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13. Analyzing a city's metabolism

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1. INTRODUCTION

Collection of urban metabolism (UM) data is required for assessing the sustainability of cities. A UM study involves quantification of the inflows, outflows, storage and production of energy and materials within an urban boundary. Such data can serve a variety of purposes, whether as input to city greenhouse gas (GHG) inventorying, for determination of urban ecological footprints, or sustainability assessment in specific areas such as water use, air pollution, waste, materials management and so on. About 20 relatively comprehensive UM studies have been published in academic literature (Kennedy et al. 2011). The World Bank has also conducted several studies of cities (Hoornweg et al. 2012), and many more cities are collecting data on some aspects of UM as part of GHG inventorying.

The objective of this chapter is to provide practical guidance for undertaking a UM study. In particular this will involve description of data collection techniques and estimation methods, and potential pitfalls to avoid in determining various components of UM. For example, it will describe how transportation fuel consumption can be determined from vehicle counts, sales data and/or transportation models; and how material stocks can be scaled up from studies of individual buildings/infrastructure segments. It is very much a 'how to do it' guide for both city managers and academics.

Figure 13.1 provides a generic framework for assessing the UM, broadly including inflows, outflows, internal flows, storage and production of biomass, energy, minerals and water. This is a comprehensive framework that integrates methods of water, energy and substance flow analysis with the Eurostat system of material flow analysis (Kennedy and Hoornweg 2012). The framework captures all biophysical stocks and flows within the system boundary, including natural components (e.g. solar radiation, groundwater flows), peri-urban activities (e.g. food production, forestry), as well as a broad range of anthropogenic stocks and flows.

For any of the materials or substances shown in Figure 13.1, there is a mass balance:

$$\text{Inflow} + \text{Net production} = \text{Increase in storage} + \text{Outflow} \quad (13.1)$$

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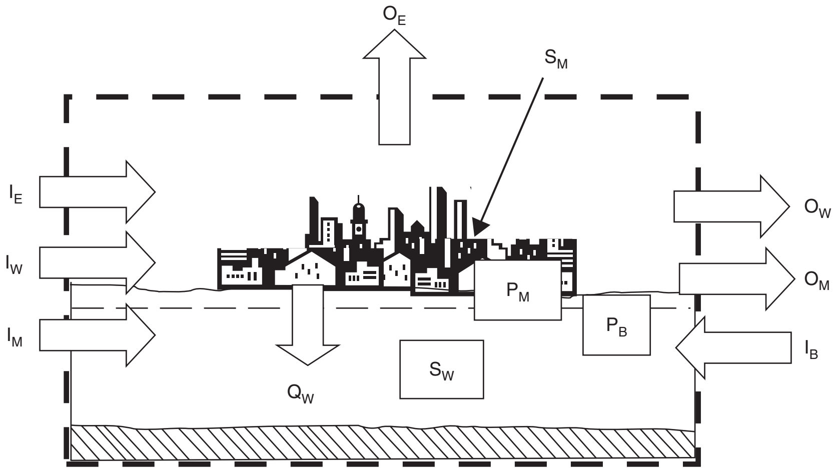

Notes:

Inflows
Biomass [t & J]
  food
  wood
Fossil Fuel [t & J]
  transport
  heating/industrial
Minerals [t]
  metals
  construction materials
Electricity [kWh]
Natural energy [J]
Water [t]
  Drinking (surface & groundwater)
  Precipitation
Substances [t]
  e.g. nutrients
Produced goods [t]

Production
Biomass [t & J]
Minerals [t]

Outflows
Waste Emissions [t]
  gases
  solid
  wastewater
  other liquids
Heat [J]
Substances [t]
Produced goods [t]

Stocks
Infrastructure / Buildings [t]
  construction materials
  metals
  wood
  other materials
Other (machinery, durable) [t]
  metals
  other materials
Substances [t]

Source: Adapted from: Kennedy and Hoornweg (2012).

Figure 13.1 Urban metabolism classification system showing inflows (I), outflows (O), internal flows (Q), storage (S) and production (P) of biomass (B), minerals (M), water (W) and energy (E)

Equation (13.1) is the basis of the method of material flow analysis (MFA), described further in Sections 3 and 5, which is used for analyzing material parameters in the UM. A similar equation, expressing the conservation of energy, applies to the analysis of energy flows in the UM.

There are potentially many parameters that could be measured within the UM, so some reduction to key basic quantities is necessary. To take an inventory of all individual goods or all chemical elements would be overwhelming. Hence Table 13.1 provides a practical list of quantities that would ideally be included in a basic UM study. Depending on the context, data availability and key environmental challenges of a specific city, the suggested list in Table 13.1 may be longer or shorter. The table shows the UM parameters required for greenhouse gas accounting for cities, including direct and indirect emissions. It also shows other parameters, including flows of water, nutrients, materials and pollutants that are of importance for urban sustainability.

A completed UM study would aim to determine the parameters of Table 13.1 within an urban region for a calendar year. In many instances, the urban region will be determined by the political boundaries of a city, or the amalgamation of city boundaries to form a metropolitan region. Clear definition of the urban region should be given in reporting on a UM, along with background information such as population, gross area and year of study. UM parameters should ideally be reported in SI units, mainly in tonnes and Joules, as per Figure 13.1.

Research in recent years has extended the analysis of UM by including upstream and/or downstream environmental life-cycle impacts associated with flows into or out of urban regions. Much of this analysis has developed from GHG inventorying approaches for cities, which includes emissions occurring outside cities as a result of driving activities inside them (i.e. scope 2 and 3 emissions). An early example is the work done by the French Agency for the Environment and Energy Management on the inventory tool Bilan Carbon (ADEME 2007). Various approaches to adding life-cycle extensions to urban metabolism have been published (e.g. Ramaswami et al. 2008; Schulz 2010; Chavez and Ramaswami 2011; Chester et al. 2012). In a study of ten cities by Kennedy et al. (2009), upstream emissions for heating, industrial and transportation fuels were found to be between 7 percent and 24 percent of the direct emissions for these sectors. Extending UM to include life-cycle impacts of GHG emissions is demonstrated further in Section 4 of this chapter.

The rest of this chapter describes how the UM parameters of Table 13.1 are collected in practice. Sections 2 to 5 discuss methodology and data collection techniques grouped under each of the four main elements of metabolism: energy, materials, water, nutrients. This is then followed by a concluding section discussing diagrammatic representation of UM.

Table 13.1 Data requirements for basic urban metabolism studies

Quantity	Required for GHG calculation	Notes
Inflows		
Food	✓*	
Water (imports)	✓*	
Water (precipitation)		Standard climate data
Groundwater abstraction	✓*	
Construction materials	✓*	Primarily cement, aggregates, steel
Fossil fuels (by type)	✓	
Electricity	✓	
Total incoming solar radiation	✓	Standard climate data
Nitrogen & phosphorus		Example nutrients
Produced		
Food	✓*	
Construction materials	✓	Cement and steel
Stocks		
Construction materials		In the building stock
Nitrogen & phosphorus		
Landfill waste	✓	Accumulated
Construction/demolition waste		
Outflows		
Exported landfill waste	✓	
Incinerated waste	✓	Air emission plus accumulated mass
Exported recyclables		
Wastewater	✓	
Nitrogen & phosphorus		
SO_2		
NOx		
CO		
Volatile organics		
Particulates		
Methane	✓	
Ozone	✓+	
Black carbon	✓+	

Notes:
* has upstream (embodied) GHG emissions.
+ typically omitted from GHG calculations due to difficulty of estimation.

Source: Adapted from Kennedy and Hoornweg (2012).

2. ENERGY

Energy consumption in cities can be broadly divided into stationary uses and mobile uses. In both cases energy use should be reported first by the type of fuel or source, and second, where possible, by the type of user, for example residential, commercial, industrial.

Stationary Energy Use

Energy consumption data for each type of fuel typically have to be obtained from local utilities or fuel providers. In some cases these may be publicly owned utilities, which may make data publicly available; in other cases access to data from private companies may be required.

The number and complexity of sources of stationary energy use in a city can differ significantly between cities. For example, in many North American cities natural gas supplied by a single utility can account for over 95 percent of the fuels used for heating and industrial purposes. In other cities, particularly older ones, there can be significant use of fuel oils or coal. Obtaining data on the use of these truck-delivered fuels can be more difficult if there are multiple companies in the market. A more extreme case of complexity is the example of Bangkok, which has a wide variety of fuel sources (at least 13), including substantial use of wood, rice-husk and bagasse (Table 13.2).

Table 13.2 Heating and industrial fuel use for Bangkok in 2006

Fuel type	Use (TJ)
Wood	8725
Fuel oil	32217
Natural gas	15407
LPG	12041
Kerosene	322
Gasoline	595
Diesel	6033
Coal and coke	20331
Lignite	22035
Anthracite	632
Rice husk	8449
Bagasse	33427
Charcoal	314

Sources: Kennedy et al. (2010); Phdungsilp (2006).

Electricity is still typically provided a by a single utility in most cities, but attention should be given to a growing amount of generation from dispersed sources. Where electricity is supplied by more than one source, the amounts supplied and means of generation should be reported separately. This is particularly the case when electricity is generated from renewable sources within the urban boundary. Care should also be taken to note whether electricity is reported based on final consumption, which excludes transmission and distribution losses, or from the power generators' or utilities' perspective, which may or may not include such line losses.

The special case of combined heat and power (CHP) generation is perhaps best treated as a separately reported item from both heating fuels and electricity use. Sometimes when CHP plants are located within a city it may not be possible to distinguish the data on source fuels from total source fuels for the city; if this is the case then CHP becomes incorporated under heating fuels by default. Another case to watch out for is district heating, when the heating source is located outside city boundaries, with typically hot water or steam pumped to the city along a heat pipe.

Mobile Energy Use

Most of the energy required for transportation in cities is in the form of gasoline or diesel, mainly combusted in automobiles or trucks. Other fuels include liquified petroleum gas (LPG), natural gas and biofuels, as well as electricity used to power subways, rail and street cars.

Three methods may be used to quantify transportation fuel use within the study area. Typically the preferred method involves multiplication of the within-boundary vehicle kilometres travelled (VKT) by the fuel economy (L/km) for each vehicle grouping, for example automobile, motorcycle, SUV and various categories of truck. The VKT must be determined from vehicle counts or surveys, often supported by computer models. The design of surveys and computer models is often unique to each city, but there are guidelines for determining VKT in some countries (see, e.g., the US Department of Transport Federal Highway Administration, or Leduc 2008, for the European Union).

Data on fuel sales, for example from gasoline stations within the study area, can also be used, but generally should be avoided unless the boundaries of the area correspond to a commutershed; that is, the amount of travel into or out of the area is small (less than 5 percent) relative to travel within the area. This may be the case if the UM study is being conducted for a metropolitan region. One potential pitfall with using fuel sales data, however, is that some commercial traffic may obtain fuel on bulk contracts, and hence be missed from data based on retail sales. In other words, fuel sales data may be suitable for estimating energy use by automobiles in a commutershed, but not by trucks.

When neither VKT data or fuel sales data are available or appropriate, a third approach is to estimate fuel consumption from data for a higher-level state, province or region. Typically this would involve scaling based on population or vehicle registrations. In a study of ten global cities, Kennedy et al. (2010) found that differences in the fuel consumption estimates using scaling, fuel sales and VKT methods were up to about 5 percent. Having established fuel use for mobile and stationary purposes, this can be converted into greenhouse gas emissions by multiplying by an emissions factor (Kennedy et al. 2010).

In addition to ground transportation within a city, there can also be substantial quantities of fuel loaded onto planes, ships and trains within cities. Combustion of these fuels might mainly occur outside city boundaries, but since these vehicles serve cities, their energy use is sometimes included in scope 3 greenhouse gas emissions. Often the amount of fuel loaded onto planes and ships can be provided by airports or marine ports. Where this is not available, estimates may be scaled from higher-level data based on the number of passenger boardings, or freight tonnage.

3. MATERIAL STOCKS AND FLOWS

The stocks and flows of materials for cities can be quantified with differing degrees of refinement, from bulk materials, through to individual goods and individual substances.

At the broadest level, material stocks and flows for cities can be classified using the Eurostat system of groupings: (i) biomass; (ii) fossil fuels; (iii) metallic minerals; (iv) non-metallic minerals; and (v) non-specified (Table 13.3). Examples of studies that have reported material flows using this system include those for Hamburg, Leipzig, Limerick, Lisbon, London and Vienna (Bongardt 2002; Browne et al. 2009; Hammer and Giljum 2006; Niza et al. 2009). Other studies have used different frameworks (see review by Weisz and Steinberger 2010), some of which may include so-called 'hidden flows' such as removal of overburden during mining or waste trimmings from forestry. Inclusion of such hidden flows will generally increase the amount of materials ascribed to cities (see, e.g., the study of York, UK by Barrett et al. 2002).

Construction materials constitute the largest stocks and flows of materials for cities. (This is aside from water, which is treated separately; see Section 4.) Quantifying the bulk stocks and flows of aggregates, cement, glass, steel, wood and so on for cities is challenging. Essentially bottom–up

Table 13.3 Material groups under the EUROSTAT system

Material group	Material examples
Biomass	Agriculture, forestry, fishery, livestock and others
Fossil fuels	Coal, petroleum and natural gas
Metallic minerals	Iron ores and non-ferrous metal ores
Non-metallic minerals	Stone and industrial use (chalk and dolomite, slate, chemical and fertilizer minerals, salt, other mining and quarrying products)
	Bulk minerals for construction (limestone and gypsum, gravel and sand, clays and kaolin, and excavated soil)
Non-specified	Items that do not fall into the above four groups

Source: Gou (2012).

and top–down approaches may be employed. The bottom–up approach typically involves classifying the buildings and other infrastructure in a city into representative groups with typical material characteristics, for example detached homes, roads and highway bridges, and collecting data on the annual additions, demolitions and stocks of each group. Statistically representative quantities for the material components of each group then need to be established; this may be done with the help of local architects and engineers who have bills of quantities from projects completed in the city. The top–down approach may involve engaging local industry groups concerned with sales of materials in the city to obtain estimates of bulk material flows for a given year. Alternatively, material quantities might be estimated from state-, province- or regional-level data weighted by building starts or infrastructure investment data.

Unless special surveys are conducted, or market research is accessed, information on flows of consumer goods into cities is most likely to be obtained by scaling from national or other higher-level data. At the national level, flows of many different types of goods are quantified, at least in economic terms, in national import, export, production and consumption statistics.

Quantification of substance flows, for example of a specific nutrient, metal or other element, will usually involve first undertaking studies of relevant goods or bulk materials, including their waste streams, and then drawing upon knowledge of the fractional component of the substance in the goods, bulk materials and wastes. The methodologies used in substance flow analysis are described further in the case of nutrients in Section 5.

Having established suitable data on material stocks and flows for cites, formal methods of material flow accounting (MFA, including substance flow accounting) may be applied. Several books describe MFA methodology (e.g. Brunner and Rechberger 2004; Baccini and Brunner 2012). These provide formal procedures for forming systems boundaries, representing processes, stocks and flows, with associated definitions and terminology. The methods have also been incorporated into software packages, such as SIMBOX (Baccini and Bader 1996) and STAN (Cencic and Rechberger 2008). As conservation of mass lies at the heart of MFA, applying the formal methodology may help to either verify or fill gaps in material flows data.

4. WATER

Despite the importance of maintaining a sustainable urban water metabolism, many cities have not developed comprehensive water balances and are hence vulnerable to changes in water use or climatic regime. Several components of urban water balances can be derived simply, but others require extensive analysis. Withdrawals are generally well documented; in the USA, the US Geological Survey documents water withdrawals (surface and groundwater) by type of use, at the county level, and finer-scale analysis can often be done via state agencies, which may maintain public data files for each withdrawal. Within the municipal system, water used for external irrigation can be estimated by comparing water use during the growing season with water use during winter. In some suburban communities with well-maintained lawns, outside irrigation can use several times more water than interior water uses. Residential end uses of water in several cities throughout the USA have been documented by Mayer et al. (1999). This study showed that nearly all the variation in household water use occurs in outside water use (mostly irrigation); interior use is remarkably similar (around 70 gallons/capita/year). Similarly, sewage flows are generally well documented and readily available in developed countries. Gains or losses of sewage flows are often measured by municipal sewage agencies, which need this information to guide maintenance operations.

Water balances for urban landscapes are more troublesome. Flows of urban runoff are often measured in US cities, as is precipitation, allowing ready calculation of yields (cm/yr). What is more difficult is the apportionment of the remaining water into evaporation and recharge, except in desert regions where most of the evaporation is the result of landscape irrigation.

Groundwater balancing is generally accomplished through modeling. Groundwater models can account for regional groundwater inflows and outflows, inflows and outflows from rivers and lakes, withdrawals and recharge, with the latter often as the 'unknown'. Once calibrated, groundwater models can then predict the effect of changes in withdrawal or recharge. The latter is greatly influenced by urbanization: as impervious surface area increases, groundwater recharge is reduced.

From a UM point of view, the role of water and the water balance of a city is of course important, due to the large quantities of water flowing through a city. Even when all natural water of rivers not collected, processed or transported by man-made systems within a city is excluded, the flows of urban water services in water supply and wastewater (stormwater and sewage) management will totally dominate the flow quantity (kg/year) and the flux quantity (kg/cap/year) of the material balance within a city.

Despite the fact that distribution, pumping and processing of water – upstream and downstream to the consumers – consume energy carriers, various construction (stock) materials and operation chemicals and transport services, and create a variety of by-products and emissions to water, air and soil, these are often poorly understood, quantitatively. So are also the associated potential environmental impacts, both the direct impacts from activities within the city and the indirect impacts from processing activities (chemicals, energy carriers, transport work) elsewhere in the global system.

Along with a growing attention to the role of UM and the search for solutions for sustainable cities, it is indeed necessary to better understand and document the quantitative relationships between the flows of water, materials, chemicals, energy carriers, emissions and wastes in cities, as well as how these factors influence the social, environmental and economic dimensions of sustainability. Such an understanding can be facilitated by a metabolism model approach to the urban water cycle services. The starting point of this approach is a generic metabolism model system definition, within which any city in principle could be studied; see Figure 13.2.

The system definition illustrates that inside a system boundary (the city total hydraulic catchment area) water is flowing from the source via the water supply subsystem to the water demand subsystem, and further via the wastewater subsystem to the recipient. This is normally a linear flow; however, future systems will probably increasingly include water reuse and recycling concepts, and therefore the system definition also includes a cyclic water recovery subsystem. Finally, there is a resources recovery subsystem, which is relevant for energy, nutrients and sludge recovery from the water and wastewater subsystems.

The first important message is that each of these subsystems must be connected in a mass-balance consistent way with respect to water. Hence the starting point is to define all relevant water flows ($Q_{i,j}$) from an origin i to a destination j. Then a quantitative mathematical model of these flows must be developed, assuring mass balance. The drivers within the system are water demand ($Q_{1,3}$), wastewater generation ($Q_{2,3}$) and stormwater runoff ($Q_{0,3}$).

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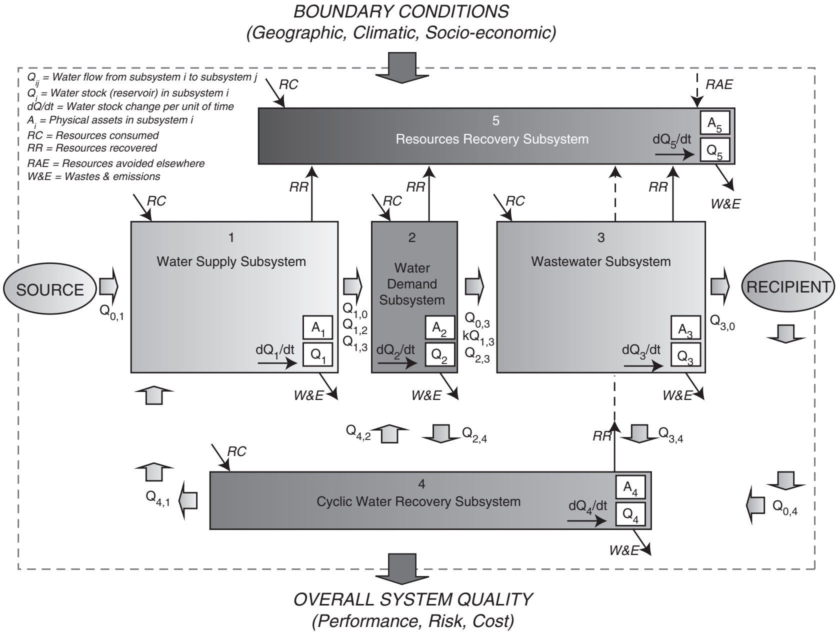
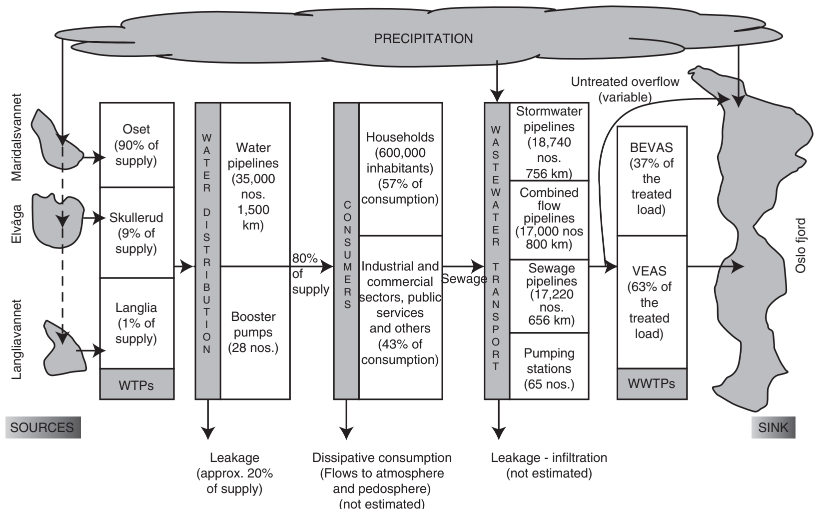


Source: Venkatesh (2011).

Figure 13.2 Metabolism model system definition of urban water services

A second important message is that each subsystem can be broken down into a set of processes or sub-subsystems. Each sub-subsystem will have to be mathematically described in terms of water flows. And each of these processes has a given function, such as particle separation in water treatment plants, pumping in distribution networks, pipe transport in wastewater collection networks, and sludge stabilization in wastewater treatment plants – and this function is provided by use of a given technology (equipment types, artifact designs). For a given technology, and a given water throughflow specification (quantity and quality), any process activity will mobilize a given flow of resources consumed (RC, such as chemicals, materials, energy carriers) and wastes and emissions (W&E, such as direct and indirect emissions of CO_2 to the atmosphere, nitrogen and phosphorus substances to water, and solid wastes to soil). The metabolism modeling challenge for this kind of system is indeed simple, yet challenging! One has to develop an overall model that is mass-balance consistent at different levels of detail, so that all activities in the system are correctly related, and when this is done, the remaining task is to add the required set of specific coefficients for input resources, output wastes and emissions (such as the



Source: Venkatesh (2011).

Figure 13.3 The urban water services of the city of Oslo

relative consumption of specific energy carriers and chemicals per m^3 of water, in kWh/m^3 and kg/m^3). Once this is done, and the model is calibrated for a given city, it will provide quantitative estimates for all metabolic flows and fluxes within the system, for a given year. Such physical information (for water, energy, chemicals, materials, wastes and emissions) can easily be further used for environmental assessment, such as by use of life-cycle assessment (LCA) methods, or for economic assessment. A model like this can also be used for examining changes over time in the past, from accounting and operations data within the water utility of a given city. It can also be used for evaluating scenarios for the future metabolism and its associated environmental impact, on the basis of prognosis for population growth, industrial water demand, changes in technologies and so on. This is more complex, and points towards a dynamic model approach.

What we can obtain from such methods, or related types of models and calculations, is a variety of information. As an example, the urban water system of Oslo (Norway) is briefly outlined in Figure 13.3, serving a population of about 600 000 inhabitants in households (57 percent of water consumption) and various industrial, commercial and public services (43 percent of water consumption), adding up to about 150 m^3/cap/year total demand.

The urban water services in the city of Oslo have been examined by the metabolism model approach since 2007, partly in close collaboration with

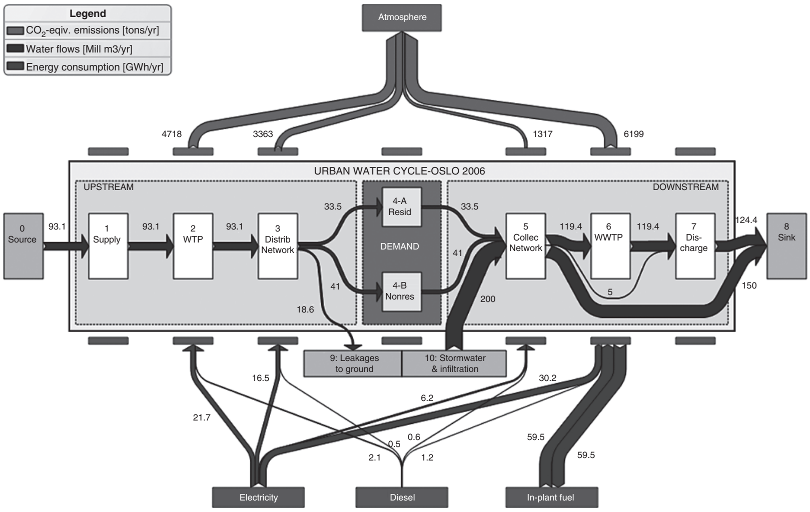


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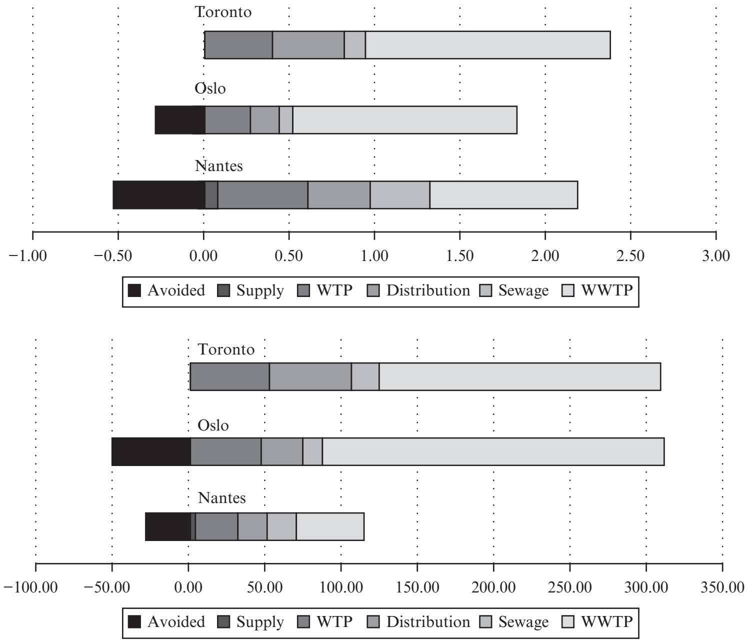
Figure 13.4 The water/energy/CO_2 nexus of urban water services in Oslo

the city's water utility, Oslo VAV. Results from this research have been published in a series of papers by Venkatesh and Brattebø (2011a; 2011b; 2012a; 2012b) and by Venkatesh et al. (2011). These studies cover issues such as material flows, energy flows, emissions, environmental life-cycle impacts and economic impacts associated with selected subsystems as well as the system as a whole. Other studies, similar to that done in Oslo, are being carried out for selected other cities: Nantes (France), Toronto (Canada), Turin (Italy). The metabolism model approach is also being developed further within a EU project called TRUST (http://www.trust-i.net/), with the aim to develop dynamic metabolism models for the evaluation of 'TRransitions to the Urban water Services of Tomorrow' and testing such models for a number of cities in Europe.

In regard to the city of Oslo, Figure 13.4 shows a Sankey diagram of the so-called 'water/energy/carbon nexus' profile of urban water services in 2006. The central section of the figure presents the water flows (in million m^3 per year) from the source to the sink. Shown also is the split between residential and non-residential demand, the high share of water losses due to leakage in the water distribution network, and the dominant role of stormwater flows downstream to the use phase as well as the share of wastewater discharged via combined sewers and the wastewater treatment plant. In the bottom section of the figure are shown flows of direct energy

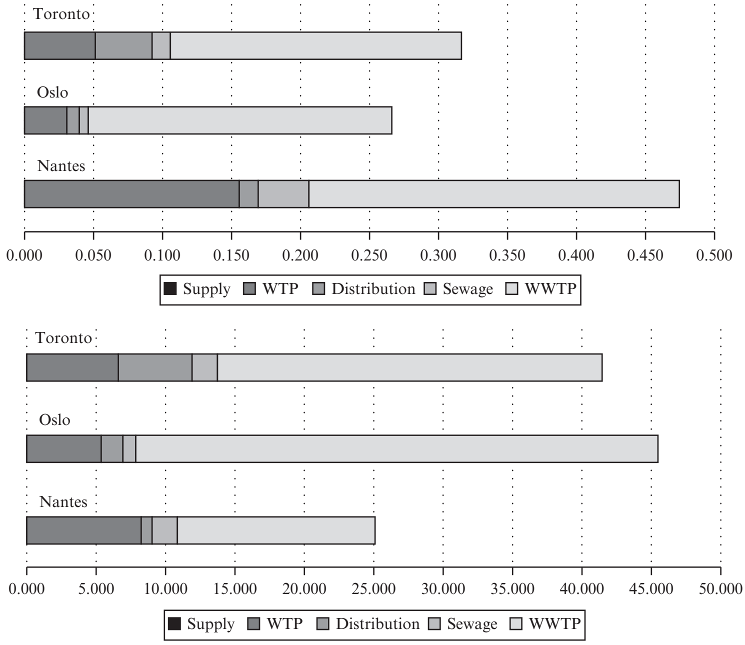


Source: Author.

Figure 13.5 Total energy consumption in the urban water services of Nantes, Oslo and Toronto, by subsystem (upper chart in kWh/m³ and lower chart in kWh/cap)

demand to each of the subsystems (in GWh/year), including heat generation and reuse from sludge fermentation in the wastewater plant, and the split between energy carriers. In the top section are shown the estimated direct emission to air flows of greenhouse gases (in tons/year of CO_2 equivalents). Metabolic quantifications like this, derived from the turnover of water in the urban water cycle, offer good insight into opportunities for environmental improvements, in this case how direct energy consumption and direct greenhouse gas emissions can be understood and, it is hoped, reduced.

By use of environmental LCA methods and models it is possible to develop further the system-wide profile (direct and indirect) of emissions and environmental impact. While direct emissions can fairly easily be measured or estimated from water/energy balance measurements, as explained above, the quantification of indirect and system-wide emissions is more difficult. Selected results from such analysis are presented in Figures 13.5, 13.6 and 13.7 with more complete and detailed data for



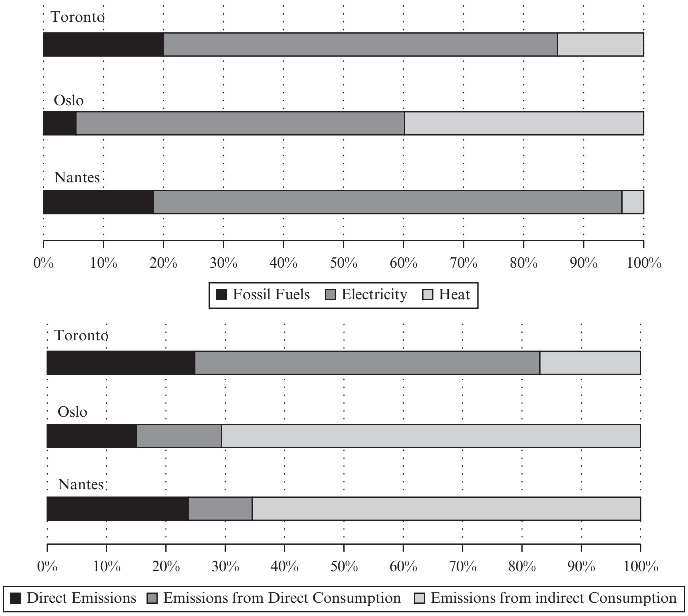
Source: Author.

Figure 13.6 Total GHG emissions in the urban water services of Nantes, Oslo and Toronto, by subsystem (upper chart in $kgCO_2$-eq/m^3 and lower chart in $kgCO_2$-eq/cap)

urban water-related direct and indirect energy and greenhouse gas emissions, for Nantes, Oslo and Toronto.

As can be seen from Figures 13.5 and 13.6, there are significant differences between cities, in both energy consumption and greenhouse gas emissions. For energy, this is due to several local conditions, such as topography and distances (water pumping), treatment processes used for water and wastewater, and how energy recovery opportunities are implemented from sludge or outflow wastewaters. When the figures are presented on a per capita basis it is also important to appreciate the importance of per capita water demand and the share of water leakages.

For greenhouse gas emissions, one should also take into consideration the share of different energy carriers. As seen in the upper chart of Figure 13.7, this distribution is indeed different between cities, and one should bear in mind that the technologies for electricity generation (i.e. the mix of primary energy sources in power generation) are very different



Source: Author.

Figure 13.7 Distribution of energy carriers consumed (upper chart) and direct and indirect GHG emissions (lower chart) from urban water services of Nantes, Oslo and Toronto

from country to country. Norway, for instance, has close to 100 percent of its electricity generated from hydropower, with very low CO_2 emissions per kWh.

An important finding is shown in the lower chart in Figure 13.7, which presents the sources of greenhouse gas emissions for the urban water services. Despite some differences between the cities, the share of direct emissions (direct process emissions and combustion of fuels within the system) is only a minor part of the total, while emissions from direct consumption and indirect consumption (of products such as electricity, process chemicals and infrastructure materials) account for the majority of total emissions. This means that sectors such as urban water services should not focus mainly on their direct emissions if they want to be sustainable in their activities regarding energy and greenhouse gas emissions. They must think about and analyse their activities in a system-wide perspective, and take advantage of methods such as MFA and LCA. This proves that urban metabolism modeling approaches also have a role to play in the urban water sector.

5. NITROGEN, PHOSPHORUS AND SALTS

Problems Caused by Poor Metabolism of Water, Nutrients and Salts

Understanding water balances (discussed in Section 4) is first necessary to deal with the essential role of nutrients (nitrogen and phosphorus) and salts in maintaining sustainable cities. Severe mismanagement of the flows of these materials often causes deterioration of urban ecosystems. Most obviously, either too much or too little water can cause serious loss of human well-being, especially during periods of climate extremes – too much or too little precipitation. Urban water problems are often associated with groundwater stored in aquifers below the city. Groundwater is often the preferred source of municipal water supply, because it often lies directly underground, is often plentiful (at least during early development), and is generally naturally 'clean', requiring little or no treatment prior to consumption. Over time, however, groundwater supplies are often depleted and/or become polluted (see examples in Kennedy et al. 2007). Groundwater depletion is often accompanied by land subsidence (sometimes by a meter or more), with damage to infrastructure. Over time, aquifers become depleted or polluted, withdrawals are often halted, and groundwater levels rise, which may flood underground structures (Foster et al. 1998; Shananan 2009). Many cities also utilize surface water, initially from rivers flowing nearby, but often imported from great distances as cities expand. Cities also discharge sewage, in various levels of treatment, urban runoff and, in the case of older cities, often 'combined' sewage (sanitary + urban runoff), often causing eutrophication of downstream rivers and estuaries.

One of the most prevalent pollutants of urban groundwater is nitrate (Wakida and Lerner 2005; Xu and Usher 2006; Xu et al. 2007). Nitrate is extremely mobile in soil; hence additions of nitrogen at the surface often result in downward migration of nitrate through the vadose zone to underlying aquifers. These inputs include fertilizers, leakage of fecal material to latrines, leaky sewer pipes and animal wastes. As a result, aquifers underlying many cities are contaminated to the point they do not meet WHO water quality standards (Wakida and Lerner 2005).

Nitrogen and phosphorus from agricultural runoff, urban sewage and urban runoff also contaminate lakes, rivers and estuaries, causing eutrophication, with severe impacts on human utilization (Carpenter et al. 1998). In addition, phosphate rock (the penultimate source of P entering cities) is a finite, non-renewable resource. In the USA, for example, the phosphate rock resource would be depleted in just 40 years if it continued to be used at current rates, compelling the USA to import P fertilizer from other parts of the world, or to move toward a 'circulate economy', recycling P that moves into cities back to farms. Finally, salt contamination is a major concern for many cities in the world: in north-temperate regions, road salt has become a major contaminant of groundwater and urban streams (Kaushal et al. 2005); coastal cities throughout the world suffer from seawater intrusion as the result of drawdown of freshwater aquifers; and inland desert cities face the problem of concentration of salts by evaporation (Baker et al. 2002).

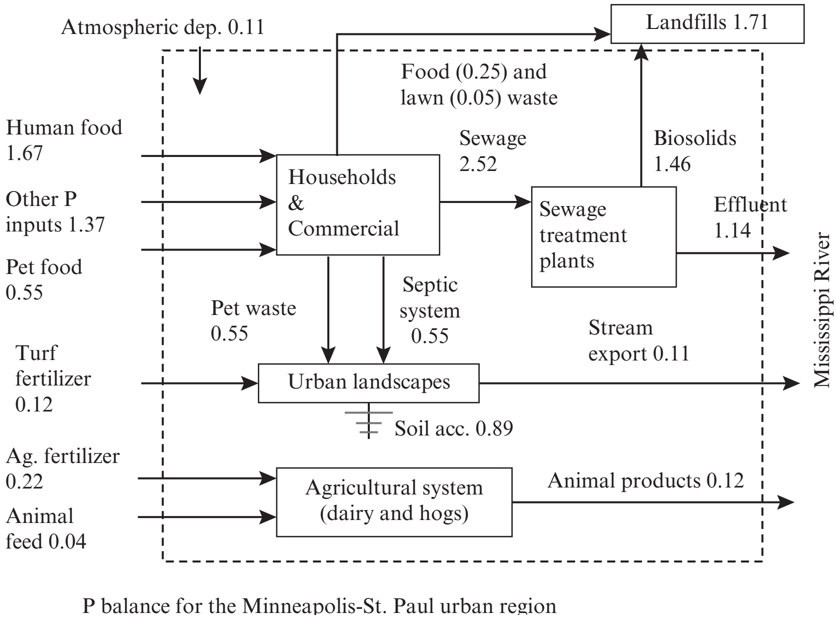
Material Flow Analysis (MFA) of Nutrients and Salts

Much about the metabolism of nutrients and salts can be learned from material flow analysis (MFA), which traces the flows of these materials through systems. (Note that MFA is a generic methodology; when applied to individual elements it can also be called substance flow analysis, SFA.) In the context of urban ecosystems, MFA is a hybrid approach that borrows from several fields: hydrology, industrial ecology and biogeochemistry. MFA is essentially a mass balance accounting of the flows of any material, in terms of mass/time through a system. These systems can be of any size; for cities, some scales of interest are urban regions, watersheds within urban regions, and households. For an urban region, a material flows through various pathways (e.g. a human food system), may be stored within a subsystem (e.g. phosphorus in residential lawns), be transformed (e.g. by fixation of atmospheric N_2 gas to NOx by combustion, and exit the system (e.g. nutrients in sewage may exit as biosolids, treated effluent and gases).

An MFA for phosphorus in the Minneapolis–St Paul region illustrates the idea (Figure 13.8). This analysis revealed that only 4 percent of P entering the MSP region was recycled, whereas 31 percent leaked (sewage effluent + runoff) to the Mississippi River, and 64 percent was stored, mostly in landfills. The latter included incinerated sewage biosolids, garbage and landscape waste, along with storage in vegetated landscapes. Reconfiguring the system (using MFA) in a 'conservation scenario' reduced P inputs and greatly reduced storage and leakage of P, while conserving enough P to supply about half of that needed to provide food to the urban region.

System boundaries

Because many data sources are from governmental databases, most MFA studies for nutrients and salts have been developed on the basis of governmental units. For urban regions, these sources might include municipalities, metropolitan regional governments (often focused on water, sewage, solid waste, transportation or planning), county or state governments,



Source: Baker (2011).

Figure 13.8 Phosphorus balance for the Minneapolis–St Paul urban region

and federal agencies (Table 13.4). For some fluxes, disaggregated data can sometimes be obtained. An example is the US Department of Energy's household energy databases, which can be disaggregated to the household unit, though only at coarse scales (climate regions). To some extent, data from larger surveys can be 'mapped' into smaller geographic units using other types of data that are acquired at smaller scales (e.g. US Census 'block-level' data) based on factors such as population distribution, race and ethnicity, age and income.

Data sources

Much of the data needed to develop urban nutrient balances can be acquired from readily accessible public databases (Table 13.4). With increasing resolution of satellite imagery, the growing using of LIDAR for fine-scale topographic mapping, the nearly universal adoption of GIS mapping by all but the smallest cities, and increasing accessibility and transparency of data made possible through the Internet, the technique of MFA is becoming a practical tool for urban management of nutrients, salts and other substances.

Table 13.4 Examples of data sources that have been used in urban MFA studies

	Original source of data	Typical unit of government	Common spatial resolution for reporting
Impervious surface	Land Sat images; LIDAR imagery	State	Variable, 0.6–10 m < 0.2 m (vertical)
Land cover/land use	Satellite or air photo	State	Variable, 0.6–10 m
Crop production	Surveys of farmers	National Agricultural Statistical Survey (NASS)	County
Agricultural fertilizer use	Surveys of farmers	NASS	State
Population characteristics	Nationwide census	US Census	Census blocks
Housing characteristics	Surveys	US Census, American Housing Survey	Metropolitan areas
Watershed boundaries	Digital topographic maps	Some states	Variable
Sewershed	Ground-based mapping	Municipality or regional sewage authority	Delineated by individual hookups
Water withdrawals	Measured withdrawal + chemical characteristics	Varying, often state agencies or water management districts; county-level summaries by USGS	Individual withdrawals
Sewage and treated effluent; biosolids	Direct measurement at sewage treatment plants	Municipality or regional sewage authority	Individual sewage treatment plants
Land parcel information	Ground-based mapping and reporting	Local governments	Individual properties

Solid waste disposal	'Tipping' studies at landfills	Cities or regional authorities; national summaries	Cities
Animal feedlots (type and size)	Ground-based reporting	State government (Minnesota)	Varying – about 30 animal units in Minnesota
Animal production	Ground-based reporting	State government; aggregated by NASS	County
Animal feed consumption	Analysis of animal operations (various studies)	None	None
Human nutrient consumption	National surveys based on 24-hour dietary recall	Federal government – Continuing Survey of Foods Study	Federal
Pet food	NAS (2006)	Pet incidence studies	
Lawn fertilizer use	Local lawn fertilizer studies. Also see Fissore et al. (2011)	Various (not systematic)	Various

Source: Adapted from Baker (2009).

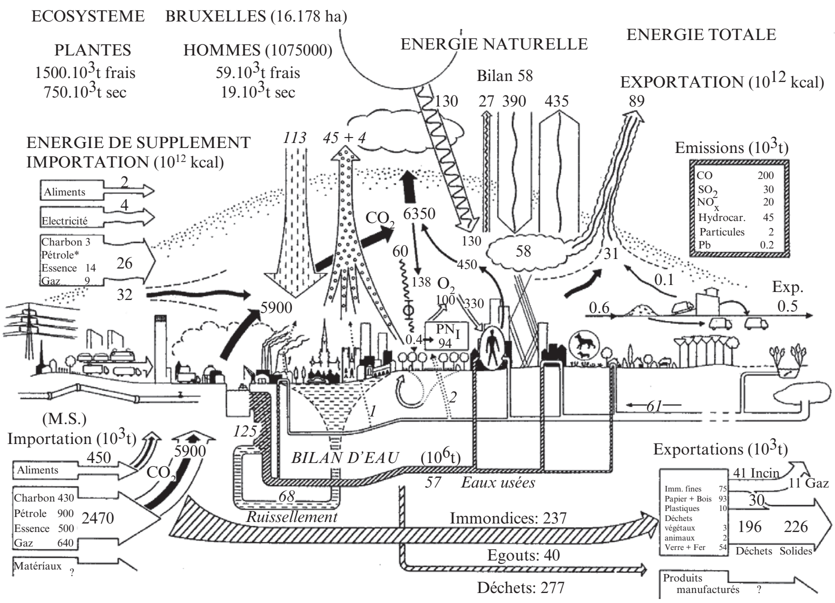
Development of new methods

As the fields of industrial ecology, urban ecology and planning converge on the topic of urban sustainability, new types of studies will yield new types of information to explain the flows of materials through cities. MFAs for nitrogen and phosphorus at the scale of urban regions are becoming common enough that 'typologies' of cities with respect to nutrient fluxes may soon be possible. At the scale of small watersheds, studies of nutrient flows through urban landscapes (Kaushal et al. 2011; Groffman et al. 2004) are providing better understanding of the dynamics of materials moving from rooftops and lawns to streets, storm sewers and streams. Baker et al. (2014) have quantified C, N, P and solids fluxes removed by street sweeping in relation to tree canopy cover, which translates to reduction of these materials entering storm sewers. The Central Arizona–Phoenix Long-Term Ecological Research Project (CAP-LTER) project has developed a spatial survey approach by which randomly sampled points throughout the urban area are sampled for soil and biota at 200 points at five-year intervals, providing a survey conducted every five years, an approach that could provide direct measurement of materials accumulating in soil (Hope et al. 2005). This will prove a great improvement on the traditional approach of estimating accumulation 'by difference' that is now used in most urban MFA studies. The Twin Cities Household Ecosystem Project (TCHEP) developed a hybrid approach using surveys, energy bills, parcel data and onsite vegetation surveys to quantify flows of C, N and P through households in relation to their demographic, social and behavioral attributes (Fissore et al. 2011; Nelson et al. 2008); also see methodologies at tchep.umn.edu. Finally an MFA study of salt in five municipal water systems in the Southwest USA used a hybrid approach that involved measurements of salts in source waters and sewers, computation of salts added by water treatment based on chemical additions; estimation of salt by human excretion from mineral intakes estimated in a national food survey, and modeled inputs of salts from water softeners, informed by a household survey of water softeners and their use (Thompson et al. 2006).

6. UM DIAGRAMS

Given the substantial amount of information contained in a UM study, some form of diagram may be useful for presenting results. A few options for UM diagrams are briefly reviewed here, although these are by no means exhaustive. Also, a UM diagram would typically be supplemented with one or more data tables.

One of the most creative UM diagrams was that presented by ecologists Duvigneaud and Denayeyer-De Smet for Brussels in the early 1970s



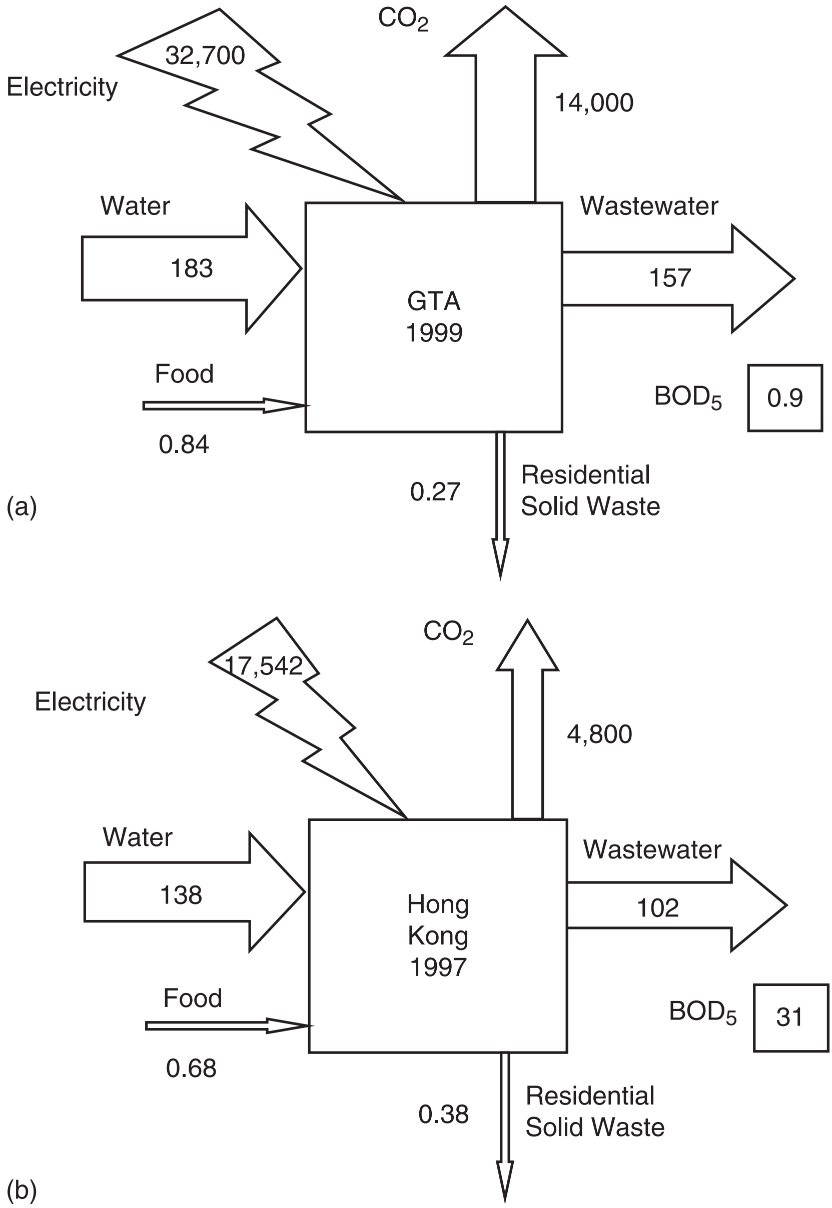
Source: Duvigneaud and Denayeyer-De Smet (1977).

Figure 13.9 The urban metabolism of Brussels, Belgium in the early 1970s

(Figure 13.9). The Brussels diagram presents the stocks and flows in an attractive way, with some attention to artistic detail. That said, while Figure 13.9 is visually appealing, it is a bit too busy for details to be picked out during a PowerPoint presentation, although it might still be used as a quick guide to the complexity of the UM.

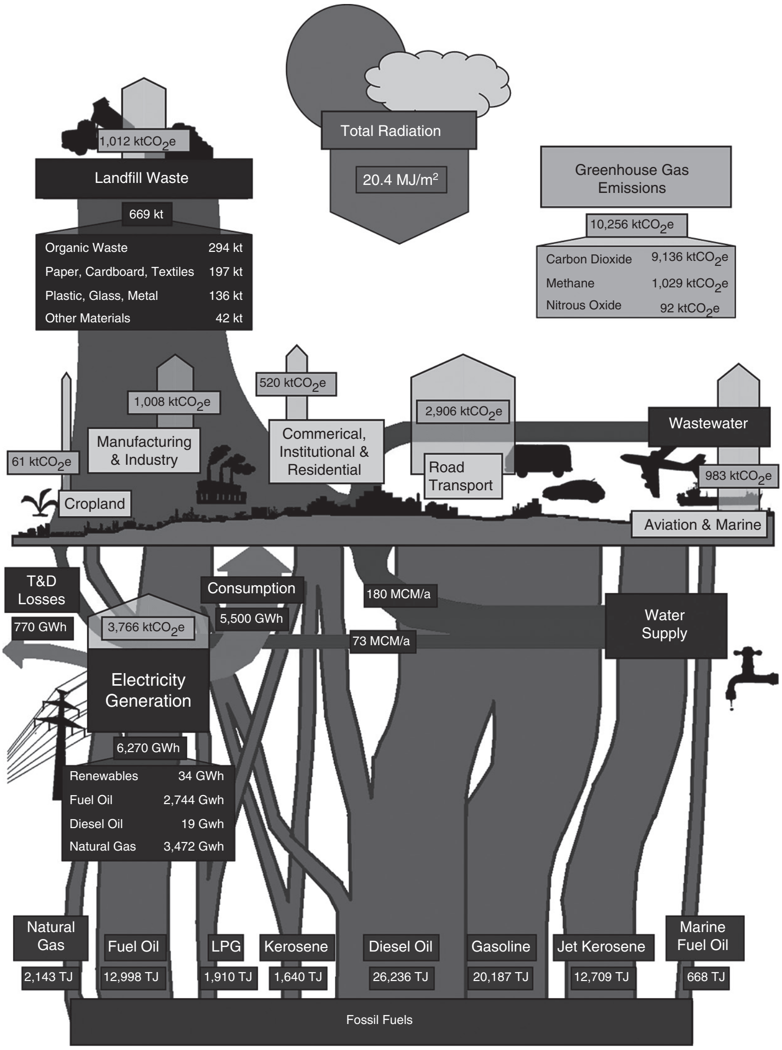
A much simpler, but less aesthetically pleasing, approach is shown in Figure 13.10, where the UM of Greater Toronto is compared to that of Hong Kong. Much less information is displayed for each city, so that it is possible to see the results easily. The approach of constructing a UM diagram out of simple boxes and arrows can be taken further, using for instance the methods used to construct MFA diagrams (e.g. Brunner and Rechberger 2004).

A further approach to presenting the UM is by use of a Sankey diagram (Figures 13.4 and 13.11). This is particularly useful for displaying upstream energy transformations and losses, as well as showing energy flows by fuel type and end use. The UM of Amman in Figure 13.11 is a customized diagram, but there are also commercially available software packages for constructing Sankey diagrams.



Source: Sahely et al. (2003).

Figure 13.10 Comparison of urban metabolism of (a) the GTA 1999 and (b) Hong Kong 1997



Source: Sugar et al. (2013).

Figure 13.11 Urban metabolism of Amman

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