Urban Metabolism of Bangalore City: A Water Mass Balance Analysis

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Abstract

Cities are increasingly depending on energy intensive water sources such as distant rivers and the ocean to meet their water demand. However, such expensive sources could be avoided using alternative local sources of water such as wastewater, rainwater and stormwater. Many cities do not have robust accounts of those localized water resources, as estimating those resources requires comprehensive accounting in complex urban water systems. In this article, we investigated whether an urban metabolism framework built on the Urban Water Mass Balance can help analyze these resources, especially in a rapidly growing developing city. We first refined the water mass balance equation developed by Kenway et al. (2011) for a developing country context with the inclusion of some significant components such as system loss. Then we applied it to Bangalore city for the year 2013-2014 which is a rare mass balance analysis in a developing country. The refined equation helped analyze Bangalore urban water system. The total available wastewater, stormwater and rainwater were 656 gigaliters. The gap between water demand and supply could be met if 54% of this recycled potential were harnessed. Wastewater had enough potential (362 gigaliters) to replace the whole centralized water supply from the river Cauvery. A scenario analysis showed that the gap between water demand and supply in 2021 can be met if 60% of total recycled potential is utilized. This approach can be used to other cities to identify the potential of alternative water sources and help integrated water planning and monitoring water metabolic performances.

Keywords: urban water accounting, system boundary, alternative water resources, water reuse. urban water planning, water performance indicator

Introduction

The growing population, urbanization and global climate change will increase demand for water, energy and other resources. By 2050, about two third of the world's population will be living in cities and urban areas (UN 2014). In 2014, 54% of the world's population was already living in urban areas (UN 2014). Fast growing cities will be facing serious problems to meet basic services needed for their people in terms of limited world resources such as water, energy and nutrients. Further, the current practice of linear (without resource reuse/supply driven approach) management of resources is pushing cities to depend on their hinterlands to cope with growing pressures of resource supplies, which in many cases requires substantial energy (Bai 2007; Kenway et al. 2011; Kennedy et al. 2011; Agudelo-Vera et al. 2012).

Water is a major resource in an urban system which requires dedicated management attention. In 1965, Abel Wolman pioneered the use of Urban Metabolism as an evaluation framework to analyse a hypothetical American city (New York) with one million population. Wolman developed this concept to address the water and air quality of American cities (Wolman 1965). His study included only the inputs of centralized flows of water managed by urban infrastructure and estimated that the input of water was 625000 tons/day for one million people in the United States of America compared to just 9500 tons and 2000 tons of fuel and wood respectively (Wolman 1965). Most of this inflow is discharged as wastewater with the remainder being lost by various human activities. His study showed that wastewater (outflow) represents between 75% and 100% of supplied water (inflow). This was further stressed by Larsen et al. (2016) in her review article on 'Emerging Solutions to the water challenges of an

Urbanized World'. The huge percentage of this wastewater can be tapped to meet urban water demand to avoid importing of remote water resources which involves substantial energy. Again system loss from a centralized urban water system is very significant in many developing cities from 30-50% example for Bangalore city (CSE 2011; Raj et al. 2013; Mehta et al. 2014; Kingdom et al. 2012) This water loss has also high potential to reduce water demand in supply main.

Few cities globally have a comprehensive accounting of their urban water resources. Systematic quantification requires good data and a thorough understanding of resources available (NWC 2005; Kenway et al. 2011; Renouf et al. 2016). An urban metabolism framework provides a broader picture of resources flow as well as quantitative analysis of all inputs and outputs, stock of water, energy, waste, nutrients and other materials (Wolman 1965, Kennedy et al. 2010; Kenway et al. 2011). This can be used as a conceptual and analytical framework (Kenway at al. 2011, Renouf and Kenway 2016; Farooqui et al. 2016).

There are many approaches and methods for analyzing resources flow in urban water systems such as 'Life Cycle Assessment (LCA)', 'Environmental Footprints' and 'Integrated Water Cycle Modelling'. LCA quantifies the resource use embodied in goods and services in an urban system (such as water and energy foot prints), 'Environmental Footprints' originates in LCA, and the Inputs-Outputs analysis is a top-down method to quantify resources flows through an entire urban entity or economy (both direct and indirect flows). Integrated Water Cycle Modelling considers a water system within an urban entity such as a precinct but not the entire urban entity or whole economy (Bach et al. 2014).

Urban metabolism can be used at different scales from global to city and household levels (Agudelo-Vera et al. 2012) and can generate inventories of resources flow (water, energy, nutrients/pollutants, carbon and other materials) over time with trends of resource utilization (Kennedy et al. 2007). Such accounting also helps to compare from city to city (Kennedy et al. 2015).

Since Wolman (1965), several studies have been undertaken on Urban Metabolism, however few focused on water (Kenway et al. 2011; Hermanowicz and Asano 1999; Baker et al. 2001; Thériault and Laroche 2009; Kenway et al. 2011). Kenway et al. (2011) developed a comprehensive Water Mass Balance Framework for a better understanding of water and related energy and material flows in cities, however system losses were not incorporated and can be a significant component of an urban water mass balance in a developing city. There are also other flows in a developing city such as water supplied by various water retailers (Raj 2013) which are important. Moreover, urban water mass balance analysis has been done so far in a limited number of cities as real case studies (Kenway et al. 2011; Farooqui et al. 2016).

Consequently, in this study, we refine the original water mass balance developed by Kenway et al. (2011) in a developing country context. We apply this to Bangalore, a fast growing city as a real case study example.

Literature Review

Studies on Urban Metabolism focusing on water after Wolman were done in the cities of Hong Kong, Toronto, Tokyo, Vienna, Brussels, London, Cape Town, Sydney as well as other Australian cities (Duvignead and Denaeyer-De Smet 1997; Hendriks et al. 2003; Gasson 2002; Chrysoulakis et al. 2015; Chartered Institute of Waste Management 2002; Sahely 2003; Gandy 2004; Kennedy et al. 2007, Decker et al. 2000; Browne et al. 2011; Kenway et al. 2011; Holmes and Pincetl 2012; Renouf and Kenway 2016). Kennedy et al. (2010) did an extensive literature review on Urban Metabolism which included more than 50 papers on cities from eight global regions. His study showed that most Urban Metabolism studies had focused on the quantification of flows of energy, wastes, nutrients, materials, food, greenhouse gas emissions (GHG), food and eco-foot prints (Bhole 1994; Zucehetto 1995; Hanya and Ambe 1976; Nilson 1995; Huang 1998; Warren-Rhodes and Koenig 2001; Barrett et al. 2002; Baker et al. 2001; Gasson 2002; Zhang et al. 2009; Forkes 2007; Barles 2009;). Only three papers in his study focused on water (Hermanowicz and Asano 1999; Baker et al. 2009; Gandy 2009). Some studies in his literature review were related to livability (Newman et al. 1999) and eco-efficiency (Zhang and Yang 2007) and others were on comprehensive metabolism study (Newcombe et al. 1978 and Stimson et al. 1999). The per capita water use and wastewater flow of some cities as reported in Kennedy et al. (2007) (figure 1) illustrates that urban metabolism of cities (example for Sydney, Hong Kong from available data) are increasing over time. In the case of Toronto, the per capita water use declined over 1990s from 1970s which was due to reduction in industrial water consumption (Kennedy et al. 2007).

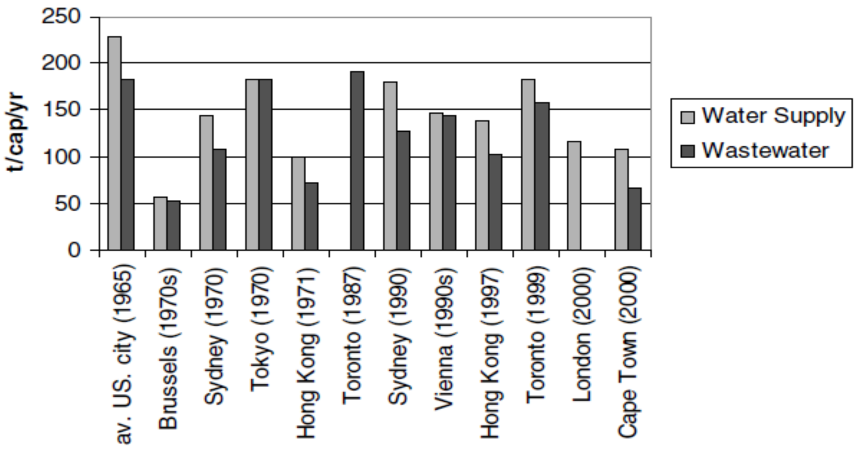

Figure 1: Inputs and Outputs of water flows in selected cities (Kennedy et al. 2007)

Note: t/cap/yr. = tons/capita/year. One ton (t)=10^3 kilograms (weight of 1 kiloliter water). So t/cap/yr. can be represented in volume as kL/cap/yr.

A comprehensive Water Mass Balance considering all components of an urban water cycle (rainwater, imported supply, decentralized water, wastewater, stormwater, evapotranspiration, groundwater recharge and water reuse) rather counting just inputs and outputs as a whole (figure 1) is of utmost importance for better understanding of urban water metabolism of cities who are particularly facing increased water scarcities so as to find alternative local water sources and identify their recycling water potentials. But in past studies, Urban Metabolism mostly followed the method of Material Flow Analysis (MFA). A MFA provides the overall mass fluxes of resources (energy, materials, nutrients, carbon, food and pollutants.), helps to understand the use of resources and their trends over time, and assists environmental reporting (Kennedy et al. 2007; Kenway et al. 2011; Renouf and Kenway et al. 2016). But when it comes to water, MFA cannot integrate individual flows such as decentralized water supplies, or hydrological flows such as rainwater, groundwater infiltration, surface runoff, and evapotranspiration so cannot provide information for the improved and holistic management of water resources. This was first understood by Kenway et al. (2011), who developed a comprehensive Urban Water Mass Balance Framework for a better understanding of water and related energy and material flows in a city.

Kenway et al (2011) explained the critical importance of a clear system boundary to define the volume flowing across the boundary and volume stored within the boundary, as shown in figure 2a (Kenway et al. 2011). If B is a defined system boundary and A is the boundary area with a depth d, water mass balance based on principles of mass conservation is inputs (Qi) minus outputs (Qo) and the changed is stored water ΔS.

$\Delta S = (S_{t1}-S_{t2}) = Qi(t_1-t_2) - Qo(t_1-t_2)$……………………(1)

Where ΔS is the change is the volume (or mass) of stored water within the boundary over a time period t_1-t_2 and also ΔS is equal to the difference in the total volume of inputs Qi and outputs Qo from boundary B $[Qi(t_1-t_2) - Qo(t_1-t_{20}]$ over the same time period.

For a particular system, if time interval and system boundary have been defined and all units are expressed as volumes or masses flowing through per unit time, equation (1) can be simplied as follows:

$\Delta S = Qi - Qo$ ………………….(2)

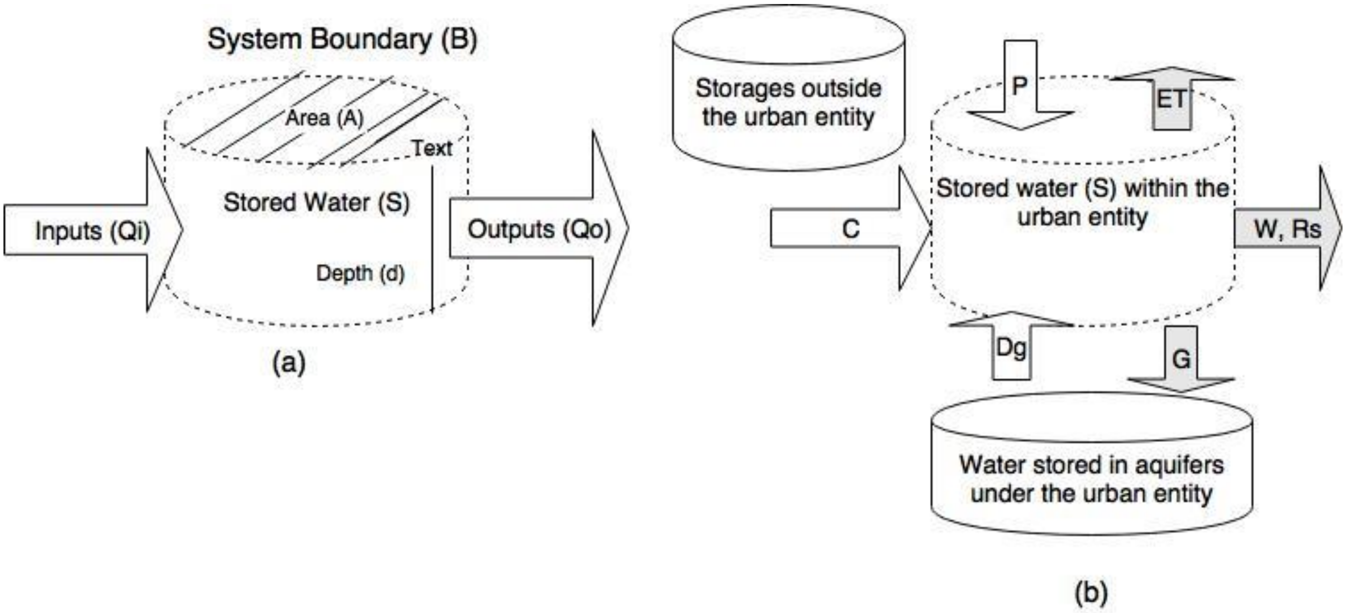

Figure 2: a) Defining System Boundary and b) Water Mass Balance Framework considering groundwater under the urban entity and storages outside the urban entity (adapted from Kenway et al. 2011)

In Figure 2b,

P - Precipitation or rainfall

ET- Evapotranspiration

C - Centralized water supply

S - Water stored by different subsystems

W – Wastewater

Rs- Stormwater runoff G - Groundwater

Dr - Decentralized water from rainwater

Dg- Decentralized water from groundwater

Rs - Surface runoff

Following equation 2, $\Delta S = Qi-Qo$

From figure 2b, $S = (P+C+Dr+Dg) - (W+Rs+G+ET)$

S can be further defined as $S = \sum Q_i$ (sum of all inflows) - $\sum Q_o$ (sum of all outflows)

Kenway et al. (2011) used this comprehensive urban water mass balance framework for real case studies in Australian cities (Melbourne, Sydney, Brisbane, Gold Coast and Perth) to assess the potential of alternative water supply options to augment centralized inputs and reduce outputs**.** The framework included alternative sources of water such as rainwater (precipitation), surface runoff, wastewater, and decentralized water supply from rainwater, groundwater, and vapor-transpiration and groundwater infiltration.

This framework was further refined recently by Farooqui et al. (2016) by incorporating other flows such as decentralized recycled water within and outside an urban system. Renouf and Kenway et al. (2016) found that the framework still has scope to develop further by incorporating other water flows such as water use for ecosystem services.

Every city has its unique characteristics in respect to its water management and geographical location. Urban Water Metabolism Evaluation Frameworks may differ based on a city's typology (system boundary, types of water supplies/inputs components, uses, reuses, losses/leakages, scales, time and other factors). From the literature review, it was further found that different studies in the past followed different scales, approaches and perspectives of Urban Water Metabolism (Kenway et al. 2011 and Farooqui et al. 2016). However, the latest Water Mass Balance Evaluation Framework still does not include other components such as an account of water loss (system loss/leakages), which is a major flow component from centralized water supply in many urban water systems in the Asian region (around 30-50%) and also other parts of the world (CSE 2011; Kingdom et al. 2012; Raj 2013; Mehta et al. 2014) This flow has significant impact on hydrological cycle. One major example is the study done by Mehta et al. (2014). He used Lump Model under a social-ecological framework, considering the loss of water from city pipelines and city return flows with a number of assumptions because of the unavailability of data to measure the groundwater recharge and variation in groundwater table. His study found that the ground water table in Bangalore has increased in the core city area, where the city's water supply is there, but not in the periphery of the city where people experience greater water shortage problems (Mehta et al. 2014). Kenway et al. (2011) also strongly recommended in their report the incorporation of such components within a defined system boundary to get better mass balance results. Among other water flows in an urban system, in developing countries especially in Asia, there are many water retailers or water tankers who use surface water or ground water and treat that water to supply to the city people. Such flow component also needs to be included to an evaluation framework for better informed water management as such services are increasing when the utilities are failing to provide adequate water supply to the people. In the refined framework under this study all these additional water flows in an urban system have been incorporated.

Further Kenway et al. (2011) identified that a system boundary is very important so as to incorporate all water inputs and outputs within that system. Prior to Kenway et al. (2007), Water Balance of an urban catchment was described by Mitchell et al. (2003) and Sahely et al. (2003). They made efforts to include key inputs and outputs, but they excluded many components in absence of a system boundary in their analysis. Again, Mitchell et al. (2003)

used a water balance equation to know the hydrological performance of a catchment but not the performance of an urban entity. Sahely et al. (2003) however, used it for cities; no system boundary was followed except for the ‘greater Toronto’ area and they used wastewater and storm water as a joint output, with other flows not clearly incorporated. In 1991, Baccini and Brunner developed Materials Flow Analysis (MFA) which was able to quantify the stocks and flows of resources in terms of mass but it also did not consider a system boundary which helps in accounting all flows. In this study a system boundary was selected to incorporate all inputs and outputs in Bangalore city.

Kenway et al. (2011) also developed some performance indicators such as ‘overall balance of inputs and outputs’ of a city, the potential of wastewater, rainwater, stormwater, ‘system centralization’ and ‘water use replaceability’ (substitution), as elaborated in table 1, and developed methods to calculate these indicators for a city. The application of these indicators on Australian cities showed that the cities varied from 0.1-22% in rainfall harvesting, 257-397% in centralized replaceability by rainfall, 26-86% replaceability potential of wastewater recycling, 47-104% in stormwater reuses potential and 1-4% in reuse of anthropogenic inputs water in 2004-2005. These indicators illustrated that these cities are not designed appropriately to take the full potential use of these substantial flows and they are rather dependent on a centralized fresh water supply. Perth is an exception where recycled water is used to a great extent (Kenway et al. 2011). As mentioned earlier a Water Mass Balance Evaluation framework depends on various factors for a particular urban setting and considerations of various water flows in and outside of a city. The new indicators could be evolved, for example for ‘water loss recovery’ and could become important urban water performance indicators in a developing country context.

The literature review found that a Urban Metabolism Framework built on Water Mass Balance is useful to analyse complex urban water systems, but this framework has not yet been tested with real cases in developing countries, for example the Urban Water Metabolism Evaluation framework of Kenway et al. (2011) refined by Farooqui et al. (2016) was tested for a hypothetical urban development area in Australia. Therefore, it is necessary to see whether this urban water mass balance equation/framework can be applied as a real case example and in developing country context. In this study, we refine the Urban Metabolism framework built on Water Mass Balance developed by Kenway et al. (2011) in developing country context and apply it as a real case example to a rapidly growing Bangalore city in India. It was explored how the refined water mass balance equation can be used to analyse the complex urban water system in Bangalore city, to improve the accounting of all waters and help planners, engineers; water managers and policy makers monitor the city water performance and integrated management of water. Such robust accounting of all waters in a city system or comprehensive water mass balance is not only important for Bangalore city but also for other cities, especially those in arid and semi-arid regions who are facing serious challenges to meet their water demands. The study also investigated the water-energy linkages in the system which will follow separate article.

Background of Bangalore City

Bangalore (officially called Bengaluru, the capital of Karnataka State in South India) is a mega city situated inland, in the middle of a semi- arid region. It is a center for education, IT industries and business, high tech health care and many multi-national companies (MNCs) which attract people to the city along with its nice climate. The city is naturally water scarce and has no perennial source of water in the city except some seasonal lakes and waterbodies which have been polluted (CSE 2011; Lele et al. 2013; Central Ground Water Board 2011). Groundwater is also polluted by nitrates, pathogens and other contaminants (Mehta et al. 2013). As a result, the city brings water from a distant freshwater source (the Cauvery River, 100 km away and 500 meter below the city) without due consideration of the energy intensity and cost, a disregard for the conflicts over the river, and dismissal of the process' ecological footprint (Gronwall, 2008, Richter and Weiland, 2012; Novotny, 2010). The Bangalore Water Supply and Sewerage Board (BWSSB) spend 60-70% of their annual operating budget for energy to supply water services to the people (CSE 2011; IBM 2010). The Cauvery River is a long disputed water stressed river managed by the Cauvery Water Dispute Tribunal (Richter and Weiland, 2012; Gronwall, 2008; Moore et al. 2013). The Tribunal has earmarked an amount of water for Bangalore, which is 1,470 MLD or 600 Cusec (CSE 2011; Lele et al. 2013). The river is shared by four States of Southern India (Kerala, Tamil Nadu, Karnataka itself and the Union territory of Pondicherry). Tamil Nadu and Karnataka depend on water from this river (about 90%) for irrigation of 1.2 million hectares of agricultural land and to produce hydropower (Ferdin et al. 2010). There is no further scope for Bangalore to withdraw water from the Cauvery River as per the Tribunal agreement (Raj, 2013). However, Bangalore is still looking for more water abstraction from the Cauvery River to meet its shortfall (Raj 2013). It also has planned to augment the Arkavathi River (Lele et al. 2013; Raj 2013) which is about 18 km away from the city (CSE 2011) with treated wastewater from nearby V. Valley Wastewater Treatment Plant (WWTP) as the river cannot be filled due to a low aquifer recharge; but again this may involve a huge cost of energy as the project plans to install four centrifugal pumps to pump about 135 MLD of treated sewage to a ground-level reservoir (GLR) at an elevation of 980 m (Deccan Herald 2013; Raj, 2013).

The residents of Bangalore also face a power crisis, and the city is dependent on the State (Karnataka) to supply energy from the Bangalore Electricity Supply Company (BESCOM). On May 6, 2014, the Energy Minister announced that the current daily power cuts would vary from two to six hours across the state. In Bangalore core area it was two hours daily, with northern Bangalore influenced the most with more than six hours without power daily. This was due to the drop in power generation by the State from 8522 megawatts (MW) to 7572 MW due to a shortfall of power generation by 600 MW and from private companies selling 650 MW of power outside the State, violating the Government's order (The Times of India 2014; The Hindu 2014).

Neither Bangalore nor any other city in India enjoys a 24 hour water supply. The piped water supply in Bangalore is intermittent and available only for a few hours a day (World Bank 2013; Raj 2013). Even the wealthy in Bangalore with piped connections receive water from the main supply for only a couple of hours a day, or on alternative days, or three or four times a week. The rich have installed expensive water tanks, pumps and filters while the poor cannot get connections to water, instead having to stand in queues for hours at municipal standpipes, wait for private tankers, or buy water from private sellers (World Bank 2013; Raj 2013).

The per capita water supply is far below the standard norm of 150 lpcd and actual demand of 173 lpcd (CSE 2011). The per capita water supply in Bangalore city is reducing. In 2001, per capita water supply was 105 lpcd against the Bangalore standard of 150 lpcd and International Standard of 200 lpcd. The demand was 750 MLD but supply was only 570 MLD. The per capita water supply has reduced to 83 lpcd in 2010 against Bangalore's supply of 138 lpcd (CSE 2011) and 65 lpcd in 2014 (BWSSB 2014). This is due to a huge system loss. The 'Unaccounted- for Water' (UFW) or Non-Revenue Water (NRW) varies from 55-60% (CSE 2011; Raj, 2013). Leakage alone is estimated at 37-40% of supply (Mehta et al. 2013). People who live in slums receive no water or a much lesser quantity (CSE 2011 and Lele et al. 2013).

Methodology

Selecting System Boundary

Identifying a system boundary is very important for a comprehensive water mass balance analysis that considers all inflows and outflows within and throughout a city (Kenway et al. 2008)]. In this study, we define the system boundary as the core of Bangalore city and the adjacent built up area that is the Bangalore Water Supply and Sewerage Board (BWSSB) service area, called greater Bangalore, including 1 km under ground level (figureS 1). The sub-system boundaries have been identified as Water Treatment Plants (WTPs), Wastewater Treatment Plants (WWTPs), various sub-sectors or land uses such as residential, commercial, industrial, public and semi-public institutions, parks and open space, transport and communication, agriculture and lakes and ponds. Water storage outside the city and ground water aquifers beneath the city has not been considered part of the system. The inflows into and outflows from the city through natural waterbodies and streams have also been excluded in order to separate the city from the natural environment, as done by Kenway et al. (2011). The subsystem boundaries and their percentages compared to the system boundary are shown in table S 1. These values were used for the calculation of sub-boundary precipitation, runoff and groundwater recharge. The land use by WTP and WWTP were considered as negligible compared to the area of the system boundary, which is 800 sq.km(BWSSB 2013).

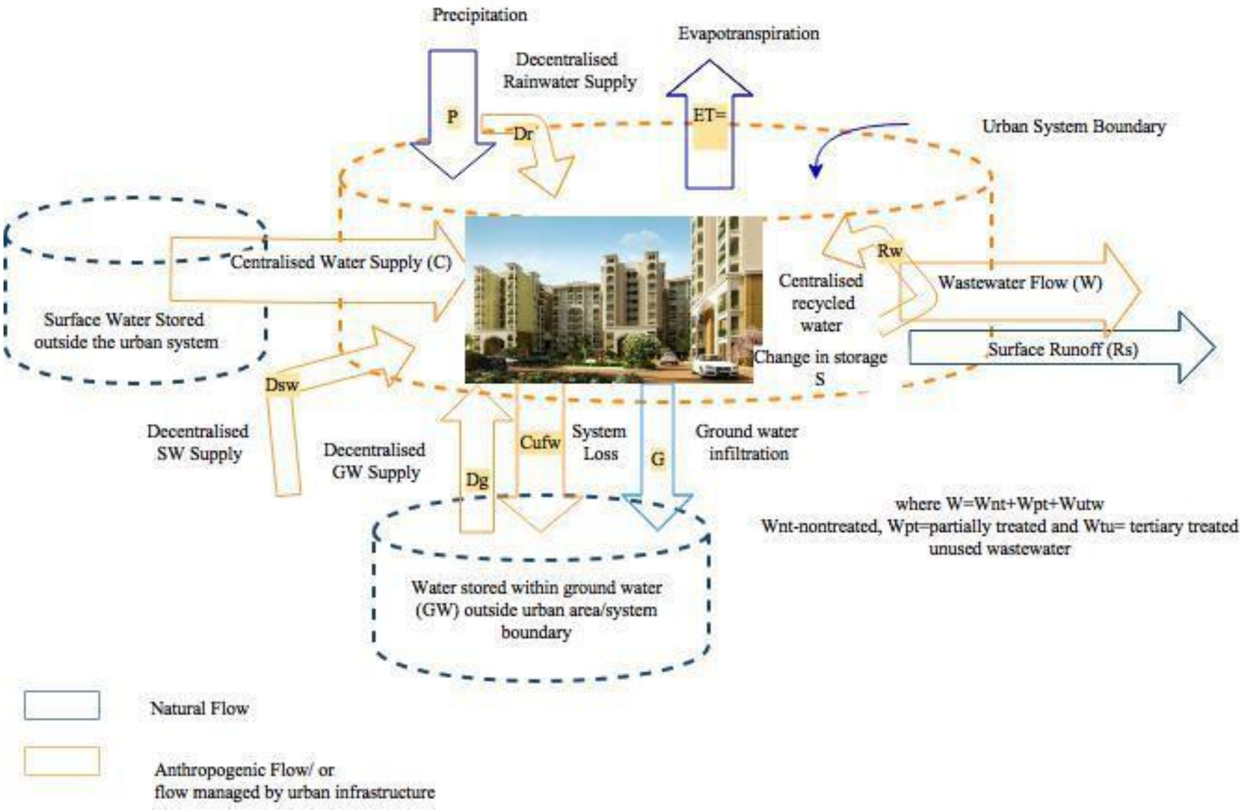

Figure 3: Water Mass Balance Evaluation Framework (Refinement from original framework developed by Kenway et al. (2011)) to enable the quantification of all water sources including alternative local water and develop performance indicators in context of Bangalore city.

In figure 4,

P = Precipitation or Rainfall ET= Evapotranspiration

C = Centralized water supply

S = Water stored or utilized by different subsystems W = Wastewater flow

Rs = Stormwater runoff

G = Groundwater flow/recharge

Dr = Decentralized rainwater supply Dg= Decentralized groundwater supply

Ds = Decentralized surface water supply by private retailers/tankers C_{ufw}= System loss/leakages

Rs= Surface water runoff Rw = Recycled water

$$S= (P+C+Dr+Dg +Ds+Rw) - (W+Rs + G+ET+ C_{ufw})$$

Table 1: Performance indicators and their definition under the study

Indicators	Method	Formula
Water System Centralization Supply centralization (%)	Centralized Supply/Total Water Use	C/(C+D)*100
Rainfall Harvesting (%) Rainfall Potential for Water Supply Centralized supply replaceability (%) Total Use Replaceability (%)	Decentralized sources/rainfall Rainfall/Centralized water supplied Rainfall/Total Use	D/P*100 P/C*100 P/(C+D)*100
Wastewater Potential for Water Supply Centralized Supply Replaceability (%) Total Use Replaceability (%)	Wastewater Flow/Centralized water supplied Wastewater Flow/Total Water Use	W/C*100 W/(C+D)*100
Stormwater Potential for Water Supply Centralized Supply Replaceability (%) Total Use Replaceability (%)	Stormwater flow/centralized water supplied Stormwater flow/Total Water Supplied	Rs/C*100 Rs/(C+D)*100
Wastewater and stormwater combined Potential of ‘total water use Replaceability’ (%)	(Wastewater+stormwater)/ Total water use	(W+Rs)/(C+D)*100

Water Loss Recovery Potential of 'total water use Replaceability' (%)	Water Loss/Total water use	Cufw/(C+D)*100

Source: Adapted from Kenway et al. (2011)
Note- C = Centralized Water Supply, D=Decentralized Water Supply, P= Rainfall, W=Wastewater Flow, Rs= Stormwater Runoff , Cufw= Uncounted For Water

Data collection and Interpretation

Both secondary and primary data were collected based on the Water Mass Balance Framework described in figure 3, developed from the original framework by Kenway et al. (2011) (figure 2), and have been discussed in details in the supplementary Information.

Based on the availability of data, the time period for the study was considered as 2013-2014 (Jan-Dec).

The area of the system boundary, population, decentralized water supply, groundwater supply and other parameters were collected from various research reports, journals and official Information. The primary data for centralized water supply, wastewater generation and wastewater reuse, and rainfall for the year 2013-2014 was collected from Bangalore Water Supply and Sewerage Board (BWSSB) and Meteorological Centre, Bangalore and other government Information. These have been discussed in details in supplementary Information.

The water cycle in Bangalore is managed by various organizations such as BWSSB (responsible for water supply and sewerage), CGWB (groundwater monitoring and management), BBMP (Bhurat Bangalore Mahanagar Pallika) (stormwater drainage and solid waste management), Bangalore Development Authority (BDA) (city planning), private water suppliers and self-suppliers with overlapping responsibilities. There is no central water database for the city water supply which made measuring various inputs and outputs a challenging task.

Rainwater use, negligible compared to total water supply, was calculated based on rainwater plants installed in Bangalore city and assumed an average plant discussed in details in supplementary Information.

Measuring groundwater recharge was difficult due to the unavailability of continuous water table monitoring data in Bangalore city. It was therefore calculated following the detailed Guidelines for Implementing Groundwater Estimation Methodology (Central Ground Water Board 2009) and the Groundwater Resource Estimation Methodology (GEM) Report - 1997 (Ministry of Water Resources 2009) recommended by Groundwater Resource Estimation Committee (Ministry of Water Resources2009) elaborated in supplementary information.

The runoff coefficient for various land uses have been used for this study based on the typical values of runoff coefficients in an urban area as elaborated in Chapter-11 of the Urban Drainage Book (Butler and Davies 2011). Evapotranspiration for sub-boundaries has been calculated with the following formula from respective values: ET = P-R-G.

Results and Discussion

The collected primary and secondary data were used for the water mass balance analysis of Bangalore city using the water mass balance equation described in methodology section and also mentioned below. The results of this analysis have been shown in table 2. All inputs and outputs are considered in the analysis (details of water mass balance flow chart can be seen in figure S 5). The equation was applied to both system and sub-system boundaries, and found a positive change of 130.58 gigaliters (GL) in the storage of the city system:

$$S = \text{Inflows} – \text{Outflows}$$

$$S = (P+C+Dr+Dg+Ds+Rw) – (W+Rs+G+ET+C_{ufw})$$

$$S = (77.6+356.3+0.004+288.4+23.7+2.9) – (362+40+4.4+33.28+1768.6) = 130.58 \text{ GL}$$

One Gigaliter (GL) = 10^9 liters (L) ≈ 2.64×10^8 gallons (gal).

In reality inputs should be equal to outputs (Kenway et al. 2011). The high value of change in storage may be due to some errors in calculation when quantifying the ground water recharge value, use of assumed runoff co-efficient and other data inaccuracy. Further, only data for the year 2013-2014 were used due to data unavailability. The data accuracy, appropriate runoff coefficient in respect to Bangalore geography and soil situation, and a longer timeframe for data could provide better results of water mass balance equation.

The total water availability of rainwater, stormwater and wastewater was 656 Giga liters (GL) during the year 2013-2014 considering full reuse potential.

The water performance indicators were derived based on the formula described in table 1, the results of which have been tabulated in table 3 and table 4.

The ‘water supply centralization’ of Bangalore city was 52% which illustrates that the Bangalore water supply system is not fully centralized. About 48% of water demand is met from groundwater and other sources. The ‘total water use replaceablity’ of wastewater was 55% and centralized replaceability was 107% which means the amount of wastewater (362 GL) could solely replace present centralized water supply in 2013 (356 GL), imported from the Cauvery river. The ‘total use replaceability’ of alternative rainwater and stormwater was 12% and 6%, respectively, which illustrates that 78 GL and 40 GL could be used as inputs in the whole urban system from these two sources. The replaceability potential of wastewater (362 GL) is about 5 times and 9 times higher than rainwater (78 GL) and stormwater (40 GL), respectively, which indicates Bangalore is a dry city.

Table 2: Inputs (Qi) and Outputs (Qo) of Bangalore city for the year 2013-2014

Inputs	Population (Million)	Area (Sq. km)	Centralized Surface Water Supply (GL/a)	Decentralized Groundwater Supply (GL/a)	Decentralized Surface Water Supply (GL/a)	Decentralized rainwater supply(rainwater tank) (GL/a)	Rainfall on Surface (GL/a)	Reuse of Wastewater (G/a)	
	9.5	800	356	288	24	0.004	78	3	
Outputs	Population (Million)	Area	Partially Treated Waste water Flow (GL/a)	Non-Treated Wastewater Flow (GL/a)	Treated Wastewater Flow (GL/a)	Surface Runoff (GL/a)	System Loss (GL/a)	Ground Water Recharge (GL/a)	Evapo-Transpiration (GL/a)
	9.5	800	167	171	24	40	179	4.4	33

Table 3: Centralized Supply Replaceability/ Supply Substitution of alternative sources of water including loss in the system for the year 2013-2014

		% of potential replaceability/substitution of water supply					
Supply	% of Total C/(C+D) *100	Rain Water (P/ C*100)	Storm Water (RS/ C*100)	Waste Water (W/ C*100)	Unaccounted For Water (UFW)Non-Revenue Water (NRW)	Waste water and Rainwater (W+P/C* 100)	All alternative waters including UFW/NRW (W+P+Rs)/ C*100
Centralized	52	23	12	107	53	130	195

Table 4: 'Total Use Replaceability'/ Supply Substitution of alternative sources of water including loss in the system for the year 2013-2014

		% of potential replaceability/substitution of water supply					
Supply	% of Total	Rainwater	Storm Water	Waste Water	Un-counted For Water	Wastewater and	All alternative
	(C/ C+D)* 100	P/(C+D)* 100	Rs/ (C+D) *100	W/ (C+D) *100	Cufw/ (C+D)*100	(W+P)/ (C+D)*100	UFWNRW (W+P+Rs)/ C*100
Total Use	100	8	6	55	27	63	90

A new significant indicator was found for Bangalore city which is derived from system loss and has been named here as 'Water Loss Recovery'. The 'total use replaceability' potential from 'Water Loss Recovery' was 27% and centralized replaceability was 53% shown in table 3 and table 4 which indicates that 179 GL could be used as inputs in the system (table 2). From this and earlier discussions, it is evident that wastewater recycling and improving water efficiency in the water supply network have good potential for augmenting water in the system, with wastewater recycling having a higher potential than 'water loss recovery'.

Investigation of roof rainwater harvesting potential in Bangalore city found that out of total rainwater potential, the roof surface available in Bangalore currently harvests 14 GL annually (BWSSB 2013, Citizen Charter, BWSSB and Rainwater Guidelines BWSSB). If we consider this potential of rainwater, the total potential of roof rainwater harvesting, stormwater and wastewater recycling and loss prevention stands at 550 GL annually or 46 GL monthly or 1.5 GL daily.

A scenario analysis was done using various water performance indicators and the current and projected water demand of Bangalore city as discussed in section 15 of supplementary Information. The water demand in Bangalore was set at 1260 million liters per day (MLD); the actual water supply in Bangalore was 927 MLD in 2013 which was found from field data and the actual gap was 815 MLD (when actual amount of water received by the end users is considered after system loss). It was found that this gap could easily be met in 2013 if even 54% of recycling potential was reused. Further, the actual water supply in 2014 was 754 MLD (adding 500 MLD Cauvery Stage-IV Phase-II-supply and considering 53% UFW) and the actual gap was found to be 675 MLD. The gap between water demand and water supply in 2014 could be met if 45% of recycling potential was reused. The water demand of Bangalore is expected to rise to 1650 MLD in 2021 as estimated based on Population growth by the census of Bangalore city with the addition of 10% more slum dwellers and using 120 lpcd demand of water. In 2021, the gap between water demand and supply can be calculated as 895 MLD (if 2013 UFW 53% prevails). This gap can easily be met if 60% of recycling potential is used.

It was observed that the wastewater or rainwater or stormwater or system loss alone cannot meet the demands of Bangalore city; however wastewater has very high potential (about 5 times that of rainwater and 9 times that of stormwater). An integrated or whole urban water cycle management that is utilization of rainwater, stormwater and wastewater together, is needed to meet the water demand of Bangalore city along with its present centralized supply (without its further energy intensive expansion). Decentralized water systems installed close to the point of use can save energy. Recycling of such water can ensure increased water security and reliability, and provide environmental benefits by reducing water pollution and improving the ecosystem.

Conclusion

Many cities around the world do not have robust accounts of all alternative resources of water in their water systems. The first question of this study was to explore a suitable framework or method to apply in Bangalore city, a rapidly growing developing city which faces serious water stress, to quantify all of its alternative water resources. The refined urban water mass balance framework originally developed by Kenway et al. (2011) was found to be very useful in a developing country context, and could be used also as a physical model (Water Mass Balance Analysis – figure S 5). The new addition to the original equation was system loss 'Unaccounted-for Water (UFW)', which is a significant flow components of water mass balance in a developing country and other water supplies such as those, supplied by private water retailers, which is common in many developing cities. It also included centralized recycled but centralized recycled water is not a common practice in developing countries. Because of a lack of data, the decentralized recycled water was assumed ‘zero’ in this study. The system boundary and the refined framework helped calculate all inflows and outflows within and outside the urban system of Bangalore city. The high value of change in storage may be due to some errors in calculation especially those for quantifying the groundwater recharge value, which can be further studied. Moreover, the decentralized recycled water and other water use could be added to get better results of the water mass balance equation of Bangalore city.

The second question was to explore how the refined water mass balance equation can improve accounting of all sources of water and help planners, engineers, water managers and policy makers improve the city water performance and management. The analysis found that the wastewater solely had the potential of 362 GL which was enough to replace centralized water supply (338 GL) for the year 2013-2014 and could be done through distributed recycled water systems (water used at the points of generation and connected to centralized water systems) following efficient technologies so that it does not further increase the energy cost. However, it was found that either wastewater or rainwater or stormwater was not sufficient to meet the total demand of water in Bangalore city. It was also needed to address the system loss which is a significant part (179 GL) of Bangalore Water Mass Balance during the year 2013-2014. Thus, a single alternative source will not meet all water demand in Bangalore city. An integrated water management of all waters sources, including present centralized supply, and improving the efficiency of the water supply network to recover system loss is essential. This can avoid further withdrawal of water from the Cauvery River and can reduce the energy cost in the system.

Further, the engineers and water managers could monitor the city's water performance over time using the indicators developed in this study and follow various strategies (recycling of water, improvement in system efficiency, rainwater and stormwater harvesting) to observe the overall performance of the urban water system - this could be done through 'learning by doing' process. The robust accounting of city water systems developed under this study is not only important for Bangalore but also for other cities in developing countries especially fast growing cities which are facing serious water shortages and use distant river sources or deep aquifers or seawater to meet their demand.

For improved results more accurate data is needed on infiltration rates and various coefficients based on local situations, decentralized water use from various sources, and wastewater generation, with this water balance framework needing to be updated as cities grow both horizontally and vertically with time.

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References

Agudelo-Vera, C.M., W.R. Leduc, A.R. Mels, and H.H.M., Rijnaarts 2012. Harvesting urban resources towards more resilient cities. *Resources, Conservation and Recycling* 64: 3-12.

Alberti, M. 1996. Measuring urban sustainability. *Environmental impact assessment review 16*(4-6):381-424

Baccini, P. and P.H. Brunner 1991. *Metabolism of the Anthroposphere (10-46).* Springer Berlin Heidelberg.

Bach, P.M., W.Rauch, P.S. Mikkelsen, D.T. McCarthy, and A. Deletic 2014. A critical review ofintegrated urban water modelling–Urban drainage and beyond. *Environmental Modelling & Software 54:* 88-107

Bai, X. 2007, Industrial Ecology and the Global Impacts of Cities. *Journal of Industrial Ecology*.

Baker, L.A., D. Hope, Y. Xu, J. Edmonds, and L. Lauver 2001. Nitrogen balance for the CentralArizona–Phoenix (CAP) ecosystem. *Ecosystems 4*(6): 582-602.

Barles, S. 2009. Urban metabolism of Paris and its region. *Journal of Industrial Ecology, 13*(6):898-913

Barrett, J., H. Vallack, A. Jones, and G. Haq 2002. A material flow analysis and ecological footprint of York. *Stockholm, Stockholm Environment Institute.*

Bohle, H.G. 1994. Metropolitan food systems in developing countries: The perspective of Urban Metabolism. *GeoJournal 34*(3):245-251

Browne, D., B. O'Regan, and R. Moles 2009. Assessment of total urban metabolism and metabolic inefficiency in an Irish city-region. *Waste Management 29*(10):2765-2771

Center for Science and Environment (CSE) 2011. *Water waste Portrait,* viewed on 10 November 2013 at http://cseindia.org/userfiles/bangaluru_portrait.pdf.

Chartered Institute of Wastes Management (CIWM) 2002. *A Resource Flow and Ecological Footprint Analysis of Greater London*. Best Foot Forward, London.

City Development Authority (CDA) 2009. *Bangalore Master Plan 2015.* Bangalore, India.

Deccan Herald 2013. *Only 44,000 houses in City have RWH.* published on 26 Feb. www.deccanherald.com/content/315171/only-44000-houses-city- have.html. Accessed on 3rd April, 2014

Decker, E.H., S. Elliott, F.A. Smith, D.R. Blake, and F.S. Rowland 2000. Energy and material flow through the urban ecosystem. *Annual review of energy and the environment 25*.

Duvigneaud, P., and S. Denayeyer-De Smet 1977. The urban ecosystem of Brussels. L'Ecosystéme Urbs, in L'Ecosystéme Urbain Bruxellois, in Productivité en Belgique. In: Duvigneaud, P., Kestemont, P. (Eds.), Traveaux de la Section Belge du Programme Biologique International Bruxelles 581-597

ETH Globe 2010. *Future Cities.* International Edition. Zurich

Færge, J., J. Magid, and F.W.P. de Vries 2001. Urban nutrient balance for Bangkok. *Ecological modelling 139*(1): 63-74.

Farooqi, M.A. 2011. Groundwater Management in Bangalore: Impact of Municipal Waste Disposal Practices on Groundwater Quality. *Journal of the Geological Society of India* 78(5): 488-489

Farooqui, T.A., M.A. Renouf and S.J. Kenway 2016. A metabolism perspective on alternative urban water servicing options using water mass balance. *Water research 106*: 415-428

Gandy, M. 2004. Rethinking urban metabolism: water, space and the modern city. *City 8*(3), 363-379.

Gasson, B. 2002. The ecological footprint of Cape Town: Unsustainable resource use and planning implications. Paper presented a National Conference of the South African Planning Institution, 18-20 September, Durban, South Africa

Gronwall, J.T., M. Mulenga, and G. McGranahan 2010. *Groundwater, self-supply and poor urban dwellers: A review with case studies of Bangalore and Lusaka.* Human Settlements Working Paper Series, Water and Sanitation 26, International Institute for Environment and Development, London, UK.

Hanya, T. and Y. Ambe 1976. A Study on the Metabolism of Cities, *In: Science for a Better Environment*. HSEC, Science Council of Japan, 228-233

Hermanowicz, S.W. and T. Asano 1999. Abel Wolman's "The Metabolism of Cities" revisited: a case for water recycling and reuse. *Water Science and Technology* 40(4-5): 29-36

Hegde, G. V., and K.S. Chandra 2012. Resource availability for water supply to Bangalore city, Karnataka." *Current Science (Bangalore)* 102(8): 1102-1104.

Hendriks, C., R. Obernosterer, D. Müller, S. Kytzia, P. Baccini, and P.H. Brunner, 2000. Material flow analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. *Local Environment 5*(3): 311-328.

Holmes, T. and S. Pincetl 2012. Urban metabolism literature review. *Los Angeles, California Centre for Sustainable Communities at UCLA.*

IBM 2010. *Rain to Drain: A roadmap to gaining control over water resource management using Information management and predictive analytics.* NY, USA.

Kennedy, C., J. Cuddihy, and J. Engel-Yan 2007. The changing metabolism of cities. *Journal of industrial ecology 11*(2): 43-59

Kennedy, C., S. Pincetl, and P. Bunje 2011. The study of urban metabolism and its applications to urban planning and design. *Environmental pollution 159*(8):1965-1973.

Kenway, S., A. Gregory and J. McMahon 2011. Urban water mass balance analysis. *Journal of Industrial Ecology 15*(5): 693-706.

Kenway, S.J. 2013. *The water-energy nexus and urban metabolism-Connections in cities*. Brisbane: Urban Water Security Research Alliance.

Kenway, S., J. McMahon, V. Elmer, S. Conrad, and J. Rosenblum 2013. Managing water-related energy in future cities–a research and policy roadmap. *Journal of Water and Climate Change*, *4*(3), 161-175.

Kingdom,B., R. Liemberger, and P. Marin 2006. *The challenge of reducing non-revenue water (NRW) in developing countries. How the private sector can help: A look at performance-based service contracting*. World Bank Group; Water Supply & Sanitation Sector Board; PPIAF, Discussion Paper Series, 8, Washington DC. USA

Lele, S., V. Srinivasan, P. Jamwal, B.Thomas, M. Eswar, and T. Zuhail 2013. *Water Management in Arkabhaty River: A Situation Analysis, Environment and Development*, Working paper No-1, Ashoka Trust for Research in Ecology and the Environment (ATREE), Bangalore, Karnataka, India.

Mitchell, V.G., R.G. Mein, and T.A. McMahon 2001. Modelling the urban water cycle. *Environmental Modelling & Software 16*(7), 615-629

Newcombe, K., J.D. Kalma, and A.R. Aston 1978. The metabolism of a city: the case of Hong Kong. *Ambio* 3-15

Newman, P.W. 1999. Sustainability and cities: extending the metabolism model. *Landscape and urban planning 44*(4): 219-226.

Nilsson, J. 1995. A phosphorus budget for a Swedish municipality. *Journal of Environmental Management 45*(3): 243-253.

Mehta, V.K., R. Goswami, E. Kemp-Benedict, S. Muddu, and D. Malghan 2014. Metabolic urbanism and environmental justice: the water conundrum in

Bangalore, India. *Environmental Justice, 7*(5):130-137

Pincetl, S., P. Bunje, and T. Holmes 2012. An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape and urban planning 107*(3):193-202.

Raj, K. 2013. *Where All the Water has gone? An Analysis of Unreliable Water Supply in BangaloreCity*. Working Paper, Institute of Social and Economic Change (ISEC). Bangalore, India

Rapoport, E. 2011. *Interdisciplinary Perspectives on Urban Metabolism. A Review of Literature*. UCl Environmental Institute Working Paper. London: University College London, Development Planning Unit.

Renouf, M., S. Kenway, S. Serao-Neumann, and D. Low Choy. 2016. *Urban Metabolism for Planning Water Sensitive Cities: Concept for an Urban Water Metabolism Framework.* Victoria: Cooperative Research Centre for Water Sensitive Cities.

Sahely, H. R., S. Dudding, and C.A. Kennedy 2003. Estimating the urban metabolism of Canadian cities: GTA case study. *Canadian Journal for Civil Engineering* 30: 468–483.

Schulz, N.B. 2007. The direct material inputs into Singapore’s development. *Journal of Industrial Ecology* 11 (2): 117-131.

Stimson, R., J. Western, P. Mullins, and R. Simpson. Urban metabolism as a framework for investigating quality of life and sustainable development in the Brisbane-Southeast Queensland Metro region. *Urban quality of life: Critical issues and options* 43-168

The Hindu 2014. Karnataka resorts to load-shedding. www.thehindu.com/todays paper/tp national/karnataka-resorts-to-loadshedding/article5980608.ece. Accesses May 2014.

The Times of India 2014. Karnataka to face two-hour long power cuts daily. http://timesofindia.indiatimes.com/city/bengaluru/Karnataka-to-face-two-hour-long-power-cuts-daily/articleshow/34706488.cms?. Accessed on May 2014

Theriault, J. and A.M. Laroche 2009. Evaluation of the urban hydrologic metabolism of the Greater Moncton region, New Brunswick. *Canadian Water Resources Journal* 34 (3):255-268.

United Nations (UN) 2014. *World Urbanization Prospects The 2014 Revision Highlights.* Economic and Social Affairs, New York, USA

Warren-Rhodes, K. and A. Koenig 2001. Escalating Trends in the Urban Metabolism of Hong Kong: 1971–1997, AMBIO: *A Journal of the Human Environment*, 30(7):429-438.

Van Leeuwen, C. J., J. Frijns, A. Van Wezel, and F. H. M. Van De Ven 2012. City Blueprints: 24Indicators To Assess The Sustainability of The Urban Water Cycle. *Water Resources Management*, 26**,** 2177-2197.

Wolman, A. 1965. The metabolism of cities. *Scientific American* 213(3): 179–190.

World Bank 2013. Karnataka: Three Towns Pilot 24/7 Water Supply. http://www.worldbank.org/en/news/feature/2013/01/01/karnataka-three-towns-pilot-water-supply. Accessed April 2014.

Zhang, Y. and Z. Yang. 2007. Eco-efficiency of urban material metabolism: a case study in Shenzhen, China. *Acta Ecologica Sinica* 27 (8): 3124-3131.

Zucchetto, J. 1975. Energy, economic theory and mathematical models for combining the systems of man and nature. Case study, the urban region of Miami. *Ecological Modelling* 1, 241-268

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