*Asian Journal of Water, Environment and Pollution,* Vol. 7, No. 4, pp. 71-79.

# Applying Industrial Ecology Tools to Increase Understanding of Demand-side Water Management in Bangalore, India

**Matthew J. Eckelman[1,2], Megha Shenoy[2,3], Ramesh Ramaswamy[3,†] and Marian R. Chertow[2,4,*]**

[1]Program in Environmental Engineering, Yale University, 10 Hillhouse Avenue, New Haven, CT 06520 USA
[2]Center for Industrial Ecology, Yale University, 195 Prospect Street, New Haven, CT 06511 USA
[3]Resource Optimization Initiative, No. 66, 1st Floor, 1st Cross, Domlur Layout, Bangalore, 560 071 India
[4]School of Forestry and Environmental Studies, Yale University, 195 Prospect Street, New Haven, CT 06511 USA
✉ marian.chertow@yale.edu

*Received April 1, 2010; revised and accepted August 18, 2010*

**Abstract:** Water balancing is a useful and increasingly popular tool for assessing stresses and opportunities in urban water systems. A streamlined water balance was constructed for the city of Bangalore, south India, using material flow analysis (MFA) drawn from industrial ecology. An extensive survey of end-users was employed to characterize residential use of water by socioeconomic groups, using housing as a proxy. This was combined with demand and supply-side data for the commercial, industrial, and institutional sectors to create a water balance for the city that is affordable and replicable for other cities that have incomplete datasets. The relationship between water supply and energy is highlighted for Bangalore which sits at a considerable height (500 m) above its main surface water source. The municipal water utility services require approximately 5% of the entire municipal electricity demand for pumping, treating, and distributing water. Bangalore's municipal water service aims to reduce unaccounted-for water, which includes water leakage through the system as well as siphoned off water, from its current level of 26% to 15% by 2025. Such loss reductions would have a large impact both for water and energy demand for a highly populated and expanding urban landscape.

**Key words:** Water balance, material and energy flow mapping, end use survey, water leakage.

## Introduction

For many rapidly industrializing regions, the lack of clean, regular water supply is a hindrance to sustainable growth. Cities in particular are vulnerable as they concentrate on demand and often force reliance on centralized systems prone to various types of disruption. The combined factors of increasing population, urban migration, economic growth, and climate change are set to constrain water resources of many cities even further (Vörösmarty et al., 2000). Using a hydrological water balance for the city, akin to the industrial ecology tool or material flow analysis (MFA), we analyze differentiated end-use demand among segments of society, and focus attention on the relationship of water to energy in Bangalore. In describing the Bangalore water system, this work gives a quantitative picture of the extreme resource challenges of a booming population.

Industrial ecology, the study of material and energy flows through multi-scale systems, offers several useful tools for analyzing the environmental impacts of complex anthropogenic systems. Erkman and Ramaswamy (2003)

*Corresponding Author
†Deceased

make the case that perhaps the worst problem facing countries, such as India, is related to the supply, allocation, and distribution of critical resources including water, materials, and fuels. In two of the cases described in their book, they use material flow analysis to identify opportunities to recycle water back into the industrial system for the textile and leather units in Tamil Nadu (Erkman and Ramaswamy, 2003). MFA has also been used to identify important sources and pathways of pollution to assess mitigation priorities for the Thachin river basin, Thailand (Schaffner et al., 2005). Mathematical models have been used to understand climatic variables and land use effects on the hydrological cycle (Javed et al., 2009) and groundwater budgets (Anuraga et al., 2006) in south India. Other methods for sustainable management of water such as, water accounting (a water balance with indicators on productivity of water resources) and water auditing (analyses to reduce water consumption by monitoring critical water resources) have been applied to watersheds in India (Batchelor et al., 2003) and agricultural landscapes in Sri Lanka (Molden and Sakthivadivel, 1999). Most of these studies in developing regions either streamline their analyses or collect new primary data to overcome problems of incomplete datasets from government or research sources.

In this study we use a streamlined water balance tool that tries to achieve what a complete water balance does but with less personnel and financial support. A complete water balance covers all water that is extracted for use up to the point of release back into the environment, and accounts for all losses in between. An important aspect of our streamlined water balance is its attention to demand-side information. End-user data are essential for (i) forecasting future demand, and (ii) understanding how diverse socioeconomic groups source and use water.

## The Water System of Bangalore, India

Over the past three decades, Bangalore (now Bengaluru) has been one of the fastest growing cities in South Asia. Its boom in the information technology (IT) sector and the resulting economic growth have led to an increase in population from 5.6 million in 2001 to above seven million in 2007 (Government of India, 2006a; Sudhira et al., 2007). During this period the city has also attracted millions of migrant workers. This dramatic growth in population has increased the burden on bodies that provide basic amenities. The municipal boundary of greater Bangalore encompasses approximately 740 sq km and is under the authority of the Bruhath Bengaluru Mahanagara Palike (BBMP, equivalent to the City Municipality). In 1964 the Bangalore Water Supply and Sewerage Board (BWSSB) was constituted by the Government of Karnataka to supply water and provide wastewater treatment for the city. This water supply system is primarily dependent on surface water sources rather than on ground water. Man-made reservoirs were historically the primary sources of drinking water and are still used to supplement household consumption (Figure 1). Currently, the city's main water source is the Cauvery River, from which it pumps in three separate schemes from up to 95 km away (Figure 2). The BWSSB launched the fourth pumping scheme in May 2008, aiming to bring an additional 500 million litres a day (MLD) to the city (*The Hindu*, 2009). The Cauvery originates in the Western Ghats and supplies water to people in the southern states of Karnataka, Tamil Nadu, Pondicherry and Kerala. Demand for water from the Cauvery is also the source of a long standing dispute between Karnataka and Tamil Nadu (Radhakrishnan, 2002). A lesser amount of surface water is also delivered to Bangalore through two pumping systems from the Arkavathi River (Figure 2). As Bangalore is located at a significantly higher elevation than these rivers, the pumping of water consumes a significant amount of electricity.

In addition to surface water sources an estimated 1,25,000 private bore wells exist within the city boundaries (Suresh, 2001). The use of groundwater has been largely unregulated resulting in the rapid decrease in the water table; a government report estimates an average 5.4 m drop in groundwater levels in Bangalore from 1978-1996 (Government of Karnataka, 2003). The Central Ground Water Board of the national government has estimated groundwater supplies by state and notes districts under particular stress (Government of India, 2006b); however, detailed stock accounting for groundwater supplies is often omitted in water accounts (United Nations Statistics Division, 2007). Not only the quantity but the quality of ground water in and around the city is quickly deteriorating due to seepage of effluent (Reddy, 2003, AusAID, 2002). Water effluent from the city is treated in three wastewater treatment plants, following the natural valleys that comprise the city. The combined capacity of these plants in 2000 was 450 MLD, well below the estimated discharge of 700 MLD. This mismatch leads to overflow, discharge of untreated water, and contamination of ground water (Sudhira et al., 2007).

Efforts that aim to sustainably manage water in Bangalore through thorough research are scarce. In May 2000, the foreign assistance branch of the Australian

**Figure 1: Sankey Tank, one of the man-made reservoirs in Bangalore (Photo: M. Shenoy).**

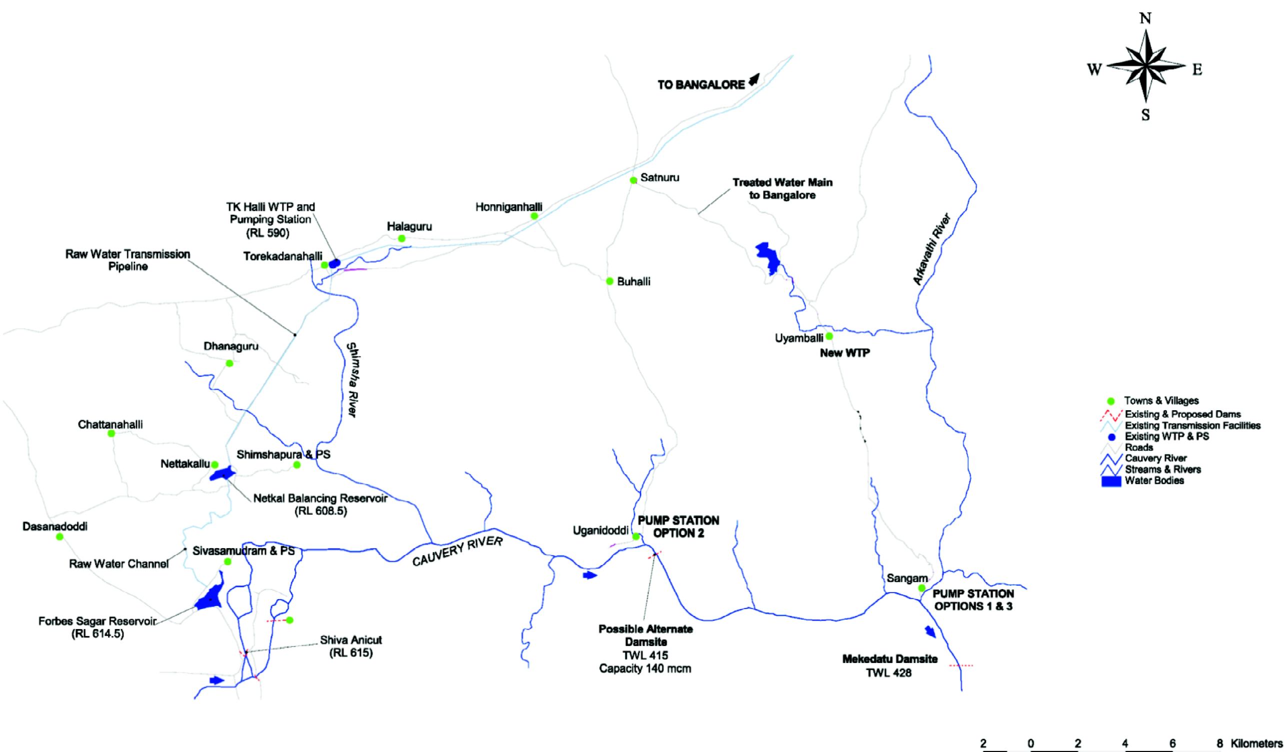


**Figure 2: Water resources map of Greater Bangalore (AusAID, 2002).**

government, AusAID, began the Bangalore Water Supply and Environmental Sanitation Project, in cooperation with the BWSSB (Table 1, AusAID, 2002). This project assessed the state of water and sewerage networks in the city and created a master plan to guide development over the following 25 years, at a cost of approximately AUS$8 million (Rs. 20 crores in 2002). Demand-side information from this survey is largely aggregated, making it difficult to differentiate among industrial users or among socio-economic groups within the residential sector. More recently, a study on the relationship between awareness of water issues and water conservation practices by the Biodiversity Conservation India Limited (BCIL), a local organization, covered approximately 400 permanent middle- to upper-class residents and primarily focussed on the relationship between awareness of water issues and actual water use practices. This survey found that only 15% of respondents engaged in individual water conservation efforts. BCIL also collected some quantitative information on residential demand; the most significant use of household water was in washing clothes. The goal of our survey is to construct a comprehensive demand-side balance of water use for the city and to illustrate how a streamlined approach can reveal valuable information about patterns of water usage among groups of city residents.

**Table 1: Water usage for the Bangalore Municipal Corporation, 2000 and 2005 (AusAID, 2002)**

| *Category* | *2000 estimate (MLD)* | *%* | *2005 projection (MLD)* | *%* |
|---|---|---|---|---|
| BWSSB metered | 655 | 60 | 1000 | 65 |
| Domestic consumption | 246 [a] | 23 | 433 [a] | 28 |
| Industrial, non-domestic | 62 | 6 | 73 | 5 |
| Fountains | 63 | 6 | 57 | 4 |
| Unaccounted for water | 286 | 26 | 437 | 28 |
| Groundwater | 430 | 40 | 533 | 35 |
| Domestic consumption | 294 | 27 | 311 | 20 |
| Industrial, non-domestic | 136 [b] | 13 | 222 [b] | 15 |
| **Total** | **1085** | **100** | **1533** | **100** |

[a] Includes rainwater harvesting
[b] Includes effluent reuse and tanker water

## Methods

This streamlined water end-use balance was performed in Bangalore by means of an end-user survey that documented consumption patterns of different socioeconomic groups; 2005 was used as the base year. The survey covered 1424 users from households, hotels and laundries (Table 2). This extensive sampling allows for sophisticated demand analysis based on affluence, housing stock, personal vehicle penetration, and other factors. Statistics from this analysis were checked against those from BWSSB (from metering data) and AusAID (2002). As there is no metering of groundwater withdrawals, this was calculated as the difference between metered readings of water supplied from BWSSB and the calculated demand. Information gathered from various user groups is given below.

### Households

A cross-sectional survey of household water use that covered urban, suburban, and slum areas of the city was carried out by researchers from ROI. Respondents were categorized by housing type, covering stand-alone residences, apartments, semi-formal housing (small dwellings with asbestos/tile roofing), and slums. For each respondent, data on (i) major sources of water, (ii) storage facilities, (iii) provisioning (piped, bore-well, trucked water), (iv) distance to source and frequency of visits, (v) total amount used per day for various activities, (vi) number of family members, and (vii) monthly billing amount (if applicable) were collected. In the case of gardening and vehicle-related water, usage was averaged over the entire survey population. Per-household water usage information was extrapolated to the total population of households in Bangalore as given by the 2001 Census (Government of India, 2006a).

### Commercial Establishments

Water usage in the commercial sector was evaluated by business type. Hotels and laundries were evaluated through direct surveys. Hotel usage statistics for drinking, cooking, washing, and cleaning were collected; for laundries, only washing and cleaning were assessed. Hotels (which also serve food) and lodges (which do not) were categorized according to size and level of luxury, to account for different patterns of water use. In 2006, there were an estimated 378 hotels in the central city, so our survey ($n$=341) was nearly comprehensive. Individual water use at each type of hotel was multiplied by the number of visitors from tourism statistics (AC Nielsen, 2006). For restaurants, the 2001 Census was used to partition the population of Bangalore into broad demographic groups: children/teenagers, working adults, and elderly/unemployed. Based on informal surveys, the following assumptions were made: (i) each meal requires four litres of water for preparation and direct consumption, (ii) children/teenagers eat out two times per week, working adults five times, and elderly/unemployed

**Table 2: Daily water balance for the city of Bangalore, 2000**

| | *Data source* | *Flow (MLD)* | *%* |
|---|---|---|---|
| *Supply* | | *1129* | |
| Surface water (Cauvery, Arkavathi Rivers) | | 655 | 58 |
| Groundwater (Private bore wells) | | 474 | 42 |
| Rainwater | | 1 | 0 |
| (Electricity Usage) | | (987 MWh) | |
| *Demand* | | *1129* | |
| Individual households | Survey (*n*=1077) | 553 | 48 |
| Drinking, cooking | | 54 | 5 |
| Bathing, washing, sanitation | | 471 | 42 |
| Gardening | | 12 | 1 |
| Vehicles | | 5 | 0 |
| Commercial establishments | | 43 | 4 |
| Hotels, lodgings | Survey (*n*=341), tourism data | 3 | 0 |
| Restaurants | Secondary data | 4 | 0 |
| Offices | Secondary data | 35 | 4 |
| Laundry | Survey (*n*=6) | 1 | 0 |
| Industrial users | Interviews, permit data | 122 | 11 |
| Manufacturing | | 107 | 9 |
| Construction | | 6 | 1 |
| Food/Beverage Processing | | 1 | 0 |
| Railroads | | 8 | 1 |
| Institutional users | AusAID report, BWSSB | 60 | 5 |
| Grounds (municipal and industry) | Survey and BWSSB | 21 | 2 |
| Fountains | BWSSB | 55 | 5 |
| Leakage | Mass balance | 286 | 25 |

once per month. The total number of people working in office-based professions was assessed using the 2001 Census. It was assumed that each person drinks approximately one litre of water during the workday either as water or incorporated into tea/coffee. Half of office workers are assumed to have access to flush toilets that require eight litres per use; the remaining are assumed to have access to squat toilets that require one litre per use.

### Industrial Users

Metered water consumption of the manufacturing sector in Bangalore was assessed from permit records at the Karnataka State Pollution Control Board (KSPCB) and BWSSB (2005), while groundwater consumption was assessed from AusAID (2002). Large food and beverage companies in the city (including bottling plants) were approached directly for information on water incorporated into final products and that required for operation.

### Institutions

Institutions in Bangalore such as the Indian Institute of Science rely on the BWSSB for approximately 75% of their water supply; the remainder comes from bore wells and water tankers (AusAID, 2002). This ratio was used along with metering information from the BWSSB to determine water usage by institutions.

### Railroads

The state railroad companies in Bangalore have traditionally been large landowners within the city, though this has changed somewhat in recent years due to sales of parcels to the city and to private property owners, as well as to encroachment by the urban poor. The railroads use significant quantities of water for cleaning and maintenance of freight and passenger cars. Such usage statistics were collected from the BWSSB (2005).

### Grounds and Fountains

Bangalore is known as "The Garden City" and has several large gardens and parks, such as Lal Bagh and Cubbon Park, as well as several golf courses and sports stadiums. All of these require extensive watering. In addition, both the old industries (aeronautics, machine tools) and the new (electronics, IT services) tend to operate on large estates that are generally well-manicured and represent another major end-use for municipal water.

Watering requirements for gardens and industrial estates in the city were assessed from garden workers to be an average of 5L/m$^2$ (Lal Bagh: 2.8 L/m$^2$, Cubbon Park: 10 L/m$^2$, and Indira Gandhi Musical Fountain: 3 L/m$^2$). This statistic was used to estimate water usage for public parks, gardens and public land on industrial estates. In addition there are hundreds of municipal fountains scattered throughout the city that operate off the public water supply and which sometimes serve as informal collection points for residents. Water usage for fountains in the city was obtained from the BWSSB (2005).

**Leakage**

The amount of leakage or Unaccounted for Water (UFW) in any complex water supply system is difficult to measure. It was established from the mass balance of supply and reported/metered consumption.

## Results and Discussion

Our water balance for Bangalore shows that the residential sector accounts for more than half of total consumption. These results are comparable to the AusAID projections for 2000 with respect to (i) relative structure of demand for every sector, (ii) total water demand (piped water and ground water) (Tables 1 and 2). The primary difference between our survey and the AusAID one is in the quantification of water use based on housing type and socioeconomic group, as well as by specific end uses. Many municipalities in developing regions would not be able to afford comprehensive master planning for their water systems, but could benefit from the kind of end-use specific information generated by this streamlined, mass balance approach.

Understanding domestic usage profiles of various socio-economic groups is important in predicting future demand. These profiles are elaborated by using housing size as a proxy (Table 3a, b, c). Our survey shows that the availability of piped water roughly increases with the size of the home: 35% of slum housing had no access to piped water in their premises; this value is more than double the number for independent homes. Therefore, a drop in the ground water levels will disproportionally affect poorer segments of the population who cannot afford to dig deeper wells or upgrade pumps. Such socio-economic profiling adds a valuable layer of information to that from the 2001 census which finds that nearly 34% of the households in Bangalore did not have any water source in their premises (Government of India, 2006a). In our survey we find that more than half of all households relied solely on piped water, while 19% supplemented piped water with bore wells.

Across all household types, most of the household water use (80-90%) is for bathing, washing, cleaning, and sanitation (Table 3b). As expected, large houses use more water for these purposes than apartments or semi-formal dwellings or slums because of larger surface areas to be cleaned, modern sanitation facilities, and the general ability to pay for high levels of use. However, all housing types report using roughly equivalent amounts of water for their drinking and cooking needs. This is due to the fact that household size stays between 4 and 5 persons per household (Table 3c, Figure 3). Per household use and household size data were used to assess per capita demand for water (Table 3c) which was found to be below the Central Public Health Environmental Organisation national standard of 150 litres per capita per day (Lpcd) (CPHEEO, 2005), except for largest homes, but above the minimum basic human water requirement of 50 Lpcd suggested by Gleick (1996). Average per capita water use is bound to increase with the rising prosperity in the city and is estimated to be between 5.1% and 6.3% per annum (AusAID, 2002). As an illustration, if average consumption were to increase to 125 Lpcd, the total consumption of the households would increase by 291 MLD to 927 MLD, or nearly all of year 2000's total surface water withdrawals. The consumption of the city as a whole would increase to 1307 MLD.

While increasing water use to internationally recommended levels should be encouraged for purposes of improving hygiene and health, it will be difficult for the BWSSB to meet such a demand amidst a rising population, along with a currently unmanaged system of

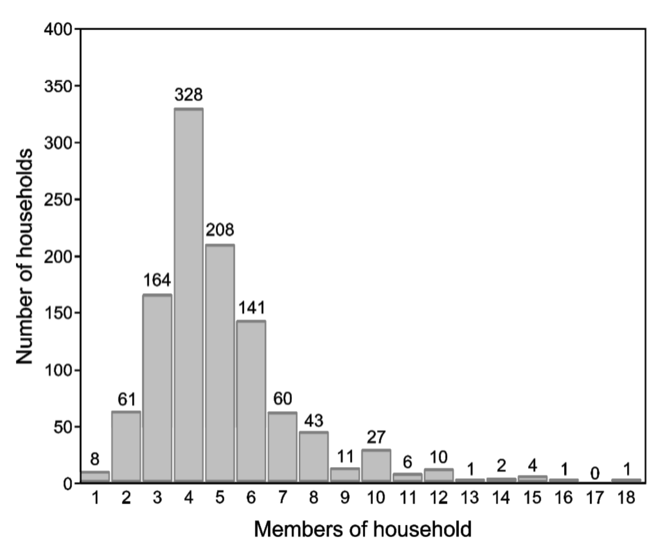


**Figure 3: Histogram of household size (*n*=1077).**

**Table 3a: Summary of water sources for various household types**

| *Household type* | *n* | *Piped (1) (MLD)* | *%* | *Bore well (2) (MLD)* | *%* | *Off-site (3) (MLD)* | *%* | *(1 & 2) (MLD)* | *%* | *(2 & 3) (MLD)* | *%* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| > 64′ × 40′ plot | 6 | 5 | 83 | 1 | 17 | – | 0 | – | 0 | – | 0 |
| 64′ × 40′ plot | 145 | 66 | 46 | 30 | 21 | 1 | 1 | 45 | 31 | 2 | 1 |
| 30′ × 40′ plot | 250 | 146 | 58 | 52 | 21 | 3 | 1 | 47 | 19 | 2 | 1 |
| < 30′ × 40′ plot | 221 | 126 | 57 | 48 | 22 | 1 | 0 | 43 | 19 | 2 | 1 |
| Apt > 1000 $ft^2$ | 44 | 7 | 16 | 13 | 30 | – | 0 | 22 | 50 | – | 0 |
| Apt < 1000 $ft^2$ | 20 | 11 | 55 | 6 | 30 | – | 0 | 3 | 15 | 2 | 1 |
| Semi-formal | 171 | 106 | 62 | 46 | 27 | 1 | 1 | 18 | 11 | – | 0 |
| Slum | 220 | 107 | 49 | 76 | 35 | – | 0 | 26 | 12 | 11 | 5 |
| **Total[a]** | **1077** | **570** | **53** | **272** | **25** | **6** | **1** | **204** | **19** | **19** | **2** |

[a] Weighted averages

**Table 3b: Summary of water use for various household types (average litres/day)**

| *Household type* | *n* | *Drinking, Cooking* | *Washing Cleaning* | *Gardening* | *Vehicles* | *Total* |
|---|---|---|---|---|---|---|
| > 64′ × 40′ plot | 6 | 40 | 775 | 10 | 14 | 839 |
| 64′ × 40′ plot | 145 | 46 | 439 | 42 | 14 | 541 |
| 30′ × 40′ plot | 250 | 45 | 381 | 14 | 1 | 442 |
| < 30′ × 40′ plot | 221 | 40 | 294 | 8 | 1 | 343 |
| Apt > 1000 $ft^2$ | 44 | 35 | 280 | 2 | 0 | 318 |
| Apt < 1000 $ft^2$ | 20 | 37 | 217 | 1 | 0 | 255 |
| Semi-formal | 171 | 36 | 219 | 1 | 0 | 256 |
| Slum | 220 | 37 | 220 | 0 | 0 | 257 |

**Table 3c: Average household sizes and per capita water use (average litres/day)**

| *Household type* | *n* | *Survey population* | *Persons per household* | *Per capita water use* |
|---|---|---|---|---|
| > 64′ × 40′ plot | 6 | 28 | 4.7 | 179 |
| 64′ × 40′ plot | 145 | 776 | 5.4 | 100 |
| 30′ × 40′ plot | 250 | 1289 | 5.2 | 85 |
| < 30′ × 40′ plot | 221 | 1041 | 4.7 | 73 |
| Apt > 1000 $ft^2$ | 44 | 196 | 4.5 | 71 |
| Apt < 1000 $ft^2$ | 20 | 82 | 4.1 | 62 |
| Semi-formal | 171 | 800 | 4.7 | 55 |
| Slum | 220 | 1092 | 5.0 | 51 |
| **Total/Average** | **1077** | **5304** | **4.7** | **85** |

groundwater extraction and high rates of leakage. Our water balance indicates that 286 million litres (26%) of UFW is lost every day primarily due to corroded and broken mains and illegal tapping of the water supply in 2005. The Bangalore Water Supply Master Plan also found this to be around 26% in 2000 and set an ambitious target to reduce this value to 15% by 2025 (AusAID, 2002). However, our results indicate no change in the percentage of UFW from 2000 to 2005. Taking future growth into account, assuming a moderate growth in demand to 1850 MLD of formal piped water, this reduction in leakage would save 530 MLD, nearly equivalent to the current residential demand. Bangalore's UFW is the fourth highest of 14 utilities in large cities across India (ADB, 2007). In addition embedded energy that is used to pump and treat water is also completely wasted with UFW.

Bangalore's water services are heavily reliant on a stable electricity supply; energy costs make up more than 60% of BWSSB's operating budget (AusAID, 2002). This is primarily because the city is at a relative elevation of 500 m and around 100 km away from its main surface water source. The total annual electrical energy consumed for pumping this water is almost 360 GWh, which constitutes nearly 5% of the total electricity consumption of the city (BESCOM, 2009). The amount of embedded energy lost due to UFW is estimated at 147 GWh. Approximately 75% of the total electricity expenditure by the BWSSB is to bring Cauvery River water to the city, 10% is for transmission of water from the Arkavathi, 10% for distribution in the trunk main system, and 5% is for sewerage (AusAID, 2002). In addition, mismatch between supplied voltage and that required for optimal operation of pump sets causes efficiency losses, short-circuiting and pump failure. This tight link between water supply and electricity clearly shows that any expansion to the water supply should be planned in concert with the electricity bodies of the state. Electricity savings from reducing UFW to 15% in 2025 would also be passed on to the electricity grid, to the tune of nearly 799 MWh per day.

Apart from reducing UFW there are alternative avenues for sustainable management of water. Effluent recycling on industrial estates currently accounts for 3-4 MLD (0.3%) of supply but is aimed to increase to 200 MLD by 2025 (AusAID, 2002). Rainwater harvesting (RWH) is being pursued by the BWSSB; upto 1700 MLD of water could be harvested from rains in the city (Sudhira et al., 2007). This is more than the projected total demand for Bangalore in 2005 (Table 1).

## Conclusion

Accurate information about the end-use demands for water is crucial in any municipality's water planning process. Such information is particularly hard to gather and verify for people living off un-regulated or unmetered connections. The data presented here represents a comprehensive view of Bangalore's water balance. This investigation leads to opportunities that refine and extend the analysis to construct scenarios to predict future use.

## Acknowledgements

The authors thank K. Muthupandi, Latha Dhujji, Marcos Sanjuan and researchers of ROI who collected and analyzed demand-side water data; M.D.N. Simha and the KSPCB; M.N. Thippeswamy and the BWSSB for additional data; and S. Viswanath of the India Water Portal. We thank Prof. Suren Erkman of Lausanne University for his early role in getting this study imagined and underway, and also Maggie Montgomery and Weslynne Ashton of Yale for helpful comments and suggestions. This work was supported in part by the Charles Leopold Foundation and the Program on Industrial Ecology in Developing Countries at Yale University.

We dedicate this to Ramesh Ramaswamy, a dedicated researcher, friend, and industrial ecology pioneer in India.

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