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Abstract

Despite urban areas covering less than 1% of the world, they host over 50% of the world's population. As population and human activities expand they exert heavy environmental pressure through the resource requirement, their production and consumption. Hence, it is important to understand the resource flows into the city, the transformations that take place and the resulting products and wastes. One method of measuring resource use efficiency is through the analysis of urban metabolism. It provides a good analytical framework for accounting of urban stocks and throughputs and helps understand critical processes as well (increasing or decreasing ground water resources, long-term impacts of hazardous construction materials, etc.). We have considered Mumbai, a business and industrial city, with a population of about 18 million, as a case study. It highlights the economic, social and environmental conditions of the city. On the input side, water, energy, food and construction material use are taken into account, and on the output side, wastewater, air pollution and municipal solid waste are examined. From the methodological point of view, it is easier to examine the input side but there are some difficulties from the output end. Similar difficulties can be found in the identification of built-in material stock (buildings, roads, etc.). The material stock is limited to building stock and passenger vehicle fleet. The concept of urban metabolism is put forth as an organizing concept for data collection, analysis, and synthesis on urban systems. The main findings and recommendations of the case study underpin efficient resource urban policy and design, as well as enhance sustainable production and consumption.

Keywords: Efficiency, Flow, Metabolism, Resources, Urban

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1.INTRODUCTION

Large urban agglomerates, referred to as mega cities, are increasingly becoming a developing world phenomenon. They will affect the future prosperity and stability of the entire world. The socio-economic and ecological footprint of mega- and million plus cities is far bigger than the actual territory they hold. Cities take up less than 2% of the earth's surface, yet use 75% of its resources (Monto and Reddy, 2011). With unlimited power (both economic and political, money and muscle), and opportunities, which cause envy to rural counterparts, the important issue in the 21^{st} century is the "Urban Challenge". This has come into focus most recently. This is because increasing urbanization results in asymmetric patterns of resource utilization resulting in the degradation of the environment. The problems of mega-cities include: (i) explosive population growth due to migration, (ii) alarming increase in the use of resources, (iii) massive infrastructure deficits in the delivery of communication services and transportation resulting in congestion, (iv) pressures on land and housing, and (v) environmental concerns, such as contaminated water, air pollution, etc.

The unsustainable pattern of resource consumption offsets the natural cycle of life. Resources like food materials, energy, and water are consumed and waste that ecosystems cannot process is dumped. This results in the consumption of large amounts of natural resources and species to exhaustion and even extinction which results in irreparable damage on the ecosystem (Deker et al, 2000 and Adamo, 2002). In order to increase the efficiency of use and reduce wastes, the first step is to find out the quantity of actual inputs into the city, the outputs that are coming out and the impact they actually make. Motivated by this alarming situation and dearth of comprehensive studies in India, this study brings out the dynamics of urban metabolism for different domains like energy, water, land, populace and waste. The author has used the "metabolism" as a metaphor to describe the physical exchange processes that is taking place and quantified the physical inflows and outflows to urban systems (Wolman 1965). The importance of the study is many fold. Firstly, the metabolism parameters provide the magnitude of resource exploitation and waste generation which can be used to study urban sustainability. Secondly, metabolism provides measures of resource efficiency and help in identifying opportunities to improvement. Thirdly, it provides a comprehensive accounting of the stocks and flows through cities which in turn help understand critical processes such as rising or falling ground water tables, accumulation of solid wastes and the long-terms impacts of hazardous materials stored in the building stock (Kennedy et al, 2011). Hence, it is pertinent for urban policy makers to understand the metabolism of their cities, to consider to what extent their nearest resources are close to exhaustion and, where necessary, develop appropriate strategies to slow exploitation.

Paying attention to urbanization is important since cities are the key to social and economic development (for example, Mumbai generates 6 per cent of India's GDP and contributes 60 per cent of custom duty collections, (Anon, 2011)). Also, mega cities offer new market opportunities to both the developing and developed world alike. Hence, it is important that mega cities of the developing world, confronted by many unsolvable problems, have a crucial need for policies and approaches that must be devised. The basic aim of this paper is to establish the metabolism of Mumbai, a typical Indian city where data are available and analyse the way the resource inputs are transformed into useful outputs and wastes. The impacts of various activities are generally not systemically quantified and managed. The present analysis provides the quantitative exploration of inputs and outputs of energy, water, nutrients, raw materials and wastes. The resource flow approach discussed in this paper would encourage urban planners to recognize the flows and stocks of the many resources within the boundaries of cities; assume management objectives to make more effective and efficient use of these resources to contribute to sustainability; and adopt appropriate policies, fiscal and legal instruments to achieve the new objectives. This will promote efficient utilization of resources, equity and participation, create opportunities for all sections of the society, provide basic amenities, better infrastructural facilities and reduce environmental degradation.

2. METHODOLOGY OF THE STUDY

Economic activity in urban regions is based on the continued availability of resources. Past efforts at the improvement of urban environmental quality have typically concentrated on the protection of environmentally sensitive areas. However, sustainable development must be more than merely `protecting' the environment; it requires a paradigm shift−economic, social and environmental. Studies on urban metabolism are crucial for helping on target setting, performance reviews and facilitating communication among policy makers, experts and public (Kuik and Verbruggen, 1991). The first such urban metabolism study was carried out by Wolman (1965). Wolman believes that cities, like organisms, need energy and resources such as fuel, water or food as inputs to sustain life. These 'metabolic inputs' are processed and ultimately released back to the environment as wastes. Hence, the basic rationale behind the urban metabolism concept is that the relationship between the environment and an urban system can be described by systematically recording *all* flows to and from the environment in physical terms. In 1978, Newcombe and his colleagues published a study on input–output of material flow in Hong Kong (Newcombe *et al*. 1978). Warren-Rhodes and Koenig pointed out that the per capita food, water and material consumption plays a significant role in urban sustainability (Warren and Rhodes, 2001). Newman studied the increasing trends of per capita resource input and waste production in Sydney (Newman *et al.* 1996). Similar studies were conducted for Tokyo (Hanya–Ambe, 1976), Vienna (Hendriks *et al*. 2000), Cape Town (Gasson, 2002), and Tipperary Town, Ireland (Browne *et al*. 2005). Analytical studies of urban ecological footprint were prepared for Vancouver (Wackernagel–Rees, 1995), and Cardiff (Collins et al. 2006). For the present study we have followed the materials flow analysis of the pioneering works of Baccini and Brunner (1991), Hendriks *et al*. (2000), Warren-Rhodes and Koenig (2001), and PomÃ¡zi and SzabÃ, (2008). The approach is scientifically valid (based on principles of conservation of energy and mass), representative, relevant to urban planners and dwellers, based on data that is comparable over time, understandable and unambiguous. In addition, it is a useful tool for early recognition, for priority setting, for effective policy making and for communication. As a tool for early recognition, this approach helps in highlighting potential future problems by demonstrating changes in flows and stocks of the city. However, the major limitation of this study is that the framework focuses only on the biophysical environment with less emphasis on social and economic issues (eg., health, employment, income, education, housing).

The concept of urban metabolism illustrates the interactions between the city, the human environment and the biophysical environment. The city in order to function, requires inputs of resources such as water, energy, food, fresh air and money, and generates a wide range of outputs including goods, services and wastes. The urban system concept also emphasises that the city's impact (for example in the area of resource needs and disposal of wastes) goes beyond its boundaries. Hence, the rationale behind this concept is that the relationship between the environment and an urban system can be described by systematically recording *all* flows to and from the environment in physical terms (Figure 2). From the figure we can identify the inputs, stocks and useful outputs and wastes. In this model, it is possible to specify the physical and biological processes of converting resources into useful products and wastes. It is based on the laws of thermodynamics, which shows that anything that comes into a biological system must pass through it and that the amount of waste is therefore dependent on the amount of resources and its efficiency of use. Sustainability of a city depends on the reduction of metabolic flows, i.e., resource inputs and waste outputs. This will result in increasing human liveability including social amenities and health. The approach can be applied to a range of levels and activities. For example, industrialists can examine the input of resources and the output of waste while measuring usual economic parameters and other issues like worker health and safety. Using this approach, an urban planner can make comparisons among various cities by analyzing indicators for resource use, waste, and liveability in other cities and suggest policies (Newmann, 1999). The relevant data have been collected from various secondary sources such as journal papers, books, reports of the government, various government agencies, international agencies such as World Bank and United Nations, non-governmental organisations, and research institutes. Further, efforts have been made and discussions were held with experts from stakeholder organizations, research institutes working in the area of urbanisation, NGOs, planners, policy-makers, etc., to substantiate the information thus gathered.

3. MUMBAI—A CASE STUDY

The city of Mumbai was established by the Portuguese (a group of seven islands that formed a sheltered harbour) and was given as *dowry*, more appropriately, *wedding* gift for Catherine of Braganza (wife of King Charles II of England). The British developed it as a port and a trading centre. In early days, textile industry was established and labour was drawn from the surrounding countryside. A ‘Chawl’ system was developed for housing the labour which has its impact on Mumbai’s ethos and life perspectives even today.

The Greater Mumbai urban agglomeration is the largest in India in terms of population and has the distinction of being among the largest cities of the world. The share of Mumbai in the state of Maharashtra area is only 0.16%, but it is a home for 16.4% of the state's population. Mumbai's population, as of 2011, stood at 18.5 million (10 per cent of India's urban population). The result is a very high population density (30, 510/km^2) which is 90 times higher compared with the state as a whole. The total area of the Mumbai metropolitan region, excluding Mumbai city, is 3,887 sq. km. This includes residential and commercial buildings (40%), forests (35.6%), and roads (9%). It has a good public transportation and water supply system which hold significance for the economy. Nine million passengers commute every day using mainly the public transport system (train and bus services) and the vehicle population is about 1.55 million. Migrants comprise about 17 per cent of the total population. Mumbai climate is tropical with temperatures in 20–38°C range (Table 1).

Mumbai generates nearly 6% of India's GDP and two-thirds of government revenue. Its per capita income (Rs. 150,000) is over two times that of the rest of India (Anon, 2011). It is the administrative and commercial center of the state of Maharashtra with the headquarters of many national and international enterprises being located. It is also the seat of manufacturing industries, more particularly electro-technical. Along with these, the concentration of docks, trading posts, and government offices led Mumbai to be a life-line of India resulting in an increase in population at an unprecedented scale. Those who can not afford a home have turned into squatter settlers. Over half of the population of the city lives in slums and the wealthy (top 10%) reside in the rich southern.

4. RESOURCE FLOW

Urban regions can be regarded as global centres of production and consumption and draw resources from around the world needed to provide essential services such as power, water and communication. The development of urban areas–whether expansive or compact with or without public transportation─determines resource consumption and thereby the global sustainability. For the present study, estimates of inflows of food, water, energy and construction materials to Mumbai are provided. Flows and stocks of other goods and services are not included due to lack of data. Each subsection describes the methodology used to obtain the estimates.

4.1 Construction material

Resources like fuel and water are transformed into useful output and waste which ultimately leave the city where as, the bulk mass of construction inputs remain in the city, either as building stock or as landfill. Material inputs to cities are generally less well quantified than say energy or water inputs, despite their significance to urban infrastructure. Major materials include: cement, reinforcement steel, bricks, sand and coarse aggregate. It has not been meaningfully possible to obtain the exact data on the quantum of construction materials produced and the related material resources consumed. Using the annual consumption of construction materials in India. Monto and Reddy (2011) estimated the quantity of various materials consumed in Bangalore. Using these estimates, we have arrived at the figures for Mumbai. These figures have been cross-checked with the Builders Association, Mumbai and log books of the weigh bridges at the entry points of Mumbai. Taking all the three estimates into consideration, we have arrived at the consumption of various materials used for building construction in Mumbai (with a 10% error).

Table 2 shows the material input to Mumbai in 2010. The use of construction materials in Mumbai is 17.4 million tonnes amounting to a per capita annual consumption of one ton. It is important to note that aggregates used in concrete and mortar account for 60% of total construction materials consumed and are derived from river beds and rocky outcrop. This imposes a significant environmental price on aggregates, which is usually not accounted for. The yearly material inputs included 9.19 million tonnes of cement, 3.16 million tonnes of steel, 0.46 million tonnes of timber, 0.05 million tonnes of glass; and 2.56 million tonnes of sand.

Between 1990 and 2010, the stock of dwellings increased significantly. According to Government of India Census, the dwellings increased from 2.4 million in 1990 to 4.1 million by 2010. Such increase in dwelling population has increased construction activity thereby increasing the demolition waste. Waste in the construction industry is important not only from the perspective of efficiency, but also concern has been growing in recent years about the adverse effect of the waste of building materials on the environment. This kind of waste typically accounts for between 15 and 30% of urban waste (Meghani *et al*, 2011). Building materials waste is difficult to recycle due to high levels of contamination and a large degree of heterogeneity, and often there is insufficient space for its disposal in large cities. For a material of 17.4 million tonnes, annual waste that is generated in Mumbai works out to 1.5 million tonnes.

4.2 Food

Estimating the consumption of food in cities is difficult due to the complexity of the production and delivery systems. Very little information is available on the flow of food through cities despite its significance to human sustenance. Hence, the data from the National Sample Survey were used for this purpose. It was assumed that the average resident of the Urban Maharashtra consumes the same way as the average citizen of Mumbai. There might be disparities in food consumption in urban regions that depend on cultural background, socio-economic status, lifestyles and consumer behaviour. Hence, a reference to "average" urban food consumption may be misleading. However, since the focus is on the total quantity of food consumed and its impact, we have used this “average” figure. The NSS divides the food items into 150 classes and we have categorised them into eight. Categories one and two relate to cereals and pulses, categories three and four to fruits and vegetables, category five to solid food (meat, poultry, fish and seafood), category six relates to dairy products (milk, butter, eggs and cheese) and category seven to processed foods and the final category to beverages. Consumers have specific needs with regard to their food. With intensive urbanization, the food systems are becoming complex and very large volumes of food move through the systems. In general, low-income houses use more cereals and pulses while high-income groups consume more animal products and vegetables.

Table 3 provides information on the food consumption of Mumbai. It shows that the consumption of cereals, vegetables and dairy products constitutes roughly 50% of food consumption. The per capita food consumption is about 43 kg/month (cereals (8.27), meat (3.3) and fruits (4.8)). On an average, Mumbai consumes 26,185 tonnes of food materials per day and generates 8,815 tonnes of waste. This means that about 30% of the food brought into the city does not find its way into human stomachs but ends up as garbage in landfills. In a country of potential food shortages this is an unacceptable way of dealing with food.

4.3 Water

Water can be considered as the largest component of urban metabolism. The bulk of Mumbai's water originates from lakes around the city. Mumbai is notorious for its leaking water pipes. Nearly 80% of the water output within Mumbai city is discharged as wastewater. This indicates the impact of water component on the sustainability of a city. In 2009–2010, households used 83.2 per cent of the water consumed in Mumbai (see Table 4) or 3,830 million l. The majority of households receive water through taps and a growing number through water tankers.

The per-capita residential water demand has been derived from the data supplied by utilities where the total volume of residential water supplied has been divided by population served. A large proportion of household water is used for purposes other than human consumption such as watering gardens, washing cars and other household activities. The proportion of indoor residential consumption going to each end use is based on figures from Shaban (2008). The data indicate that for a household using approximately 200 l/d, of which bathing, washing clothes constitute nearly half of the total. Toilet use consumes about a fourth. The waste water inside the households (excluding water used for gardening) includes the use in the kitchen, toilet, bath room, washing clothes and house cleaning. About 20% of the water is lost in leakages.

4.4 Energy

Energy flow analysis is also an integral part of an urban metabolism model since energy supply and consumption are essential to a proper functioning of the urban system. In the present study we focus on the patterns of energy use rather than taking into account the full range of natural resources used in production and consumption processes. Metabolic changes in the production of consumer items have significant impact on the indirect household energy use, but changing consumption pattern, has its effect on the structure of the production side of the economy (Carlsson-Kanyama and Karlsson, 2002*)*

For the present study, the inputs of solids (coal and fuelwood), liquids (various petroleum products such as petrol, diesel, fuel oil and ATF), gas (LPG and natural gas) and electricity are discussed. Most of the electricity used in Mumbai is generated elsewhere, much by thermal power stations and so an additional 20% can be expended in generation losses. Among the sectors, transport energy is a very significant component of total urban energy use; it accounted for 36% of total energy end use. Per-capita petrol consumption is closely related to urban form (as expressed by population density) and transportation characteristics.

There are various forms of energy consumption that should be measured within a city such as energy used for power generation, domestic use (cooking, water heating and appliances) and for industrial use and mobility. Table 5 provides information on the energy use pattern in Mumbai. During 2010, the household sector consumed 74.2 TJ of energy. Significant quantity of energy carrier consumption (30%) is for thermal use, predominantly for cooking and space cooling. Electricity accounts for all non-thermal uses including lighting, domestic/kitchen appliances, TV and other household goods, as well as for some space cooling and water heating. In the industry sector, energy is used for high-temperature and process-specific applications. Considerable quantities of steam are used for technical applications, as well as for space cooling and hot-water generation. Electricity and fuel oil are also used for these purposes. Non-thermal electrical uses are predominantly for motor applications, including pumps, fans, compressors (i.e., fluid handling, refrigeration) and motive power (e.g., drives, conveyors). There is also considerable non-thermal electrical consumption for lighting, office equipment and sector-specific applications. In the service sector, space cooling, cooking/hot-water generation, and lighting are important services. Transport sector uses mainly petrol and diesel. When looking at the useful energy, the per capita energy is only half of the primary energy which indicates that about half of the final energy that enters into the system goes as waste heat and emissions.

Urban energy use has significant environmental consequences. Its local impacts include 'waste' heat (i.e. degraded thermal energy), particulates and gases such as CO and SO_2. At present, Mumbai consumes around seven million tonnes of oil equivalent to producing some 20 million tonnes of CO_2. In addition other wastes are also emitted into the atmosphere by various industrial processes.

4.5 Solid waste

Appropriate waste management is one of the key conditions for sustainable urban regime. Until now, the interactions between urbanisation and waste management activities have not been discussed in detail. This is due to the fact that waste management is often underestimated as a global problem and faced as a national or local one by most decision makers and institutional bodies. Also, waste recycling and recovery activities are usually dealt with in the framework of the economy and resource management even when the environmental benefits are highlighted. Increasing waste volume is not just a waste management issue; it reflects on the inadequacy of methods of producing and consuming products and goods. Waste represents not only an environmental threat but also a loss of valuable resources and energy that could be reused or recovered. Hence, it is important to monitor waste flows, and the diversion of waste to reuse and recycle.

In Mumbai, the quantity of municipal solid waste collected in 2010 was 15050 tonnes/day (0.81 kg per capita). The waste is from residential, commercial and industrial sectors, as also from construction and demolition waste. The share of residential waste is the highest with 58.5% followed by construction and demolition waste at 27.3% (Table 7). With further population growth, disposal of residential solid waste is likely to increase further. These wastes are either dumped in landfills or used for electricity generation. In Mumbai, over 60% of solid waste ends up in illegal dumps and about 6% is burnt. Urban waste management is a serious problem in the space-constrained cities.

4.6 Air pollution

A vital part of the urban metabolism is clean air, but effective metabolism also requires a constant source of energy, which often conflicts with the goal of maintaining clean air. Cities draw resources from large distances and also accumulate large amounts of emissions. A large part of the increasing amount of carbon dioxide in the atmosphere is attributable to combustion in the world's cities. In addition, most rail, road and aircraft traffic occurs between cities. Virtually all the world's climatologists agree on their concern about climate change, resulting mainly from fossil fuel burning enhancing the natural greenhouse effect. Pollution also has externalities which are regional and often transboundary. The externality occurs when pollution (e.g., acid rainfall effect, GHG emissions) created by a city is transferred to another place and the inhabitants incur additional costs due to treatment and the sufferer has no economic recourse to recover the cost from the polluter.

The air quality of Mumbai city is recorded on a frequent basis at several stations. However, it does not include open sources such as roads, landfill and construction sites. The coal-fired power generating station in Mumbai is a major source of critical pollutants, in particular, sulphur dioxide and nitrogen oxides. Transportation is another source of several pollutants. Fuel combustion, especially from wood and coal (industrial use) is also significant. Transportation accounts for over 60% of NO_X, and 70% of CO and HC emissions. Fuel combustion, especially from wood, accounts for over 50% of the particulate matter releases. The total pollutant load is 580 tonnes per day (NO_x, HC, CO and particulates (excluding CO_2)) with a per capita of emission of 1.18 kg per year (Table 8).

4.7 Flows and stocks of the city of Mumbai

Urban metabolism consists of the entire input of resources used by the inhabitants resulting in waste as output. The present day cities tend to have a linear rather than a circular metabolism[1]. Many materials are used only once which then end up in a landfill and there is no proper mechanism of recycling. With ever increasing population, the resource consumption increases and there by the waste. Every new decade brings in an additional three million to the existing population resulting in greater resource needs and waste generation. The use of the methodology developed earlier made possible the quantification of Mumbai's resource balance for 2010 (Figure 2). The resource inputs totalled at 1700 million tonnes in 2010. The same year, industrial and municipal wastes totalled 625,000 tonnes.

Table 9 reflects the resource efficiency of Mumbai with inputs, consumption and outputs in selected material flows. This urban metabolic flow naturally exceeds production rates and CO_2 fixation rates. The total material resources consumption in 2010 stood at 1700 which is 20 times higher than food requirement (human metabolism, 9.6 MT yr^{-1}). Fossil fuel emissions are 0.3 million tonnes and solid wastes 5.5 million tonnes. The amount of materials added to Mumbai's material stock totalled about 17.4 million tonnes (55.6%). Quick consumption materials such as food represented about 30% (9.56 million tonnes) of the total input into Mumbai. Renewable

[1] Circular metabolism is the one where every input is also able to renew and sustain the living environment by recycling the outputs.

resource consumption (biomass) made up only 1% of the total consumption and the remaining portion was made up of various fuels. This large gap between renewable and non-renewable resource consumption may reflect on the socio-economic phenomena that is happening in urban regions. In the same year, industrial and municipal waste totalled 5.4 million tonnes. Additionally, the amount of substances in air emissions was 0.26 million tonnes.

5. DISCUSSION

The most noticeable feature of Mumbai's metabolism is that more materials and energy are coming into it than are leaving, and these materials are coming from farther and farther places. This indicates the need for improvements to the utilisation efficiency of various resources which require enlightened policy and wise investments. There is another dimension to this. The metabolism accounting not only enables us to track what goes in and out of the cities. It also includes what stays inside: in buildings, soil, and people. For example, 85% of all construction material inputs to Mumbai never leave the city. Another issue is about finding ways to "give back" nutrients to surrounding rural areas—from waste water or food waste. Instead, cities like Mumbai handle waste differently, relying on landfills and incinerators. It is time for the planners to think of urban-to-rural nutrient transfer practices.

However, the greatest concern is from the transport sector (diesel and petrol) which consumes the largest share of energy. Transportion is becoming increasingly less efficient owing to the increase in personal transport. This inefficient form of use which creates automobile dependency comes at a greater expense. For example, personal vehicle, particularly car, costs Rs. 3 per person-km, compared to Rs.0.9 per person-km by bus and Rs.0.2 by local train (Reddy, and Balachandra, 2012). As a result of this, the fuel use is high and so are the CO emissions. Reducing the emissions would be a challenge for the authorities. A vast quantity of resources is stored in the built environment, and the material inputs and outputs associated with this accumulation impact the natural environment. For example, construction and demolition accounts for about 10% of all the wastes. Accumulated stocks reflect the built form intensity while material flow data provides a measure of material efficiency. But to quantify the *overall* environmental impact of planning and design decisions, additional analysis is required. Also, building material accounting data provide inventory but to study the impact on the environment a life cycle assessment is required. Per capita consumption of food is not high when compared to other urban regions of India. The per capita water consumption is high and the city also has a high per capita discharge of wastewater. This is because the level of treatment is not good and the city faces serious sewage problems. Reduction in solid waste can be achieved through increased recycling and of wastewater through improved treatment facilities.

Even though metabolism studies have a great potential to influence policy these are not being mainstreamed into the toolbox of the urban planner. Governments, particularly from the West, are recognizing the value of urban metabolism through benchmarking studies and indicator-based approaches to monitor progress of their programs and policies (Ward, 2007). The indicators of change related to resource use can be evaluated over time using baseline measures. The changing urban metabolism due to drivers of resource supply and use can be attributed to changes in industrial development, urbanization or lifestyle. Specific indicators can be drawn from resource flow analysis so that particular policy instruments can be used more effectively. The resource accounting indicators derived from metabolism approach are valuable for policymaking since traditional environmental and sectoral indicators are difficult to attribute to a social and economic process. The resource utilisation data raise awareness among various stakeholders such as the general public, government and industry/commercial establishments and can elucidate the inefficiencies of resource use in the system. This makes material flow analysis a very useful tool for actual policy support. The use of metabolism studies using the resource flow analysis can result in progress towards urban sustainability.

Using Mumbai as a case study, it is possible to develop a framework for arriving at metabolism models for other Indian cities. First of all, it is important to emphasize why such a tool is necessary for the policy makers. This is because metabolism is a tool that can be used for early recognition of the problem, setting priorities and timely policy making and communication (Sahely *et al.,* 2003). It would also be useful to think about how a metabolism that supports growth is different from one that doesn’t, or what kinds of growth can be supported with different “approaches” of metabolism. This would help make urban metabolism studies even more useful in the policy and planning processes.

6. CONCLUSIONS

Cities transform food and raw materials, fuel, and water in urban environment into human biomass, and waste. An analysis of urban energy and material flows as an urban metabolism will show the fundamental processes that govern the growth and functioning of a city. Information pertaining to urban inputs, outputs, and transformations of materials and energy shows the efficiency of the system. This provides significant insights into the underlying processes. Although socio-economic perspectives are important to analyze urban dynamics, technological approaches may also be useful, in particular by advancing our understanding of cities. The choice of approach can be determined by the final goal, which for many urban regions is to facilitate the sustainable resource use. In order to do this effectively, problems, such as resource scarcity, either through human or natural drivers, need to be addressed. As specific indicators can be drawn from the metabolism approach, particular policy instruments can be used more effectively, namely, initiating tailor-made resource service cost-recovery programs through use of targeted economic instruments

It has been suggested that that densely populated cities use land, energy and materials much more efficiently resulting in fewer negative environmental impacts. This hypothesis can be tested by comparing the resource-use patterns of various urban forms. If it is found that the benefits of compact cities out-weigh the costs, planners and policy makers can turn to such forms. Thus, metabolism approaches can enhance the decision-making process by helping planners identify areas of concern and impacts that can be made. This is especially true for Mumbai. By 2020, the population of the city is expected to reach 25 million. Until 1990s, the city used to have one of the best managed suburban transport systems. Due to lack of finances and the changing life styles of consumers, there is a continuous increase in the use of fossil fuels resulting in increased CO_2 emissions which points to inefficient urban form. It is important that the authorities monitor resource use trends and the discharge of outputs and develop appropriate and timely policy responses.

Experience with urban metabolism studies dates back to the 1970s. The earlier studies focused mainly on methodological development. Case studies well suited for evaluating the metabolism, particularly from the developing world, as a tool for policy decisions are still rare. Hence, the findings from this study can be regarded as first assessment. The vitality of cities depends on the symbiotic relationships with the surrounding rural regions and also from outside the country. As cities grow and technology transfer takes place, resources travel greater distances to reach cities. Hence to evaluate the full impact of urban metabolism a broad analysis is necessary. Policy makers should understand the urban metabolism and know if the resources such as water, energy, materials, and food are used efficiently or not. It is also important to undertake studies at the national level to understand urban driving processes.

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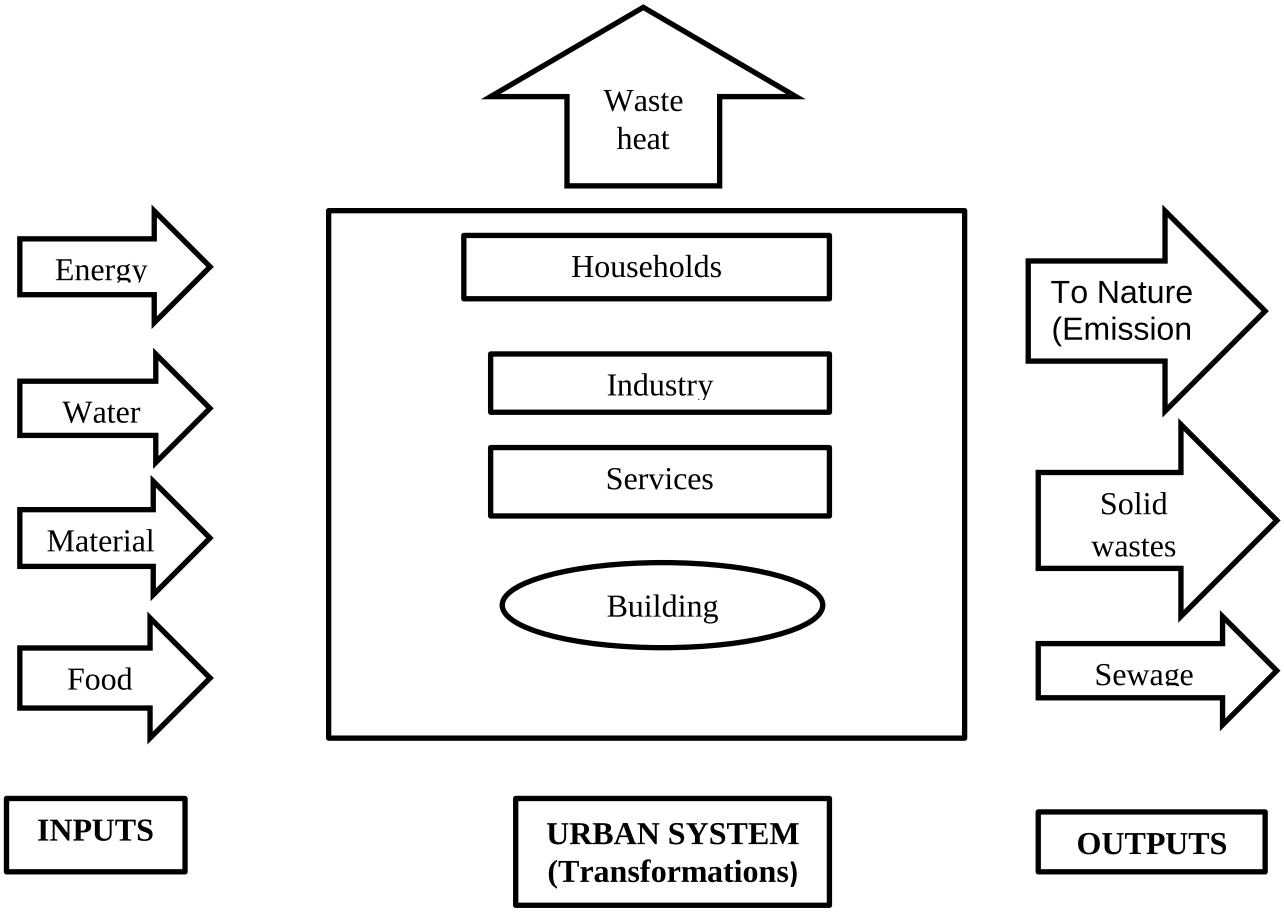

Figure 1: Concept of Urban Metabolism: Categories of inflows and outflows

Fig 2: Inflows and outflows of resources in Mumbai

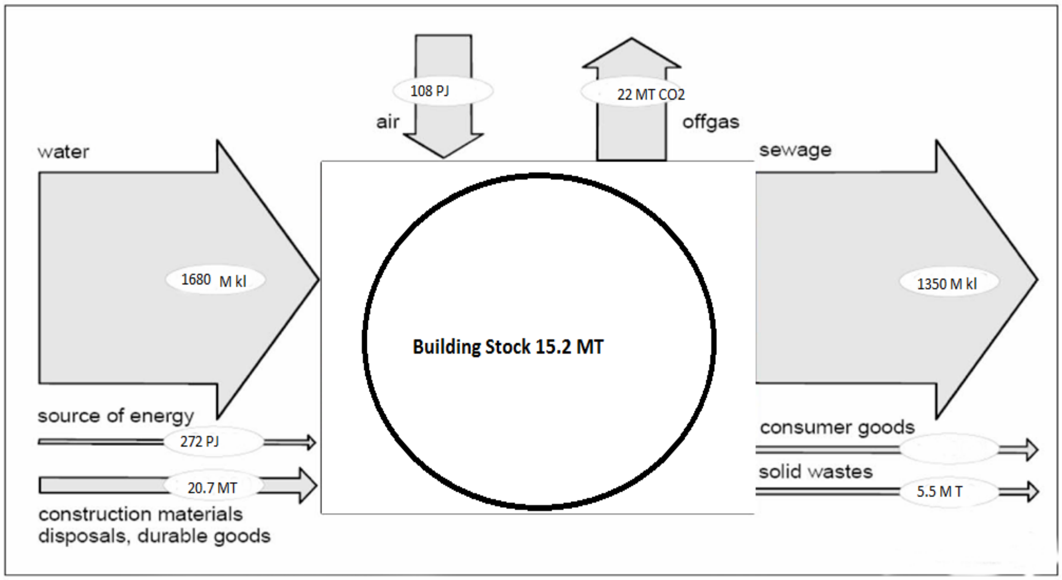

Table 1: Main economic, social and environmental indicators of Mumbai, 2010

Demography	
Population	
Population (Million)	18.4
Area (sq. km)	603
Population density (000/sq.km)	30.51
Slum Population (million)	10.12
Density (000/sq.km)	67.47
Rest (million)	8.28
Density (000/sq.km)	18.40
Inhabitant/HH (No)	4.5
Economy	
GDP (Rs. billion)	9800
Per capita (Rs.million)	0.53
Lowest 10%	18000
Highest 10 (million)	5
Passengers (Million)	9
Vehicle population (million)	1.55
Land use	
b. Residential Formal (%)	36.2
c. Residential Informal (%)	2.5
d. Business	11.5
e. Agriculture (%)	1.5
f. Transport /Roads (%)	9.5
Green cover (forest, coastal wet land, etc.)	35.6
Per capita green cover (m^2)	32.7
Wet land	1.4
Water body	1.8
Climate	
Tropical	
Average temp (summer)	20-38
Winter	17-25
Average rain fall (cm)	254

Table 2: Annual consumption of Materials

Material	million tonnes
Earth stone (+)	1.5
Burnt clay bricks (+)	0.04
Cement (million tonnes)	9.19
Steel	3.16
Aggregates (*)	0.05
Plywood/timber etc.	0.46
Glass	0.05
Aluminium	0.07
Paints	0.03
Ceramic tiles	0.26
Sand/year	2.56
Total	17.4
Construction and demolition waste	1.5

(*) Assumed a ratio of 1:5/6 (cement: aggregates);
(+) Volume is converted into weight.

Table 3: Food consumption

Category	Tonnes/annum	Per day	Per cap (kg/m)
Cereals	1836162	5031	8.27
Pulses & pulse products	202242	554	0.91
Vegetables	1778220	4872	8.01
Fruits	1065600	2919	4.80
Meat	732600	2007	3.30
Dairy	1385280	3795	6.24
Processed food	559440	1533	2.52
Other (including beverages)	1998000	5474	9.00
Total	9557544	26185	43.05
Waste		8800	1.5

Table 4: Water consumption

Use	Quantity (million l /day)	%	End use	Quantity (%)
Domestic	3700	80.0	Bathing	23.7
Gardens	150	3.2	Washing cloths	24.3
Total domestic	3850	83.2	Drinking	4.2
Industry	430	9.3	Cooking	1.7
Commercial	65	1.4	Toilet	21.6
Others	285	6.1	Cleaning house	6.6
Total (ml/day)	4630		Washing utensils	17.4
Per capita/day (l)	208		Others	0.5
Slums (l/day)	30			
Others (l/day)	380			
Waste water generation	2271			
Effluent generation	840			

Table 5: Energy utilization patterns

Energy use (TJ)	Sectoral use (%)					
	Residential	Industrial	Commercial	Transport	Others	Total
Solid	3.6	8.0	1.1		0.2	12.9
Liquid	6.3	11.43	0.2	91.0	12.00	120.8
Gas	20.8	11.30	2.91	5.2	0.1	40.2
Electricity	43.55	31.86	21.24	5.31	4.25	106.2
Final energy supply	74.2	62.6	25.5	101.5	16.5	280.1
% share	26.4	22.4	9.1	36.2	5.9	100.0
Per capita (GJ)	4.00	3.38	1.38	5.49	0.89	15.14
Losses	30.56	30.20	10.48	40.07	9.11	120.42
Total useful (PJ)	43.44	32.41	14.97	61.40	7.44	159.66
Eff. Of utilisation	58.70	51.76	58.82	60.51	44.95	57.01
Per capita (GJ)	2.35	1.75	0.81	3.32	0.40	8.63

Table 6: End use analysis of energy

End use analysis	HH	Industrial	Commercial	Transport	Others	Total	% of total
Cooking	26.50		3.06			29.56	10.56
Water heating	7.51		5.4			13.01	4.65
Lighting	16.21	3.19	0.8			20.19	7.21
AC	6.53	4.35	12.2			23.09	8.24
Appliances	17.4	2.61	4.04			24.07	8.60
Industrial applications		45.1				45.10	16.11
Transport		4.2		101.5		105.70	37.75
Others		3.1			16.5	19.60	6.89
Total	74.2	62.6	25.5	101.5	16.5	280	100

Table 7: Municipal solid waste

	Quantity (tonnes/day)	%	Per cap (Kg/day)
Type of waste			
Domestic	8800	58.47	0.48
Commercial	1200	7.97	0.06
Industrial	940	6.25	0.05
Total municipal solid waste	10940	72.69	0.59
Construction and demolition waste	4110	27.31	0.22
Total solid waste	15050	100.00	0.81
Landfill	5925		
Open burn	690		

Table 8: Emission load of Mumbai (tonnes/day)

Source	SO_2	PM (particulate matter)	No_x	CO	HC	Total
Domestic	3.57	10.77	4.22	108.36	17.56	144.48
Industry	30.78	3.77	16.1		0.01	50.66
Refuse burning	0.11	1.37	0.25	5.42	1.92	9.07
Transport						
Petrol	4.64	1.85	26.65	14.1	5.46	52.7
Diesel	0.59	0.13	7.35	265.58	39.46	323.11
Total	39.69	17.89	54.57	393.46	64.41	580.02
Per cap (kg/year)						1.18

Table 9: Material flows in Mumbai (2010)

Resource inputs	Total (TJ)	Per cap (MJ/cap)	**Out puts**		Total (million tonnes)	Per cap (kg)
Energy	271573	14680	Solid Waste		5.49	30
Share (%)	Coal	2.95	Share (%)	Municipal		72.7
	Wood	1.72		Construction and demolition		27.3
	Petroleum products	46.32	Sewage		1480	80
	Gas	9.90	Emissions		0.26	14.05
	Electricity	39.11	Share (%)	S0x	0.015	0.8
	Million tonnes	t/cap		PM	0.019	1.05
Food	9.56	0.52		N0x	0.024	1.3
	Million tonnes	t/cap		CO	0.172	9.27
water	1680	90.81		HC	0.036	1.94
	Million tonnes	t/cap				
Construction materials	17.37	0.94				
Share (%)	Earth stone and bricks	8.8				
	Cement	52.9				
	Steel	18.2				
	Plywood/timber	2.6				
	Sand	14.7				
	Others	2.8				