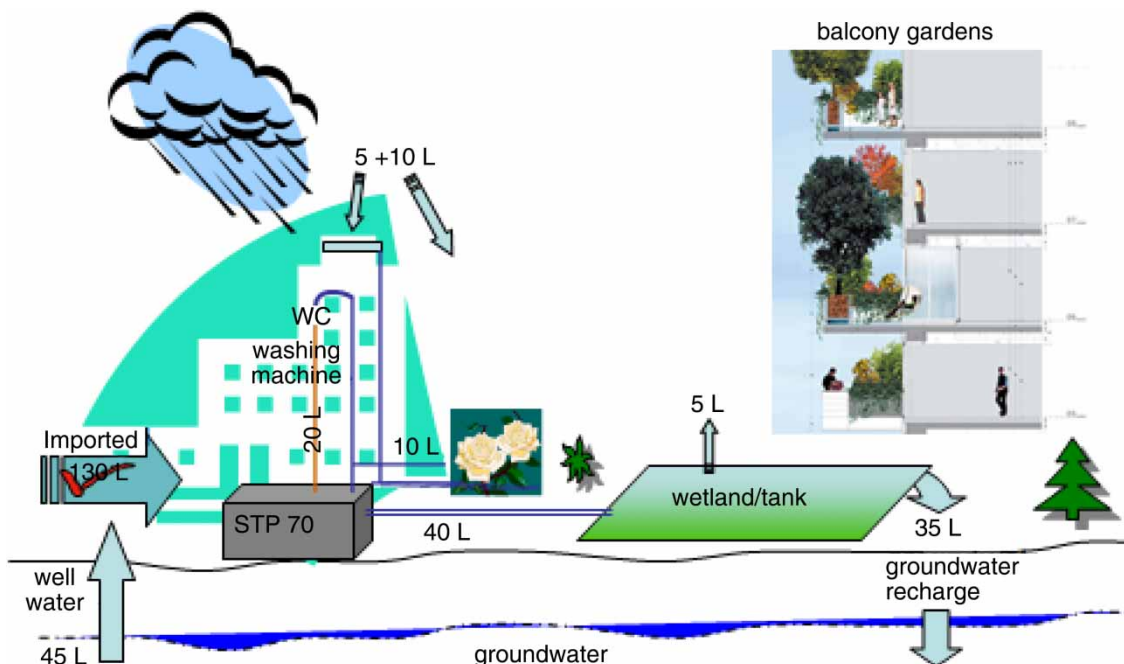


Fig. 4. Self-contained housing complex with 24/7 water supply (L = lpcd).

flush low-flush toilets, fill the washing machine, and water the garden. The remaining 40 lpcd are treated further (polished) in a vegetated horizontal-flow wetland, of which 5 lpcd evaporate or are lost through plants, and 35 lpcd are diverted to groundwater recharge wells. Rainfall over the whole compound adds some 10 lpcd to the groundwater, and 5 lpcd are collected on the roof. Therefore, 45 lpcd of groundwater can be pumped up without compromising the groundwater level.

The extracted groundwater and collected rainwater may be treated further in a modern water treatment unit, comprising a sand filter and ozonation, reverse osmosis or ultrafiltration. This provides households with all the good-quality water they need for drinking, cooking and showering, while toilets and washing machines use lower-quality recycled water (dual piping).

The system is robust and caters for the risk factors mentioned above, e.g., by diluting the wastewater with 35% of fresh rainwater. Another risk factor is that residents may use much more water than the design value of 70 lpcd, with the effect that the mini-STP becomes overloaded and delivers an effluent with some odour. Such wasteful behaviour may arise because indoor tap water is so easy to access. In many households, adults are at work the whole day, and the *de facto* water managers are children and the maid. Their incentive to save water is likely to be small. Individual water meters for each flat, which are monitored by the condominium board, allows targeting of those who waste water and the risk of wasteful use is negligible.

Nutrients in excreta flowing in separate pipes can be recovered and turned into perfect fertilisers for food production (World Health Organization (WHO), 2006). In addition, organic solid waste is collected, composted, and used as a soil conditioner. An interesting short-loop option is to build and use roofs and balconies to grow plants thriving on recovered nutrients (Stringer, 2010; Figure 4). Precedent for this invention exists in an increasing number of cities (Smit *et al.*, 1996; Spångberg *et al.*, 2014). These extremely short nutrient and water loops have the potential to recreate the link between household waste products and food production, while at the same time greening the city.

The investment for the whole mini-STP system in a housing complex of 500 flats is about 1 million USD, equal to 2,000 USD per flat. Each flat is sold for some 80–120,000 USD in Bangalore. The monthly cost to run a mini-STP unit is some 3,000 USD or 6 USD per flat per month (Akme Harmony, 2010; pers. com. Symphony Ltd in 2012). The corresponding life-cycle cost for communal water without wastewater treatment would be Rs. 240 or 5 USD per family (Deloitte, 2014). The recycling system provides safe drinking water and no effluent at a lower cost than the present erratic supply alternative, and water is available 24/7. After ten years, the life-cycle cost will be lower than paying utility water bills every month. The system can easily be modified to suit local preferences and the residents' physical and economic status. In most cases, only minor changes are required in resident water-use attitudes and routines.

8. Conclusion

The '*flexible water balance*' and proposed Integrated Water Resources Management (IWRM) measures indicate that there is no scarcity of water in Bangalore city, only lost opportunities. If scarcity occurs, it is the result of poorly developed or implemented water management at some or all levels.

The approach presented here points to the important role that users can play. They have so far been involved indirectly by being forced to dig wells, install storage tanks and treatment units in their kitchens, provide a water container in the bathroom to secure toilet flushing, and buy bottled water. They have also paid the price of living along foul-smelling drains and lakes, where children face high risk

of disease. All these activities are prompted by erratic municipal water supply and sewage. A large proportion of Bangalore's residents can become engaged in pro-active localised arrangements to conserve, treat and recycle water and nutrients as well as reducing contamination of water while using it. In short, Bangaloreans can continue to assist in reducing global risks of trespassing the planetary boundaries for water and nutrients.

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