

Social Ecology of Domestic Water Use in Bangalore

VISHAL K MEHTA, RIMI GOSWAMI, ERIC KEMP-BENEDICT, SEKHAR MUDDU, DEEPAK MALGHAN

The rapid growth of urban India has added new saliency to the resource conflict between the burgeoning cities and village India that continues to be the home for vast majority of Indians. Cities, like living organisms, depend on external metabolic flows to keep them alive. Among all the metabolic flows of matter and energy none is more important than water – especially water used for meeting basic drinking water and other domestic consumption needs. This paper develops a metabolic framework for domestic water use in Bangalore, one of the fastest growing urban agglomerations in India. Our urban metabolism framework treats the city as a tightly-coupled social-ecological system and shows that a spatially explicit understanding of consumption patterns is crucial to addressing three central aspects of the water conundrum – equity, ecological sustainability and economic efficiency.

As India continues to rapidly urbanise, it is vital to understand cities' crucial dependence on social and natural resources of rural areas, and on its own natural resources (Wimberley and Morris 2006). Cities are like living organisms, depending on external metabolic flows of matter and energy to keep them alive and for growth, generating waste in the process (Decker et al 2000; Newman 1999). In a deeply unequal society like India, the political economy of this "social metabolism" is characterised by conflicts across caste, class, economic and geographic-demographic axes – urban versus rural, the rich versus the poor, agriculture versus industry, adivasis versus the rest, upper castes versus the subaltern castes, slum-dwellers versus the rest of the city, men versus women, etc.¹

Among all the metabolic flows of matter and energy none is more important and more contested than water – especially water used for meeting basic drinking and other domestic consumption needs. India is home to a significant proportion of an estimated 1.5-2 billion people around the world without access to clean sources of drinking water. Only 35% of households in rural areas and 71% of households in urban areas have access to drinking water within their household premises.² Utility provided piped water supply being inadequate in all Indian cities, water is consumed from a mix of surface and groundwater sources (CGWB 2011), through a combination of utility piped supply, private borewells (self-supply), tankers, bottled water and untreated waterbodies (Srinivasan et al 2010, Misra and Goldar 2008). Many large urban centres import surface water from sources that are a hundred or more kilometres away and across large gradients (Narain 2012a: 6).

Domestic water consumption is driven by a complex set of intersecting social, economic, demographic, political, geographic, infrastructural, and hydrological factors. There is considerable variation of these drivers within a city, reflecting the spatial diversity that characterises most metabolic flows in a city. However, official water planning in Indian cities reduces this complexity to one of expanding the physical water utility infrastructure to meet a simplistic per capita water target which is called "demand", in conjunction with a simple extrapolation of trends in population growth. In actuality, "no city municipality knows what the real water demand is in the spaces they govern" (Narain 2012a: 1). Utility performance metrics based on such planning are therefore overoptimistic and narrow. The social metabolism of domestic water consumption in a city demands an assessment against three aspects – justice, ecological sustainability and economic efficiency (Malghan 2010). In this regard neither public nor private or public-private-partnership (PPP)

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water utilities have met the criteria in India (Bajpai and Bhandari 2001; Bhaduri and Kejriwal 2005). When one considers the spatial pattern of growth in a city, a programme designed in the interest of economic efficiency might fail to deliver on its promises even while deepening existing inequities (Ranganathan et al 2009).

In this paper, we argue that the traditional “planning” exercise in urban water utilities needs serious overhaul. A much broader framework to urban planning is needed, one that (1) situates urban planning within regional, multi-sectoral planning; (2) uses formal approaches for planning under uncertainty; (3) is capable of evaluating both supply- and demand-side measures; (4) explicitly accounts for the patterns of spatial variation (of social, economic and ecological variables) in a city; and (5) does not collapse questions surrounding equity and ecological sustainability to an economic efficiency problem.

We propose a social metabolism framework for urban water planning. There are four central features to our framework. First, as with any metabolic process, we account for both the flow of resources coming into the city, and waste flows from consumption. Thus, our framework will account for both water imported into Bangalore and the sewerage generated by its use.

Second, we show why metabolic flows in general, and water flows in particular are best understood as tightly coupled social ecological systems (Ostrom 2009). We show how the metabolic flow of water is directly shaped by social, political, economic and policy variables. In our example, the social and economic variables contribute as much to groundwater dynamics as the natural systems – Bangalore as a metabolic structure alters the background hydrology that would have existed without the city.

Third, using Bangalore’s domestic water use as a case study, we demonstrate the spatial diversity that is inherent in any urban metabolic processes. A city is spatially clustered along various social, economic and demographic axis.³ There is also inherent geographic and topological differences between various parts of the city (in our example, distance from the piped water supply infrastructure and the underground topology are important spatial variables).

Finally, we make the case that the urban metabolism framework is well-suited to investigate the nexus between social equity, biophysical sustainability and economic efficiency. In our example, the metabolic framework helps uncover why certain policy solutions like privatisation of public utilities in the interest of economic efficiency may fail in meeting their objectives.

The remainder of the paper is organised as follows: in Section 1 we describe the urban metabolism framework. Sections 2-5 illustrate key elements of the framework for Bangalore. In Section 2 we analyse the spatial pattern of Bangalore’s growth in the last decade; Section 3 documents the spatial disconnect between this growth and water supply infrastructure; and Section 4 develops the hydrological nexus among Bangalore’s imported surface water, the efficiency of its public utility and groundwater levels. Section 5 outlines ongoing

activities that will complete the urban metabolism framework. We conclude in Section 6.

1 Urban Metabolism Framework for Water

India’s first nationwide analysis of urban water consumption was aptly titled *Excreta Matters: How Urban India Is Soaking Up Water, Polluting Rivers, and Drowning in Its Own Waste* Volumes 1 and 2 (Narain 2012a; 2012b). The physical and social infrastructure that Indian cities use to manage its waste flows is the locus of some of the worst affronts on human dignity. No Indian city would function without the families that live in shanty settlements abutting the sewers and former rivers that now carry the city’s excreta, and make a living rummaging through the city’s waste. When both water flowing into the city and the waste emptying out of the city are properly accounted for, a social metabolism framework allows for combining questions of justice and ecological sustainability. The social metabolism framework (Fischer-Kowalski and Hüttler 1998 and 1999; Martinez-Alier 2007 and 2009) offers a particularly convenient apparatus to address the social, economic, and ecological complexities of urban water consumption. It provides a basis for understanding not only the physical flows of matter and energy through a society, but also to understand social relations that generate these metabolic flows. The city is a living entity whose survival and growth is contingent on a steady throughput of matter and energy into the city, and the return flow of waste product. Waste flows are a defining characteristic of any metabolic process. Thus, social metabolism helps understand the co-evolution of social and ecological systems (Sieferle 2011; Weisz 2011).

The central approach of an urban metabolic framework is to explicitly acknowledge that human and natural systems are tightly coupled in urban environments (House-Peters and Chang 2011). Since policy choices determine the physical shape of the urban environment, they have substantial, often long-term and unexpected, consequences on the social-ecological feedbacks.⁴ Policies have a lasting impact on hydrology, as illustrated by the evolution of the groundwater systems of other major cities around the world (Onodera et al 2008; Kim et al 2001; Hayashi et al 2009). The Tokyo metropolitan area is particularly instructive of the surprises that a tightly coupled “social-ecological system” can hold in store. In the 1950s and 1960s, unregulated extraction led to declining groundwater levels and land subsidence. Regulations limiting extraction manifested themselves in recovering groundwater levels decades after the regulations. However, these recoveries are now endangering underground structures like subways that were constructed before the regulations and their impacts were manifested (Hayashi et al 2009). In Seoul, Korea, researchers found that groundwater pumping and leakage from pipes were dominant components of the city’s socioecological groundwater budget. The feedback in Seoul was such that total groundwater barely changed, as leakage made up for extraction, but water quality was impaired (Kim et al 2001). The examples from Tokyo and Seoul are of immediate relevance to Bangalore, given the expansion of Bangalore metro, artificial recharge

from leaking piped supply, and increasing groundwater use (Sekhar and Kumar 2009). Elsewhere, in Bangkok and Jakarta, excessive groundwater extraction led to the water table falling below sea level, causing intrusion of seawater and shallow groundwater into deeper aquifers (Onodera et al 2008).

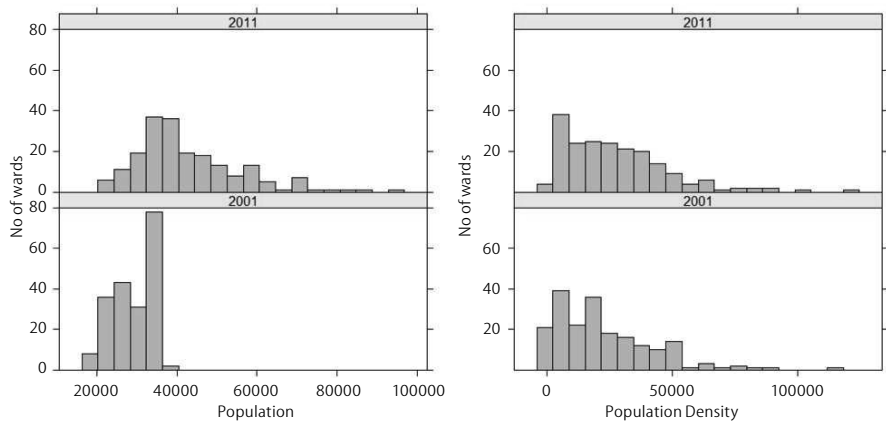
The first step in implementing the coupled social-ecological systems approach in the water sector is the construction of a well-defined water mass balance (Kenway et al 2011). A water mass balance is the most basic description of water metabolism – it details how a city draws upon many different sources to meet its water needs and also keeps track of waste flows. Even within the context of water consumption and supply, there exists a burgeoning literature on combining hydrologic and economic factors in a unified modelling framework (Harou et al 2009). In the Indian context, Srinivasan et al (2010) developed a detailed, dynamic hydrologic-engineering-economic model to study Chennai’s water supply and transcend the simplistic population projection models used by public utilities. Based on publicly available data, we develop a spatial snapshot after reviewing the disconnect in patterns of growth and the urban water supply infrastructure.

2 Spatial Pattern of Bangalore’s Growth

Bangalore is a poster child of the problems confronting urban India. Rapid economic and population growth is driving concomitant growth in not only water and energy demands, but also waste creation that utilities are increasingly unable to cope (NIUA 2005; Narain 2012a). In four decades, Bangalore has grown from 1.65 million people in 1971 to 8.5 million people in 2011 (Table 1). The pace of growth has also increased in recent decades – in the last 10 years, almost three million people were added compared to the previous two decades’ growth of one million each. It is now the third-most populated Indian city, and one of the fastest growing city-economy in the country (GOK 2006).

Much of the new population growth in Bangalore between the last two decennial census enumerations has happened in the peripheral areas of Bangalore – including regions that were incorporated into the city when it expanded its physical jurisdiction by nearly 40% in 2007. The Bruhat Bengaluru Mahanagara Palike (BBMP) or the Greater Bangalore City Corporation was formed in 2007. The BBMP extended the jurisdiction of the

Figure 1: Ward Distributions of Population and Population Density (2001-11)



earlier Bangalore Mahanagara Palike (BMP) by merging it with eight smaller municipal jurisdictions and over 100 villages under various panchayat jurisdictions surrounding the city. The newly added areas include peri-urban areas as well as large swathes of new industrial development including information technology parks.⁵ Even as the administrative boundaries of the city have increased over time, Table 1 shows that population density has also increased – the city has not only expanded, but has also progressively become more crowded. Using official 2011 BBMP ward boundaries as a common frame, we gathered ward population numbers from Census 2001 and Census 2011.⁶ The majority of wards now have more than 40,000 people living in them, whereas in 2001, there were no wards with more than 40,000 people (Figure 1). The figure also shows that population density (people/km²) remains high in almost all the wards, reflecting the overall citywide population density increase reported in Table 1.

The pace of population growth has by no means been uniform across the city. Figure 2, showing the spatial pattern of population growth between 2001 and 2011, clearly illustrates that peripheral areas around the city centre experienced very high growth rates – greater than 300% in some of the outlying wards. Figure 2 shows how the city has expanded in all directions.

Table 1: Forty Years of Bangalore’s Evolution: Population, Population Density and Percentage Built-Up Area

Year	Population (Mill People)	Density (People/km ²)	Built-up Area (%)
1971	1.7	9,465	20
1981	2.9	7,990	26
1991	4.1	9,997	39
2001	5.7	11,545	69
2011	8.5	12,142	na

Sources: Iyer et al (2007); Census 2011.

Figure 2: Spatial Distribution of Population Growth between Census 2001 and 2011

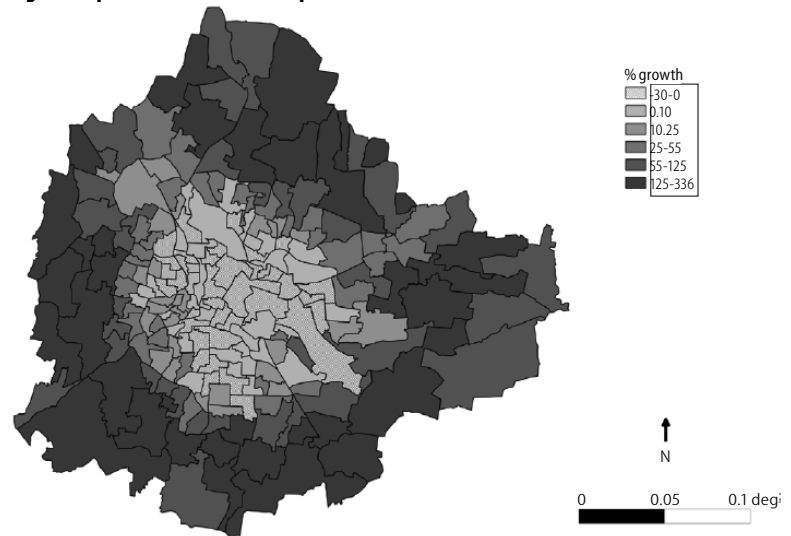
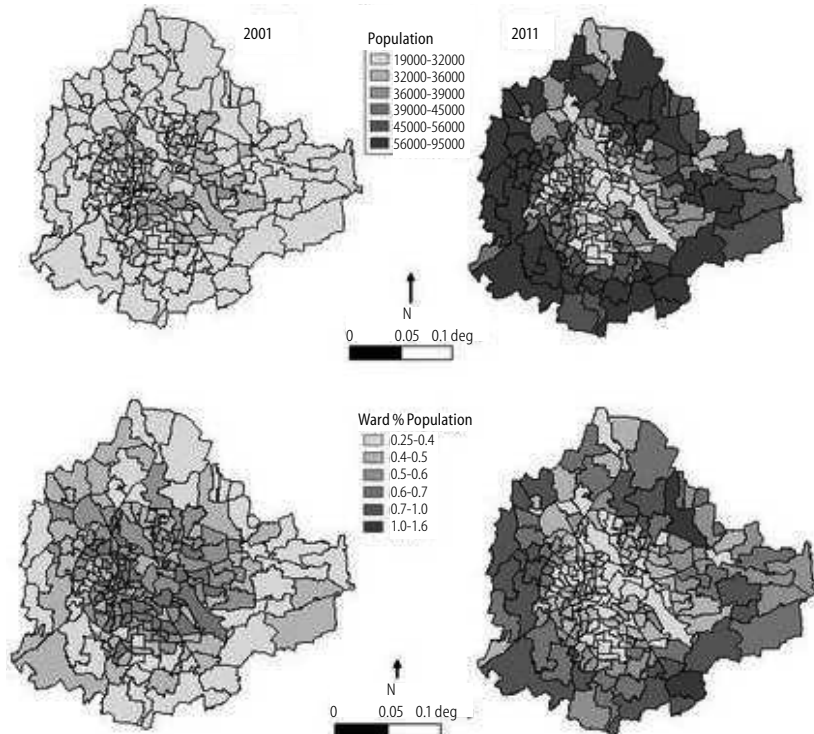


Figure 3: Spatial Transformation of Bangalore: 2001-11

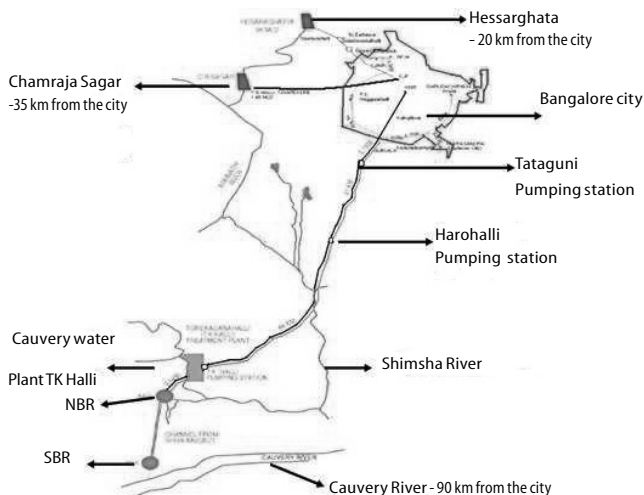
Population, and (bottom) population percentage contained within current (2011) ward boundaries. Map generated using provisional Census 2011 numbers for wards provided by the Bruhat Bengaluru Mahanagara Palike (BBMP).

While certain areas to the south-east of city centre have grown particularly fast, the city has seen increases all around its periphery. This pattern of growth has transformed the city such that more people now live in the peripheral areas away from the city centre than in the central areas (Figure 3).

3 Domestic Water Consumption and Supply in Bangalore

3.1 Overview of Bangalore's Piped Surface Water Supply

Unlike other big cities, Bangalore is not close to any large perennial waterbodies. Before 1896, Bangalore residents used wells, lakes and *kalyanies* (temple wells) as water sources. In

Figure 4: Schematic of Piped Water Supply to Bangalore City

Source: BWSSB 2011.

1896, the first piped water supply came from Hesaraghatta lake, built across the river Arkavathi, with water pumped to the city where it was treated before distribution.⁷ The next major expansion came in 1933, when Chamaraja Sagar reservoir was built across Arkavathi, downstream of Hesaraghatta, about 26 km west of Bangalore. Since 1964, Bangalore's piped water supply has been managed by the Bangalore Water Supply and Sewerage Board (BWSSB) which is an autonomous body under the state government. The BWSSB is responsible for providing adequate water supply and sewage disposal for Bangalore. Its mandate calls for collection of charges for its services on a "no loss no profit basis" (BWSSB 2011). The current BWSSB jurisdiction covers a little over 800 km², divided into six maintenance divisions which are in turn divided into 26 subdivisions and 106 service stations. Since the 1970s, water from the Cauvery river, over 90 km away, is the main source of surface water supplied by the BWSSB. The total installed capacity from the Cauvery and Arkavathi rivers currently stands at 959 million litres per day (MLD), with a (March 2011

estimate) supply of 900 MLD. The Arkavathi only supplies 59 MLD of this total surface water imported into Bangalore. Figure 4 provides a schematic representation of these two surface water sources that supply water to Bangalore. The BWSSB also supplies about 70 MLD of groundwater from over 7,000 borewells (Narain 2012b).

Approximately every 10 years since 1974, a new stage of the Cauvery Water Supply Scheme expanded surface water supply to the city. In 1974, the first stage added a capacity of 135 MLD to the system. Successive stages added 135 MLD (1983) and 270 MLD (1993). Phase 1 of the fourth stage brought the total current surface water supply from the Cauvery to 900 MLD. A second phase of Cauvery fourth stage is planned for 2012, which would add another 500 MLD of system capacity. The Cauvery River Water Disputes Tribunal Award caps Bangalore's withdrawal of Cauvery water to approximately 1,400 MLD.⁸ While the public utility (BWSSB) cites the limit placed on Cauvery withdrawals as a constraint on expanding Bangalore's water supply, the relatively prosperous farmers of the Cauvery command area have protested the tribunal award as a case of urban industrial interests usurping the water needs of irrigation. Pumping from Cauvery and Arkavathi river sources and through the distribution network requires a total of 60 booster pumps, 52 reservoirs in the city and close to 6,000 km of pipeline. The total energy consumed is approximately 50 GWh per month. Electricity charges alone account for Rs 280 crore annually (BWSSB 2011).

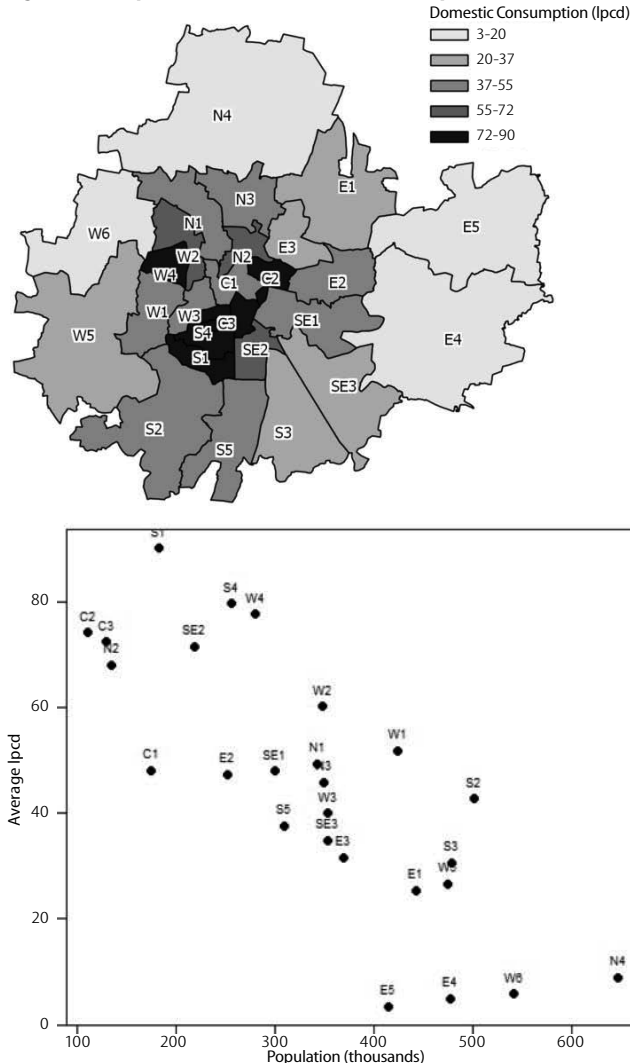
The city's water treatment capacity, at 810 MLD, is approximately on par with current water supply. However, sewage treatment and disposal is lacking largely due to the lack of an

adequate sewage network. Only half of an installed sewage treatment capacity of 721 MLD is utilised, whereas waste water is generated at 1000 MLD (Narain 2012b). The result has been the conversion of possible water sources – rivers and lakes in the Vrishabhavathi, Hebbal and Koramangala-Challaghatta valleys – into waste sinks and carriers, and the pollution of another water source – groundwater. Limited data on groundwater quality shows that some of the most contaminated sources correspond with areas in the city that are likely to depend most on groundwater (Reddy 2003).

3.2 Spatial Snapshot of the Pipe Dream

Using domestic water consumption data from the public water utility, BWSSB for the month of March 2011, we present a snapshot of this spatial mismatch and its implications. Since the highest available resolution for piped water supply information is at the BWSSB-subdivision scale and not at ward level, both population and per capita domestic water consumption are analysed at this BWSSB-subdivision scale. We used Geographic Information

Figure 5: Per Capita BWSSB Domestic Water Consumption

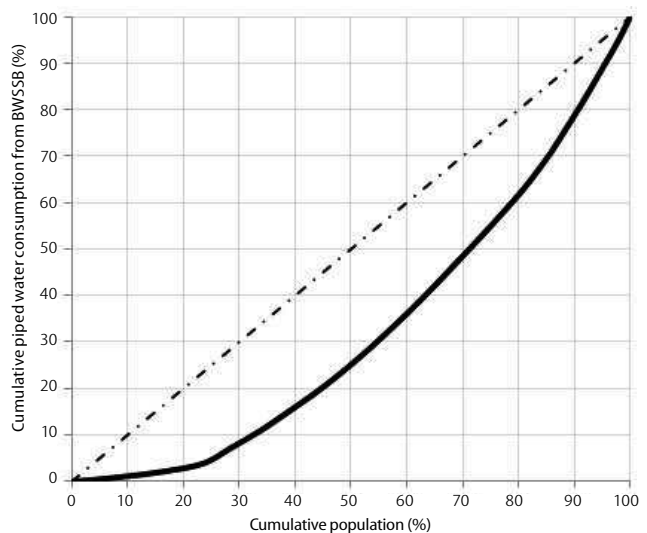


The top figure shows the spatial pattern of domestic consumption of piped surface water supplied by BWSSB in the month of March 2011 (data from BWSSB). The same data is plotted against subdivision population in the bottom figure where the X-axis represents subdivision population in thousands.

Systems (GIS) to develop subdivision-scale population estimates from the ward population geodata and subdivision boundaries.⁹ In Figure 5 we present a scatter plot of the average domestic water consumption (litres per capita per day, lpcd) in each subdivision against subdivision population, along with the spatial representation of the same. This startling graphic shows that on average, BWSSB supply for domestic consumption is very low, especially in the outer, newer wards where population growth has been very high. The often-quoted BWSSB average figures of 110-120 lpcd is a gross overestimate because it is based on total water pumped into the city and not what actually reaches customers after leakage. Its own estimate is that as much as 37% to 40% of water is lost to leakage at various parts of the transmission and distribution network (BWSSB 2011). Furthermore, there is considerable spatial variability. The peripheral wards that have grown much faster than the wards in the central city are also the wards that are least served by the public utility. The residents of some of these areas in the periphery of Bangalore also bear a disproportionate financial burden of extending utility-provided piped water through the Greater Bangalore Water and Sanitation Project (Ranganathan et al 2009).

Figure 6 sketches out the Lorenz curve for piped surface water supplied by BWSSB using aggregate subdivision level data. What this mapping makes clear, even with aggregate low-resolution data, is that at least 20% of Bangalore does not have any access to piped surface water simply based on their location within the city. The Lorenz curve is approximately parallel to the line of perfect equality for the next 60% of the population, and the top 20% of Bangalore consumes 40% of its piped surface water. This Lorenz curve underestimates the actual inequality among households because we are able to capture the variation between the 26 subdivisions of BWSSB, but not variations within a given subdivision. As we will show in the next section, this spatial inequality

Figure 6: Lorenz Curve for Piped Surface Water Supplied by BWSSB

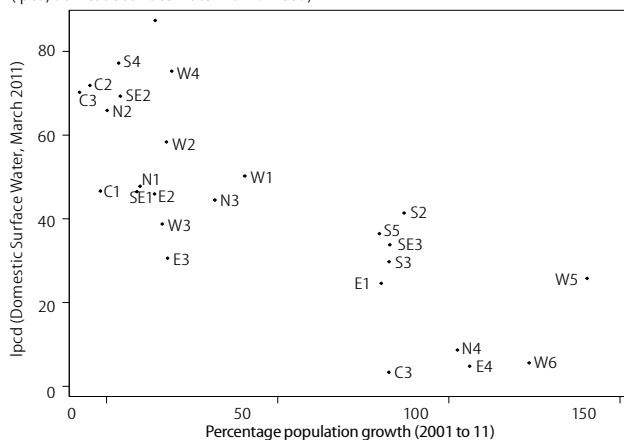


The solid black line is the Lorenz curve constructed using BWSSB data for the month of March 2011. The dashed-line is the line of perfect equality. The Lorenz curve represented here underestimates the actual inequality among households as this curve was obtained using aggregate data at the level of BWSSB subdivisions rather than individual households. We capture the variation between the 26 subdivisions of BWSSB, but not variations within a given subdivision.

in supply of surface water has important hydrological and ecological consequences, besides obvious political and economic consequences.

Figure 7 illustrates the spatial mismatch between the growth of Bangalore and its utility-provided surface water through a scatter plot of domestic water consumption (from piped surface water sources supplied by bwssb) and the percentage population growth in each subdivision between Census 2001 and Census 2011.¹⁰ The fastest growing subdivisions also contain the most populated wards in the city (as seen in Figure 2).

Figure 7: Average Domestic Water Consumption
(lpcd, domestic surface water from BWSSB)



The figure shows how the fastest growing regions of Bangalore (which also happen to be the most populated – see Figure 6) are least served by the piped surface water infrastructure of Bangalore.

Obviously, people in the peripheral wards are not getting by on less than 10 lpcd (the average domestic consumption from bwssb-supplied surface water sources in the eastern, western-most and northern-most parts of Bangalore). The World Health Organisation estimates an absolute minimum requirement of 70 lpcd to sustain a healthy life, and at least 100 lpcd for minimal additions to mere sustenance (WHO 2003). Even the 20% of the total population of Bangalore that lives in the central wards and accounting for 40% of all piped surface water supplied by bwssb consume less than 100 lpcd of piped surface water. To make up the difference, like in all Indian cities, water is consumed from a mix of surface and groundwater sources (CGWB 2011). A recent CGWB study estimates that approximately 40% of Bangalore's population depends on groundwater. Even in older parts of the city with better water supply infrastructure, people use a mix of sources including self supply drawing from groundwater – from private borewells, and from tankers. There is great variability even with the central 30 km² of Bangalore – with the groundwater fraction of water supply ranging from 1% to 51% of total consumption (Sekhar and Kumar 2009). Housing colonies, commercial and industrial establishments that have come up in extension areas are almost entirely dependent on groundwater. One estimate puts the number of groundwater-extracting structures at 1,50,000; and the size of the tanker market at about 2,800 tankers supplying 8.4 MLD or 10% of BWSSB water supply (CGWB 2011). However, a study by the Institute for Social and Economic Change (ISEC) in 2005 estimates that the number of

private borewells to be between two and three times higher, and the corresponding supply to be three times higher at almost 30% of BWSSB supply (Narain 2012b). Thus, the spatial mismatch between the patterns of population growth and the domestic water supply infrastructure has serious economic, political and ecological consequences that we illustrate in the next section.

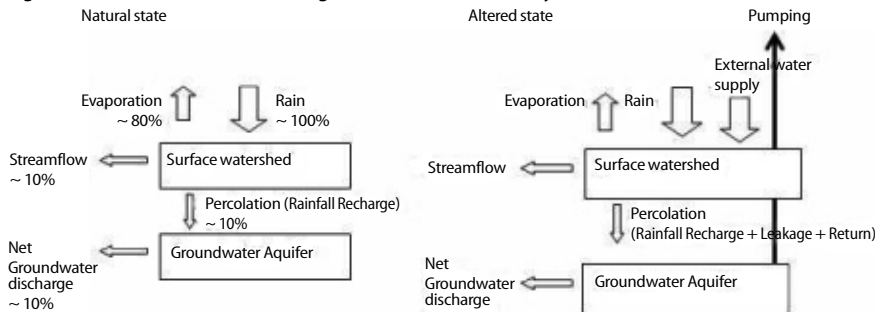
4 Socioecological Water Balance of Bangalore

How has this pattern of city growth, spatially skewed piped water supply and groundwater extraction affected the groundwater resource? There is evidence that it has affected both the quantity and quality of groundwater. From a quantity perspective, the CGWB has estimated a state of groundwater overdraft for the Bangalore urban district as a whole, at 142% of net groundwater availability.¹¹ From a quality perspective, 50% of monitored wells had more nitrate than the permissible limit (45mg/l) (CGWB 2011: 23). However, these impacts on groundwater – and therefore, the impacts on the urban population – are not spatially uniform. Another study shows that some of the most contaminated sources correspond with areas in the city that are likely to depend most on groundwater (Reddy 2003). Also, the central parts of the city, far from seeing overdrafts, are experiencing a rise in groundwater levels. This is shown in part by shallow groundwater levels (CGWB 2011; Sekhar and Kumar 2009) and in part from (limited) long-term monitoring data, which shows a rise in groundwater levels in areas where BWSSB supply is available or where no significant development has taken place (CGWB 2011). This is almost certainly a consequence of leakage from water supply, waste water and sewer lines. In contrast to the city centre, a number of observation stations in outlying areas (Bannavara, Doddakalsandra, Chikkajala and Talaghatpura) have dried up, falling below their screen-depth of 10m below ground level. In at least some of these areas, for example, in the south-eastern and north-eastern parts of Bangalore, depth to water levels is directly related to pace of development (CGWB 2011). However, as of now there are no long-term monitoring wells to quantify this effect at sufficient spatial resolution.¹²

4.1 Pedagogical Thought Experiment

The narrative above underscores the urgent need for situating urban water within a spatially explicit, metabolic framework because human and natural systems are tightly coupled in urban environments (House-Peters and Chang 2011). The first step in such a framework is a well-defined water mass balance (Kenway et al 2011), which we call a “socio-ecological water balance” to make explicit the coupled nature of the system. In India, the lack of data on both water demand and biophysical dynamics of urban environments severely limit such an approach – after all, “we cannot plan what we do not know”.¹³ Acknowledging this limitation, we present a thought experiment to clarify what a socioecological water balance of Bangalore could look like, one that can be refined in the future as data and knowledge accumulate.

Figure 8: Schematic of the Socioecological Water Balance of a City



We first consider the city as a whole. Figure 8 is a conceptual model of net groundwater recharge under two conditions for Bangalore – on the left, a “natural” state; on the right, the current state.¹⁴ The natural state is unobserved – it is the state of the water balance if the city did not exist, with no surface water imports and no groundwater pumping. Research in similar sub-humid to semi-arid ecosystems in peninsular India shows that, after rain has fallen, around 80% of it subsequently evaporates or is used by plants (transpires); the remainder is partitioned in roughly equal parts into stream flow and groundwater recharge as the rain percolates into the soil. In the natural state, the dominant source of groundwater recharge is rainfall-recharge. Urban environments drastically change this natural water balance, by adding new components – leakage and return flows add to net recharge; pumping subtracts from net recharge – and by modifying existing balance of components – built-up areas modify groundwater recharge and runoff.

In the absence of measured data, empirical formulae have been used for portions of the water budget. For example, Hegde and Chandra (2012) use empirical formulae to estimate groundwater recharge as a function of rainfall over built-up and natural landscapes. The weighted average rainfall-recharge from their paper evaluates to 3% for Bangalore under current (altered) state. For our lumped model of net groundwater recharge, under the natural state, we assume groundwater recharge at 7% of annual rainfall, which we set at 900 mm. In the altered state, there are two additional sources of artificial recharge – leakage from piped water supply, and return flows, and one source of extraction from groundwater – pumping. The following assumptions were used for the altered state. Total BWSSB surface-water supply and domestic consumption is 900 MLD and 334 MLD, respectively (March 2011 data from BWSSB). To convert to length units, BBMP boundary area of 700 km² was used. The simple water balance picture depicted above can be written out as:

$$NR = r_{nat} * P \quad \dots(1)$$

$$AR = r_{alt} * P + (l * Q_{supply}) + (l_{return} * Q_{cons}) - Q_{pump} \quad \dots(2)$$

where:

- NR = groundwater recharge under natural conditions;
- AR = groundwater recharge under altered conditions;
- r_{nat} = rainfall recharge factor under natural conditions = 0.07
- r_{alt} = rainfall recharge factor under altered conditions = 0.07
- P = rainfall;
- Q_{supply} = BWSSB total water supply ;

Q_{cons} = domestic water consumption;
 l_{return} = return flow fraction = 0.8 (from NIUA (2005)).

Q_{pump} = estimated net pumping

Since no systematic data is available on actual volumes of private pumping in the city, Q_{pump} was estimated by assuming a 150 lpcd uniform total domestic consumption and subtracting from it the BWSSB surface water domestic consumption. Also note that although infil-

tration and recharge would be affected by increasing built-up environments, for the purpose of illustration of possible impacts even under optimistic conditions, we retain the same recharge factor $r_{nat}=r_{alt}$ in both natural and altered states – in other words the results for groundwater recharge could be interpreted as upper limits of altered state recharge.

Table 2 summarises the results from this aggregated or “lumped” model for Bangalore, under three scenarios: the natural state; the altered state with leakage and pumping; and the fully altered state with leakage, pumping and return flows.¹⁵

Table 2: A ‘Lumped’ Water Balance for Bangalore for the Domestic Sector (mm/yr)

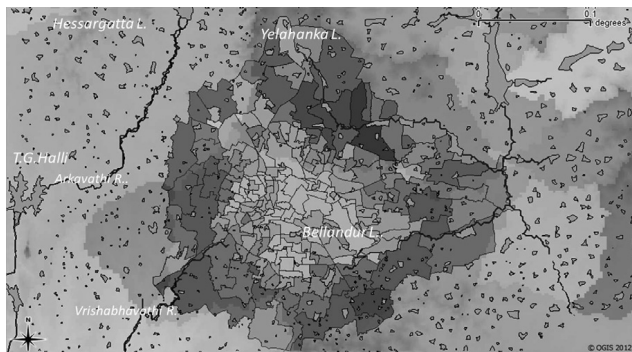
	Natural	Altered (No Return Flows)	Fully Altered (Return Flows)
Rainfall recharge	63	63	63
Piped supply leakage	0	140	140
Net pumping	0	-360	-360
Return flow	0	0	138
Net recharge	63	-157	-19

The first column shows the water balance for a hypothetical “natural” state in the absence of the city (with no surface water imports and groundwater withdrawals). The second column considers groundwater pumping and surface water imports but no return flows; and finally the last column includes return flows. As seen from the second and third columns, the artificial recharge from the BWSSB infrastructure exceeds annual rainfall-recharge. (Water supply and domestic consumption data are from BWSSB, rest is authors’ calculations).

Table 2 highlights that Bangalore as a whole is in a state of groundwater overdraft, echoing recent independent estimates by Hegde and Chandra (2012). Further, two important aspects of the socioecological water balance of Bangalore stand out. The first is that artificial recharge leakage is very high, more than twice natural rainfall recharge – with the important difference that the leaking water is largely polluted. Similar patterns have been reported in other Asian megacities (Onodera et al 2008; Kim et al 2001; Hayashi et al 2009). As detailed in the introduction, the experiences of Seoul echo the second important message from Table 2: the high degree of sensitivity of recharge estimates to the fate of return flows. We have assumed return flows at 80% of consumption (NIUA 2005), but this analysis only includes pumping and return flows from the domestic sector. This means that leakage from piped water supply and its effluent components buffer groundwater extraction, but pollute the resource while doing so; further, whether they make up quantitatively for extraction from pumping will depend on the balance of pumping versus artificial recharge from all sectors, not just the domestic sector.

Continuing with this conceptual model, we now extend it to see what the socioecological water balance looks like in different parts of the city. The city core, at 930 m above mean sea

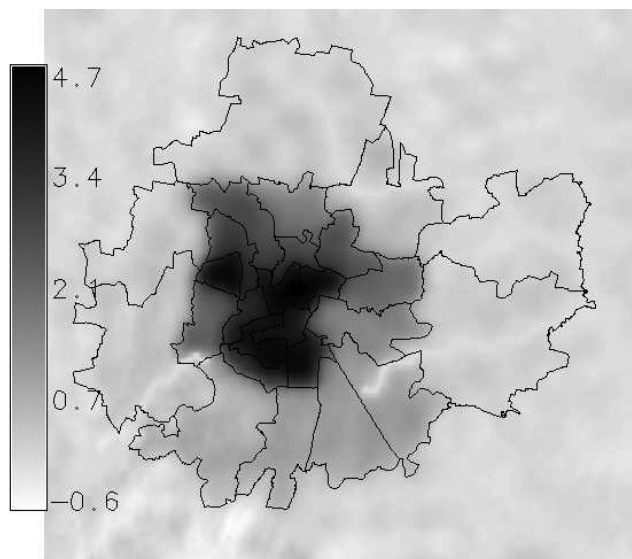
Figure 9: Bangalore 2011 Population Overlaid over Terrain, Watersheds and Waterbodies



level is on a divide that lines up on a roughly north-south axis lying between the Arkavathi River on the west, and the South Pennar to the east (Figure 9). The city sits on lateritic and red loamy soils. Below the soils are granitic landforms. Granite by itself does not conduct water, so any groundwater passage through this lower layer depends on how fractured the rocks are; the net result is low groundwater yields. Using the same assumptions as in Table 2 and Figure 8, we ran a GIS-based distributed groundwater model.¹⁶

The model was run for one year at monthly time step using natural and altered state conditions. We simulated groundwater recharge, extraction, and flow in natural and altered states, considering as before only domestic water use. Figure 10 shows the change in groundwater level from domestic consumption.¹⁷ In the central parts of the city, this analysis shows groundwater levels that are higher (shallower) than in the natural state by up to 4.7m. This is consistent with the trend documented by the CGWB for core areas of cities supplied by piped water supply (CGWB 2011). Although receding water levels have been reported

Figure 10: Groundwater Impact of Domestic Consumption



Predicted changes in groundwater depth relative to the "natural" state.

in the popular press and in qualitative narratives for the outer areas (ibid), our analysis does show only a slight lowering of water levels in outer areas from domestic consumption alone. We note however that pumping from industrial, commercial

and institutional sectors are likely progressively higher away from the city centre and that these could be lowering groundwater levels in outer areas.

With the data currently available, only conceptual models – such as the ones described in this section – are feasible. Nevertheless, the conceptual models are compelling and illustrate the potential value of further research. An important lesson learned from the preliminary spatial analysis above is that even though the aggregate impact of domestic water consumption on net recharge seems to be negative compared to the natural state, the spatial distribution of impacts is highly variable in magnitude and direction. Given the complex water supply and use within Bangalore, a better picture of the socio-ecological water balance can only emerge from a systematic, data-driven understanding of water demand across sectors and across multiple water sources.

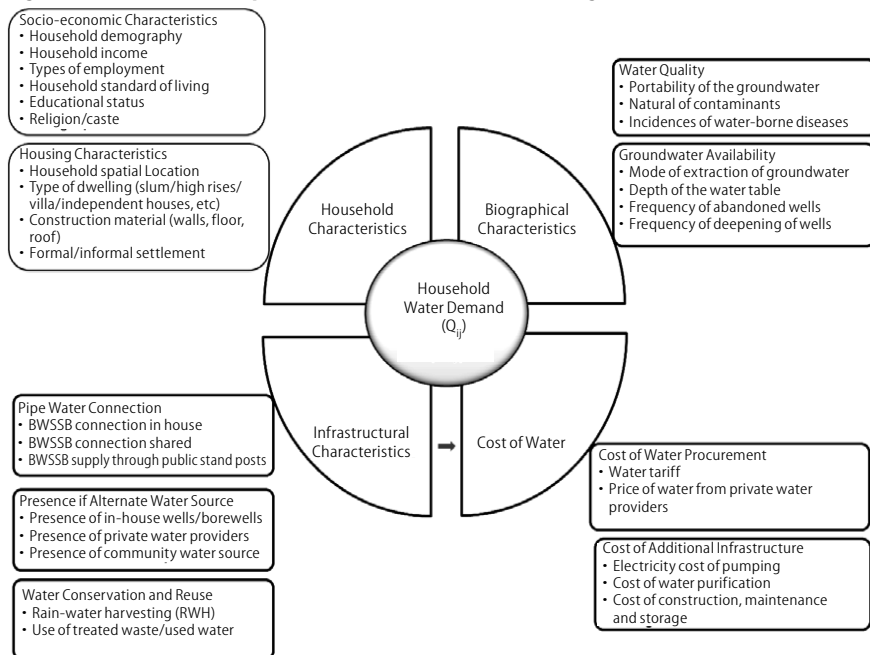
5 Refining the Metabolic Framework

Section 4 illustrated the social-ecological nexus, albeit with limited data. In this section we describe two key elements of the metabolic framework that we are currently working on that need special attention in the Indian context: one that is data-driven to fill in crucial knowledge gaps, and the second that extends the planning effort beyond simple trend analysis towards a scenarios analysis.

5.1 Robust Water Demand Models

A severe limitation of any planning is that we have no systematic idea of actual water demand across different sectors – domestic, commercial, industrial – within a city. In the case of Bangalore, we only have bwssb supply information. However, as discussed in this paper, private groundwater sources make up a large proportion of the domestic sector alone and groundwater sources account for the majority of the water consumed within Bangalore if non-domestic uses of water are also accounted for, as the public utility's core mandate is limited to supplying water for domestic household consumption. A crucial first step towards any comprehensive planning for water that is able to address all three aspects of social equity, ecological sustainability, and economic efficiency is the delineation of a comprehensive water demand model. A robust and spatially explicit demand model is needed for each sector of the city, for each distinct demographic, and for each of the many different water sources. Such a demand model is also vital for completing and refining the evaluation of the socioecological system illustrated in Section 4. A spatially explicit demographic model combined with a spatially explicit groundwater distribution model will be a better predictor of water metabolism in a city and will improve our understanding of the linkages between social and ecological systems as has been shown in some other contexts (Ostrom 2009; Anderies et al 2004; Janssen et al 2007).

Figure 11 (p 48) illustrates a schematic of such a comprehensive demand model. The authors of this paper are currently fielding a large city-representative household survey in Bangalore that attempts to obtain the most comprehensive source

Figure 11: Schematic of a Comprehensive Water Demand Model for Bangalore

Household water demand, Q_{ij} is the water demanded by household i from the source of type j .

explicit demand equation for domestic water consumption attempted in India. We are combining traditional quantitative household socio-economic profiles with physical measurements of water quality, water consumption, groundwater depth and household electricity consumption associated with domestic water use. We are sampling 1,500 randomly selected households in Bangalore such that our survey is statistically representative of the city not only on the usual social demographic variables, but also on hydrological, spatial, and infrastructure variables.¹⁸

5.2 Planning under Uncertainty – A Scenarios Approach

Current planning in the city of Bangalore must keep up with a rapidly expanding population on the city's periphery. But it is equally important to prepare for futures that look quite different from the present (Benjamin 2000). Dramatic drivers of population growth, like real estate and information technology booms, and industrial growth are not guaranteed (Wenban-Smith 2000). The kinds of uncertainties that we are describing are critical to Bangalore's development, in that their resolution strongly affects the way the future will unfold. The idea to explore futures through such "critical uncertainties" was developed by Pierre Wack at Shell in the 1980s (Wack 1985), and is now arguably the most popular way to construct scenarios (Bishop et al 2007). These kinds of uncertainties – which produce large changes – distinguish scenario planning from the more conventional trend analysis. Among the critical uncertainties identified at a workshop held at the Indian Institute of Management in Bangalore in February 2012, participants mentioned: Bangalore's importance in the global economy, the level of corruption, migration rates of both high and low-income earners, the evolution of urban-rural conflicts, and people's attitudes towards the environment.

Combining quantitative models with imagination, scenarios allow planners and other stakeholders to think through what could happen in the future and adapt their plans accordingly (Godet 2010). In the context of the spatially explicit metabolic framework that we have outlined, the scenarios approach can be integrated to model uncertainties in a manner that allows planners to see the impacts of these uncertainties on inequality and sustainability in addition to economic efficiency.

6 Conclusions

This paper documented how cities are tightly coupled social-ecological systems, using Bangalore's domestic water use as a case study. Our analysis of domestic water consumption in Bangalore underscored two principal components of a urban metabolism framework. First, any metabolic approach must consider

not only resource flows into the city, but also waste flows after resources have been consumed. We demonstrated how return flows (flow of used water to the underground aquifers) and leakage flows from imported river water brought into the city are crucial to understanding depletion of groundwater. Second, we showed how urban metabolism is an inherent spatial problem. From both biophysical sustainability and social equity perspectives, it is crucial to delineate the spatial variation in resource flows.

The current clamour for privatisation and PPPs as the solution to urban India's water woes disregards the central precepts of urban metabolism. The privatisation and PPP experiments in various cities have so far exclusively focused on water supply, while disregarding the sewerage side of the problem (Narain 2012c). This is not surprising as water supply is financially more lucrative than processing a city's sewerage. However, this not only further ruins the fiscal health of public water utilities (who are now starved of water supply revenue), but will also result in two separate entities being responsible for what is physically and ecologically a unified flow. An urban metabolic framework can thus help uncover the nexus between economic efficiency, social equity and biophysical sustainability.

The urban metabolism framework discussed here can also help understand the potential conflicts between cities and the surrounding countries by situating the urban space within the larger regional context. Bangalore has been awarded 1,425 MLD of water from the Cauvery River as part of the Tribunal formula used to allocate water between various riparian interests. This represents nearly 5% of the total water available in the river. With the domestic demand already exceeding the maximum water it is allowed to draw from the river, any further growth in the city will

only exacerbate the pressures on groundwater. By treating the city as a tightly coupled social-ecological metabolic system, the framework presented here can help planners move beyond a narrow focus on continuous augmentation of utility-supplied water. For example, in the pedagogical groundwater model that was discussed in the paper, we assumed that

Bangalore's domestic water needs are entirely met by imported surface water and groundwater. However, it is simple to use the scenarios approach discussed here to understand measures like recent bylaws mandating rainwater harvesting, reuse of treated water for non-potable uses, and other conservation strategies.

NOTES

- For an example of how the social metabolism framework (Fischer-Kowalski and Hüttler 1998, 1999) has been used to study the political economy of resource use, see Martinez-Alier (2007, 2009).
- Provisional results from Census 2011.
- For recent evidence in the Indian context, see Vithayathil and Singh (2012).
- For example, it is local and state-level land-use decision-making that led to a loss of some 30% of Bangalore's lakes and other waterbodies between 1973 and 1996 (Narain 2012b: 317). Zoning and instruments such as floor area ratio (FAR) have far-reaching impacts on growth patterns (Sridhar 2010, 2007).
- See Ranganathan et al (2009) for a detailed account of the great diversity among the new areas added to BBMP in 2007, and its implications for extending piped water supply to these new areas.
- The 2001 population numbers that are presented here and in the remainder of this paper have been corrected such that both 2001 and 2011 population numbers correspond to a common geographic frame. The 2001 population simply represents the number of people enumerated by Census 2001 inside the current ward boundaries.
- This original source of piped water to Bangalore is no longer functional as the Hesarghatta lake has dried up.
- The planned BWSSB installed capacity is 1,400 MLD or 95% of the 600 cusecs cap mandated by the tribunal award.
- In estimating subdivision population we computed the intersections between subdivision and ward boundaries and allocated ward population between intersecting subdivisions assuming uniform population density. An estimate that accounts for actual land use patterns is unlikely to make any significant material difference to our estimates for two reasons. First, the assumption of uniform ward population density is a very good assumption for the central parts of Bangalore. Second, for the newer areas incorporated into Bangalore (where there is significant diversity in land use patterns), the intersection geometry between wards and subdivisions is such that majority of these wards are wholly contained within a single subdivision.
- Even after controlling for 2001 population and subdivision slum population the regression of domestic-lpcd and population growth (between 2001 and 2011) yields a negative coefficient ($p < 0.000$).
- Also cf Hegde and Chandra (2012).
- Since 2010, the Department of Mines and Geology has added monitoring wells at 12 locations around the city: however, historical and existing monitoring is nowhere near the spatio-temporal resolution that is required to comprehensively understand Bangalore's groundwater system.
- Olcay Unver, UN World Water Assessment Programme, cited by Gilbert (2012).
- Soni (2003), attempts a similar conceptual "lumped" water balance for Delhi.
- For simplicity, we consider only domestic withdrawals in this conceptual model and do not change the rate of infiltration in the altered state.
- We used the GRASS GIS (Neteler and Mitasova

2008) module r.gwflow. The module solves for each cell, groundwater flow partial differential equation of the form:

$$(dh/dt) \cdot S = K_x \cdot (d^2h/dx^2) + K_y \cdot (d^2h/dy^2) + q$$

where:

h: piezometric head (m);

dt: time step for transient calculations (s);

K_x, K_y : hydraulic conductivity in x and y directions respectively (m/s);

q: source or sink flows (m/s);

S: specific yield (-)

For hard rock aquifers, hydraulic conductivities and specific yields are very low. We assumed a fully penetrating, homogeneous unconfined aquifer formulation with parameters $K_x = K_y = 0.5 \text{ m/day}$ and $S = 0.0075$. q was set to the net recharge term, estimated spatially from equations (1) and (2). Monthly rainfall data for Bangalore were extracted from WMO. http://grass.fbk.eu/gdp/html_grass63/r.gwflow.html and divided the city into 90m resolution pixels.

- Technically, the figure shows change in groundwater head, which is the level to which the water would rise (or fall) if a well were dug at that point.
- The survey results are likely to be available in the middle of 2013.

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Survey

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Econophysics: An Emerging Discipline

by

Sitabhra Sinha, Bikas K Chakrabarti

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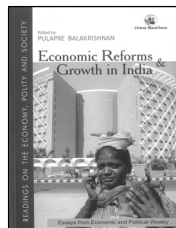
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