ARTICLE IN PRESS

Environmental Pollution xxx (2010) 1–9

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

The study of urban metabolism and its applications to urban planning and design

C. Kennedy [a,*], S. Pincetl [b], P. Bunje [b]

[a] Department of Civil Engineering, University of Toronto, Toronto, Canada
[b] Institute of the Environment, UCLA, CA, United States

The presents a chronological review of urban metabolism studies and highlights four areas of application.

ARTICLE INFO

Article history:
Received 12 October 2010
Accepted 15 October 2010

Keywords:
Cities
Energy
Materials
Waste
Urban planning
Urban design
Greenhouse gas emissions
Sustainability indicators

ABSTRACT

Following formative work in the 1970s, disappearance in the 1980s, and reemergence in the 1990s, a chronological review shows that the past decade has witnessed increasing interest in the study of urban metabolism. The review finds that there are two related, non-conflicting, schools of urban metabolism: one following Odum describes metabolism in terms of energy equivalents; while the second more broadly expresses a city's flows of water, materials and nutrients in terms of mass fluxes. Four example applications of urban metabolism studies are discussed: urban sustainability indicators; inputs to urban greenhouse gas emissions calculation; mathematical models of urban metabolism for policy analysis; and as a basis for sustainable *urban design*. Future directions include fuller integration of social, health and economic indicators into the urban metabolism framework, while tackling the great sustainability challenge of reconstructing cities.

1. Introduction

The concept of the urban metabolism, conceived by Wolman (1965), is fundamental to developing sustainable cities and communities. Urban metabolism may be defined as "*the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste*" (Kennedy et al., 2007). In practice, the study of an urban metabolism involves 'big picture' quantification of the inputs, outputs and storage of energy, water, nutrients, materials and wastes for an urban region. While research on urban metabolism has waxed and waned over the past 45 years, in the last decade it has accelerated. Moreover, as this review will show, practical applications of urban metabolism are emerging.

The notion of urban metabolism is loosely based on an analogy with the metabolism of organisms, although in other respects parallels can also be made between cities and ecosystems. Cities are similar to organisms in that they consume resources from their surroundings and excrete wastes. "*Cities transform raw materials, fuel, and water into the built environment, human biomass and waste*" (Decker et al., 2000). Of course, cities are more complex than single organisms – and are themselves home to multitude of organisms – humans, animals and vegetation. Thus, the notion that cities are like ecosystems is also appropriate. Indeed, the model of a natural ecosystem is in some respects the objective for developing sustainable cities. Natural ecosystems are generally energy self-sufficient, or are subsidized by sustainable inputs, and often approximately conserve mass, through recycling by detrivores. Were cities to have such traits, they would be far more sustainable. Contemporary cities, however, have large linear metabolism with high through flows of energy and materials.

The first purpose of this paper is to review the development of the urban metabolism concept largely through academic research literature. The chronological review shows that after a few formative studies in the 1970s, interest in urban metabolism almost disappeared in the 1980s. Then after slowly reemerging in the 1990s, study of urban metabolism has grown in the past 10 years, with over 30 papers produced. The review also describes how two related, non-conflicting, schools of study have developed. One, primarily based on the work of Odum, aims to describe urban metabolism in terms of energy equivalents. The other takes a broader approach, expressing a city's flows of water, materials and nutrients in terms of mass fluxes.

The second purpose of this paper is to ask: What use are urban metabolism studies for urban planning and design? Most studies of urban metabolism have primarily been accounting exercises. These are useful in that they provide indicators of urban sustainability, and the measures of energy consumption, material flows and

* Corresponding author.
E-mail address: christopher.kennedy@utoronto.ca (C. Kennedy).

0269-7491/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envpol.2010.10.022

wastes from the urban metabolism are also necessary to quantify greenhouse gas emissions for cities. Beyond accounting exercises, moreover, the review of applications shows how study of urban metabolism is also being used as a basis for sustainable *urban design*, and how a few mathematical models of urban metabolism have been used for policy analysis.

2. Development of the urban metabolism concept

Since the first study of an urban metabolism by Wolman in 1965, about 15–20 comprehensive studies of urban metabolism have been undertaken, in addition to numerous related studies (Table 1). This section describes the evolution of methodological approaches for studying urban metabolism. The primary focus is on quantitative studies, as opposed to works that invoke urban metabolism in a political science context (e.g., Heynen et al., 2005), or in a qualitative historical context (e.g., Tarr, 2002).

In his seminal study, Wolman (1965) used national data on water, food and fuel use, along with production rates of sewage, waste and air pollutants to determine per capita inflow and outflow rates for a hypothetical American city of one million people (White, 2002). His approach to determining material flows, even with the omission of important inputs such as electricity, infrastructure materials, and other durable goods, helped focus attention on system-wide impacts of the consumption of goods and the generation of wastes within the urban environment (Decker et al., 2000).

The first metabolism studies of real cities were conducted in the 1970s. Interestingly the first three studies of Tokyo (Hanya and

Table 1
Chronological review of urban metabolism studies.

Author (year)	City or region of study	Notes/contribution
Wolman (1965)	Hypothetical US city of 1 million people	Seminal study
Zucchetto (1975)	Miami	Emergy approach
Stanhill (1977); Odum (1983)	1850s Paris	Emergy approach
Hanya and Ambe (1976).	Toyko	
Duvigneaud and Denayeyer-De Smet (1977)	Brussels	Includes natural energy balance
Newcombe et al. (1978); Boyden et al. (1981)	Hong Kong	Particularly comprehensive metabolism study
Girardet (1992)		Recognized link to sustainable development of cities
Bohle (1994)		Critiqued metabolism perspective for studying food in developing cities
European Environment Agency (1995)	Prague (comprehensive metabolism study)	Energy use data for Barcelona and seven other European cities given in the report.
Nilson (1995)	Gävle, Sweden	Phosphorus budget
Baccini (1997).	Swiss Lowlands	
Huang (1998).	Taipei	Emergy approach
Newman (1999); Newman et al. (1996)	Sydney	Adds liveability measures
Stimson et al. (1999)	Brisbane & Southeast Queensland	Framework relating urban metabolism to quality of life.
Hermanowicz and Asano (1999)		Water
Hendriks et al. (2000).	Vienna & Swiss Lowlands	
Warren-Rhodes and Koenig (2001).	Hong Kong	
Baker et al. (2001)	Phoenix & Central Arizona	Nitrogen balance
Sörme et al. (2001)	Stockholm	Heavy metals
Svidén and Jonsson (2001)	Stockholm	Mercury
Obernosterer and Brunner (2001)	Vienna	Lead
Færge et al. (2001)	Bangkok	Nitrogen & Phosphorus
Chartered Institute of Wastes Management (2002)	London	
Gasson (2002)	Cape Town	
Barrett et al. (2002)	York, UK	Materials
Obernosterer (2002)		Metals
Sahely et al. (2003).	Toronto	
Emmenegger et al. (2003)	Geneva	
Burstrom et al. (2003)	Stockholm	Nitrogen & Phosphorus
Gandy (2004)		Water
Lennox and Turner (2004)		State of the Environment report
Hammer and Giljum (2006)	Hamburg, Vienna and Leipzig	Materials
Kennedy et al. (2007)		Review of changing metabolism
Schulz (2007)	Singapore	Materials
Barles (2007a)	Paris	Historical study of nitrogen in food metabolism
Forkes (2007)	Toronto	Nitrogen in food metabolism
Zhang and Yang (2007)	Shenzhen, China	Develops eco-efficiency measure
Ngo and Pataki (2008)	Los Angeles	
Chrysoulakis (2008)		New project under EU 7th framework
Schremmer and Stead (2009)		New project under EU 7th framework
Barles (2009, 2007b)	Paris	Analysis of central city, suburbs and region.
Zhang et al. (2009)	Beijing	Emergy approach
Niza et al. (2009)	Lisbon	Materials
Deilmann (2009)		Studies relationship between metabolism and city surface
Baker et al. (2001)		Water
Thériault and Laroche (2009)	Greater Moncton, New Brunswick	Water
Browne et al. (2009)	Limerick, Ireland	Develops measure of metabolic efficiency

Please cite this article in press as: Kennedy, C., et al., The study of urban metabolism and its applications to urban planning and design, Environmental Pollution (2010), doi:10.1016/j.envpol.2010.10.022

Ambe, 1976), Brussels (Duvigneaud and Denayeyer-De Smet, 1977) and Hong Kong (Newcombe et al., 1978) were conducted by chemical engineers, ecologists and civil engineers respectively, recognizing the interdisciplinary nature of the topic. Given Hong Kong's status as a quasi-independent city state, the study by Newcombe et al. was particularly rich, including description of material inputs that were difficult to establish in later studies. The Hong Kong study was conducted under a UNESCO Man and the Biosphere project, which also included work on Barcelona and Rome (Barles, 2010; data on energy flows through Barcelona from Pares et al. (1985), are given by the European Environment Agency, 1995). The Brussels metabolism study was also unique in that it went beyond quantification of anthropogenic energy inputs to include a natural energy balance (Fig. 1).

Also during the 1970s, systems ecologists primarily under the leadership of Odum were studying urban metabolism from a slightly different perspective. The Odum school was primarily concerned with describing metabolism in terms of solar energy equivalents (or emergy with an 'm'). Using Odum's systems notation, Zucchetto (1975) produced a study of Miami's urban metabolism. Odum (1983) applied his approach to data presented by Stanhill (1977) for 1850s Paris, producing in a sense the oldest study of an urban metabolism. Although Odum's approach to studying urban metabolism has not become mainstream, it continues today through the work of Huang, primarily for Taipei (Huang, 1998; Huang and Hsu, 2003) and Zhang et al. (2009) for Beijing.

During the 1980s and early 1990s, progress in the study of urban metabolism was modest. There was an international symposium on urban metabolism held in Kobe, Japan, September 6–11, 1993, but few of the papers were published. One exception was the paper by Bohle (1994) which considered the potential to use an urban metabolism perspective to examine urban food systems in developing countries, and was critical of its application. Writers such as Girardet (1992), however, began to see the key connection between urban metabolism and the sustainable development of cities.

During the 1990s, there was progress in the development of the method of material flow analysis (MFA), which included application to cities. Baccini and Brunner's (1991) *Metabolism of the Anthroposphere* was followed by a substantial textbook *Regionaler Stoffhaushalt* on regional material flow analysis by Baccini and Bader (1996). Differing from Odum's focus on energy, MFA reports stocks and flows of resources in terms of mass. As an example, in the EUROSTAT guidelines for MFA, quantities of fossil fuels are reported in units of kilotonnes or kilotonnes per year. The work of Baccini and Brunner, however, building upon the earlier metabolism studies of the 1970s, more usually reports energy flow in terms of joules, with a city's flows of water, material and nutrients expressed as mass fluxes. This is arguably the approach of the mainstream school of urban metabolism.

From a deep sustainability perspective there is some merit to Odum's emergy approach, but the mainstream school of urban metabolism uses more practical units. The approach of Odum and co-workers is an attempt to apply a biophysical value theory that is applicable to both ecological and economic systems (Huang, 1998). It recognizes that there is variation in the quality of different forms of energy, i.e., different forms of energy (fuels, electricity, solar) accomplish different amounts of work. Hence solar energy equivalents are used as a universal metric. The mainstream school of urban metabolism, however, essentially just uses the units that local government officers would use, recognize and understand, e.g., in water works departments, solid waste management, or utilities, etc. Nevertheless, the two schools are not that far apart; they quantify the same items, but just use different units.

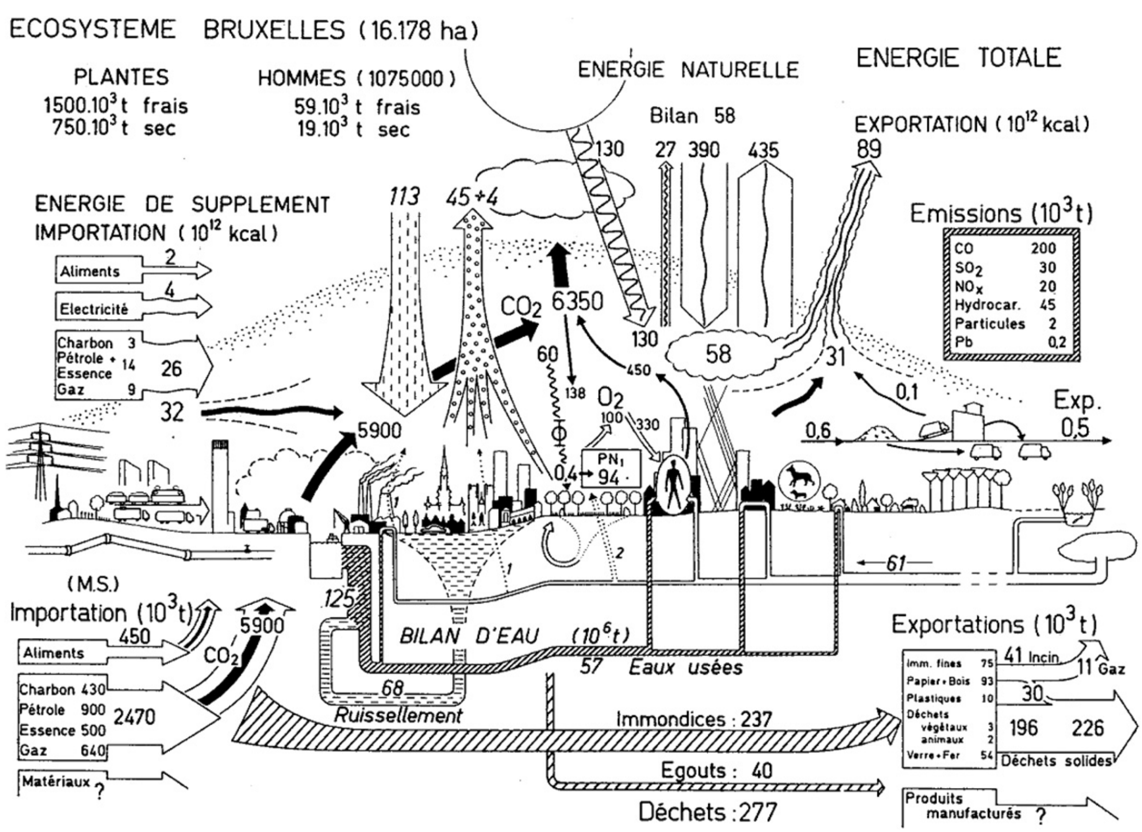

Fig. 1. The urban metabolism of Brussels, Belgium in the early 1970s (Duvigneaud and Denayeyer-De Smet, 1977).

The turn of the millennium saw rejuvenation in studies of urban metabolism: Newman (1999) published a study of the metabolism of Sydney; Baccini, Brunner and co-workers provided applications of MFA to Vienna and part of the Swiss Lowlands (Hendriks et al., 2000; Baccini, 1997); and Warren-Rhodes and Koenig (2001) produced an update of the metabolism of Hong Kong. This latter study was particularly powerful in demonstrating the need to understand urban metabolism. It described the increasing environmental impacts that of Hong Kong's transition from a manufacturing centre to a service-based economy with the addition of more than 3 million people between 1971 and 1997. Per capita food, water and materials consumption increased by 20%, 40% and 149%, respectively over 1971 values. Moreover, total air emissions, carbon dioxide outputs, municipal solid wastes and sewage discharges rose by 30%, 250%, 245% and 153% respectively (Warren-Rhodes and Koenig, 2001). These increases in the per capita metabolism of Hong Kong may be linked to higher consumption related the city's substantially increased wealth, although the authors do not fully explore the reasons behind the changes.

Newman's work on the metabolism of Sydney was conducted as part of a State of the Environment (SOE) report for Australia (Newman, 1999; Newman et al., 1996). Of particular note, was Newman's inclusion of *liveability* measures. He proposed an extended metabolism model, which included indicators of health, employment, income, education, housing, leisure and community activities. Connections between urban metabolism and quality of life have subsequently been made by other Australian researchers (Stimson et al., 1999; Lennox and Turner, 2004).

Kennedy et al. (2007) conducted a review of urban metabolism studies with a focus on understanding how metabolism was changing. Incorporating analyses of Greater Toronto (Sahely et al., 2003), Cape Town (Gasson, 2002), and Greater London (Chartered Institute of Wastes Management, 2002) with earlier studies, the review showed that the metabolism of cities is generally increasing. Kennedy et al. also highlighted the importance of understanding changes in stocks within the urban metabolism. Accumulation processes such as water in urban aquifers, construction materials, heat stored in rooftops and pavements, and nutrients deposited in soils or waste sites, need to be appropriately managed.

Studies of nutrients in the urban metabolism are amongst narrower studies focused on individual substances. Two key nutrients: nitrogen and phosphorus, were studied for Bangkok (Færge et al., 2001) and Stockholm (Burstrom et al., 2003), as well as in the Hong Kong metabolism studies. Nitrogen fluxes in food metabolism have been studied for Toronto (Forkes, 2007) and historically for Paris (Barles, 2007a). A full nitrogen balance was also conducted for the Central Arizona-Phoenix (CAP) ecosystem (Baker et al., 2001), and a phosphorus budget for the Swedish municipality of Gävle (Nilson, 1995). These studies have generally found that nutrients are accumulating in cities.

Further work has invoked the urban metabolism when addressing urban water issues. For example, see: Hermanowicz and Asano (1999), Gandy (2004), Thériault and Larcohe (2009), Sahely and Kennedy (2007) and Baker (2009).

Other studies have focused primarily on urban material stocks and flows. These include studies of Lisbon (Niza et al., 2009), Singapore (Schulz, 2007) and York, UK (Barrett et al., 2002). Hammer and Giljum (2006) quantified material flows for Hamburg, Vienna and Leipzig. Some researchers have studied specific metals in the urban metabolism, recognizing them to be both environmental burdens, but also potentially future resources (Sörme et al., 2001; Svidén and Jonsson, 2001; Obernosterer and Brunner, 2001; Obernosterer, 2002). Further material flow studies for Shenzhen, China (Zhang and Yang, 2007) and Limerick, Ireland (Browne et al., 2009) are notable for the development of measures of efficiency of the urban metabolism.

As Table 1 reveals, there has been an increasing amount of research on urban metabolism in recent years. In addition to the studies in the paragraphs above, quantification of urban metabolism has been conducted for Los Angeles (Ngo and Pataki, 2008), Geneva (Emmenegger et al., 2003) and Paris (Barles, 2007b, 2009). Broader work has linked urban metabolism to: ecosystem appropriation by cities (Folke et al., 1997); the accumulation of toxic materials in the urban building stock (Brunner and Rechberger, 2001); historical growth in the transportation of materials (Fischer-Kowalski et al., 2004); economies of scale for urban infrastructure systems (Bettencourt et al., 2007); and differences in greenhouse gas emissions from global cities (Kennedy et al., 2009a). There is rich variety in the scope of research: Deilmann (2009) studies spatial attributes of urban metabolism; Kaye et al. (2006) review urban biogeochemical cycles in the urban metabolism; and Fung and Kennedy (2005) develop links with urban macroconomic models. Further research papers may be expected from two projects on urban metabolism recently funded under the EU 7th framework: SUME (Schremmer and Stead, 2009) and BRIDGE (Chrysoulakis, 2008).

3. Applications

From its conception by Wolman, urban metabolism was studied for practical reasons; Wolman was particularly concerned with air pollution and other wastes produced in US cities. So beyond the study of urban metabolism to understand it, in a scientific sense, there are practical applications. Here we review applications in sustainability reporting, urban greenhouse gas accounting, mathematical modelling for policy analysis, and urban design. This list of four is perhaps not exhaustive; urban metabolism studies are data rich and may have other potential applications. These four serve as examples that demonstrate practical applications of urban metabolism for urban planners and designers.

3.1. Sustainability indicators

Study of the urban metabolism is an integral part of State of the Environment (SOE) reporting and provides measures that are indicative of a city's sustainability. The urban metabolism includes pertinent information about energy efficiency, material cycling, waste management, and infrastructure in urban systems. The parameters of the urban metabolism generally meet the criteria for good sustainability indicators as outlined by Maclaren (1996); they are: scientifically valid (based on principles of conservation of energy and mass), representative, responsive, relevant to urban planners and dwellers, based on data that is comparable over time, understandable and unambiguous. The main objectives of SOE reporting are to analyze and describe environmental conditions and trends of significance and to serve as a precursor to the policy-making process (Maclaren, 1996).

3.2. Inputs to urban greenhouse gas accounting

With many cities and communities aiming to reduce their greenhouse gas (GHG) emissions, a particularly useful application of urban metabolism metrics is their role in quantifying urban GHG emissions. The actual emissions of carbon dioxide, methane and other GHGs that are directly emitted from a city are legitimate components of the urban metabolism in themselves. The GHG emissions that are attributed to a city are, however, usually broader in scope including some emissions that are produced outside of urban boundaries, e.g., from electricity generation or disposal of exported waste. Whether the GHG emission occurs inside or outside of city boundaries, its calculation requires measures of

Table 2
Components of urban metabolism that are required for the inventorying of GHG emissions for cities and local communities.

Components of urban metabolism	Preferred units
Total electricity consumption	GWh
Consumption of heating and industrial fuels by each fuel type (e.g., natural gas, fuel oils, coal, LPG – includes fuels used in combined heat and power plants).	TJ for each fuel type
Total consumption of ground transportation fuels (gasoline, diesel, other) based on sales data.	Million litres for each fuel type
Volume of jet fuel loaded onto planes at airports within the boundary of the city/urban region.	Million litres
Volume of marine fuel loaded onto vessels at the city's port (if applicable).	Million litres
Tonnage and composition of landfill waste (% food, garden, paper, wood, textiles, industrial, other/inert) from all sectors; and percentage of landfill methane that is captured	t and %
Tonnage of solid waste incinerated (if applicable)	t
Masses of steel, cement, and other materials or chemicals produced in the city causing non-energy related industrial process emissions.	t

energy consumption, material flows and wastes from the urban metabolism.

According to the IPCC guidelines, GHG emissions for many sectors are broadly calculated by multiplication of an *activity level* by an *emissions factor*. For example, GHG emissions for a communities electricity supply are calculated by multiplying the level of consumption by the GHG intensity of the regional/state/provincial or national electricity supply. Emissions factors for fuels used in heating, transportation or industrial combustion are well established from national GHG inventory reporting; they are based on the combustion properties of the fuel. While the calculations are more complex for some sectors (e.g., waste), for urban GHG

Table 3
GHG emissions for cities and metropolitan regions (adapted from Kennedy et al., 2009b; note see Table 2 in source for differences in methodology).

City or metropolitan region	Definition	Year	Population	Total emissions million t CO_2 e	Per capita emissions t CO_2 e
Athens	Metropolitan region	2005	3,989,000	41.57	10.4
Barcelona	City	2006	1,605,602	6.74	4.2
Bologna	Province	2005	899,996	9.97	11.1
Brussels	Capital region	2005	1,006,749	7.55	7.5
Frankfurt	Frankfurt/Rhein Main	2005	3,778,124	51.61	13.7
Geneva	Canton	2005	432,058	3.35	7.8
Glasgow	Glasgow and the Clyde Valley	2004	1,747,040	15.30	8.8
Hamburg	Metropolitan region	2005	4,259,670	41.52	9.7
Helsinki	Capital region	2005	988,526	6.94	7.0
London	Greater London	2003	7,364,100	70.84	9.6
Ljubljana	Osrednjeslovenska region	2005	500,021	4.77	9.5
Madrid	Comunidad de Madrid	2005	5,964,143	40.98	6.9
Naples	Province	2005	3,086,622	12.49	4.0
Oslo	Metropolitan region	2005	1,039,536	3.63	3.5
Paris	Ile de France	2005	11,532,398	59.64	5.2
Porto	Metropolitan region	2005	1,666,821	12.14	7.3
Prague	Greater Prague	2005	1,181,610	11.03	9.3
Rotterdam	City	2005	592,552	17.64	29.8
Stockholm	Metropolitan region	2005	1,889,945	6.88	3.6
Stuttgart	Metropolitan region	2005	2,667,766	42.57	16.0
Torino	Metropolitan region	2005	2,243,000	21.86	9.7
Veneto	Province	2005	4,738,313	47.29	10.0
Austin	City	2005	672,011	10.48[a]	15.6[a]
Calgary	City	2003	922,315	16.37[a]	17.7[a]
Denver	City and county	2005	579,744	11.08	19.4
Los Angeles	County	2000	9,519,338	124.04	13.0
Minneapolis	City	2005	387,711	7.03[a]	18.3[a]
New York	City	2005	8,170,000	85.87	10.5
Portland	City	2005	682,835	8.47[a]	12.4[a]
Seattle	City	2005	575,732	7.82[a]	13.7[a]
Toronto	Greater Toronto Area	2005	5,555,912	64.22	11.6
Washington	District of Columbia	2000	571,723	11.04[a]	19.3[a]
Mexico City	City	2000	8,669,594	35.27[a]	4.1[a]
Rio de Janeiro	City	1998	5,633,407	12.11	2.1
Sao Paulo	City	2000	10,434,252	14.22	1.4
Bangkok	City	2005	5,658,953	60.44	10.7
Beijing	Beijing Government administered area	2006	15,810,000	159.00	10.1
Delhi	Metropolitan area	2000	15,700,000	20.65[a]	1.6[a]
Kolkata	National capital territory	2000	13,200,000	17.80[a]	1.1[a]
Shanghai	Shanghai Government administered area	2006	18,150,000	211.98	11.7
Seoul	Seoul City	1998	10,321,496	42.03[a]	4.1[a]
Tianjin	Tianjin Government administered area	2006	10,750,000	119.25	11.1
Tokyo	Tokyo metropolitan government admin. area	2006	12,677,921	62.02	4.9
Cape Town	City	2006	3,497,097	40.43	11.6

[a] Excludes aviation and marine emissions.

Please cite this article in press as: Kennedy, C., et al., The study of urban metabolism and its applications to urban planning and design, Environmental Pollution (2010), doi:10.1016/j.envpol.2010.10.022

inventories, the urban metabolism parameters essentially provide the required measures of activity levels (Table 2).

A comparison of the GHG emissions from ten global cities was undertaken by Kennedy et al. (2009a, 2010), largely drawing upon urban metabolism studies. Results from a wider study of GHG emissions from forty cities are shown in Table 3 (Kennedy et al., 2009b).

3.3. Dynamic mathematical models for policy analysis

While most researchers have primarily used the urban metabolism as the basis of an accounting framework, others have begun to develop mathematical models of processes within the urban metabolism. Such mathematical models have mainly been developed by the MFA community, usually to study specific substances – metals or nutrients in the urban or regional metabolism. Example model platforms include SIMBOX (Baccini and Bader, 1996) and STAN (Cencic and Rechberger, 2008; Brunner and Rechberger, 2004). These models include representation of sub-processes, stocks and flows within the metabolism, sometimes linked to economic input–output models.

While the models are useful for determining present material stock and flows, they can also be used to simulate future changes to the urban metabolism as a result of technological interventions or policies. The models are particularly useful for identifying solutions to environmental issues beyond "end of pipe" approaches.

3.4. Design tools

The potential to use the concept of urban metabolism in an urban design context is a relatively new development. Perhaps the first serious attempt to move beyond analysis to design is described in *Netzstadt* by Oswald and Baccini (2003). Fernandez and students in MIT's School of Architecture have used the perspective of urban metabolism in considering redesign of New Orleans, while students in Civil Engineering at the University of Toronto study the urban metabolism in order to design infrastructure for sustainable cities.

In Netzstadt, Oswald and Baccini begin to demonstrate how a combination of morphological and physiological tools can be used in the "*long process of reconstructing the city*." Their starting point is recognition that the center–periphery model of cities is outdated, but the new urbanity is not sustainable. They proceed to provide four principles for redesigning cities: shapability; sustainability; reconstruction; and responsibility. Five criteria of urban quality: identification; diversity; flexibility; degree of self-sufficiency; and resource efficiency, are then sought in a design approach that includes analysis of urban metabolism. The four major urban activities: to nourish and recover; to clean; to reside and work; and to transport and communicate, as identified by Baccini and Brunner (1991) are assessed in terms of four major components of urban metabolism: water, food (biomass), construction materials, and energy. Several examples partially demonstrate the integration of morphological and physiological perspectives.

Urban metabolism has also been invoked in the much more rapid reconstruction of New Orleans that followed after Hurricane Katrina. John Fernandez and students at MIT, use material flow analysis to help with producing more ecologically sensitive designs for the city (Quinn, 2007).

Civil Engineering students at the University of Toronto also use the urban metabolism as a tool to guide sustainable design (Fig. 2). The students are faced with design challenges typically at the neighborhood scale, which involve integration of various infrastructure using the concept of neighborhood metabolism (Codoban and Kennedy, 2008; Engel Yan et al., 2005; Kennedy, 2007). The students use best practices in green building design, sustainable transportation and alternative energy systems in their work. By tracing the flows of water, energy, nutrients and materials through an urban system, it can be designed to close loops, thus reducing the input of resources and output of wastes.

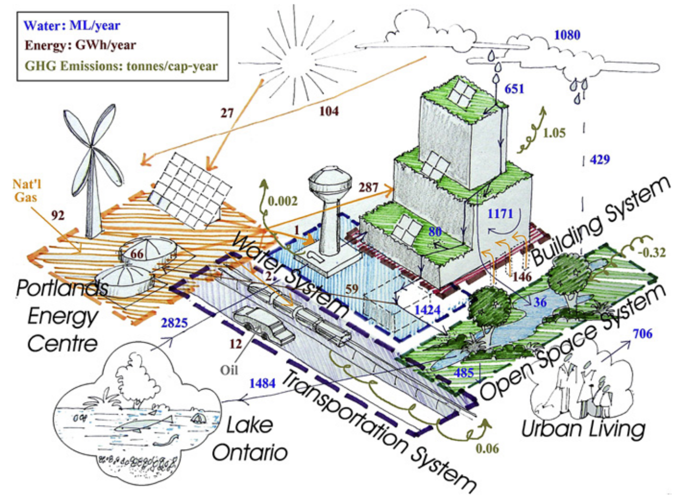

Fig. 2. Representation of a sustainable metabolism for the Toronto Port Lands, designed by graduate students at the University of Toronto.

The urban metabolism analysis of one group shows just how close it came to a fundamentally sustainable design (Fig. 3). Greywater was used for toilets, and outdoor use; sludge from waste water was used on community gardens for food production. Energy from the imported municipal waste not only powered the buildings, it also provided for the light rail system and returned some excess electricity to the grid. Moreover, fly-ash from the waste gasification plant was recycled as building material. By partially closing these loops, inputs of energy, water, materials, and nutrients were significantly reduced.

The tracking of energy and material flows in urban design in order to reduce environmental impacts is also conducted by practitioners. Arup's Integrated Resource Modelling (IRM) tool which was used for master planning of Dongtan and the Thames Gateway is essentially an urban metabolism model. It is used to assess the sustainability performance of different strategies for the built environment.

4. Future directions

There is a growing body of knowledge on urban metabolism. Over 50 papers have been referenced here, some of which are relatively comprehensive studies of metabolism, others that analyze particular components, such as energy, water, nutrients, metals etc. These studies provide valuable insights into the functioning of specific cities at particular points in time, but there is still more to learn. There are only few cross-sectional studies of multiple cities and a lack of time series studies of urban metabolism.

As Barles (2010) observes much of the research on urban metabolism is now being conducted within the industrial ecology community, which has broadened from its initial focus on industrial metabolism to include social and urban metabolism. A workshop held by industrial ecologists at MIT in January 2010, identified several research needs, including:

- work on the relationship between urban metabolism and the urban poor
- efforts to collect and combine energy use data from world cities

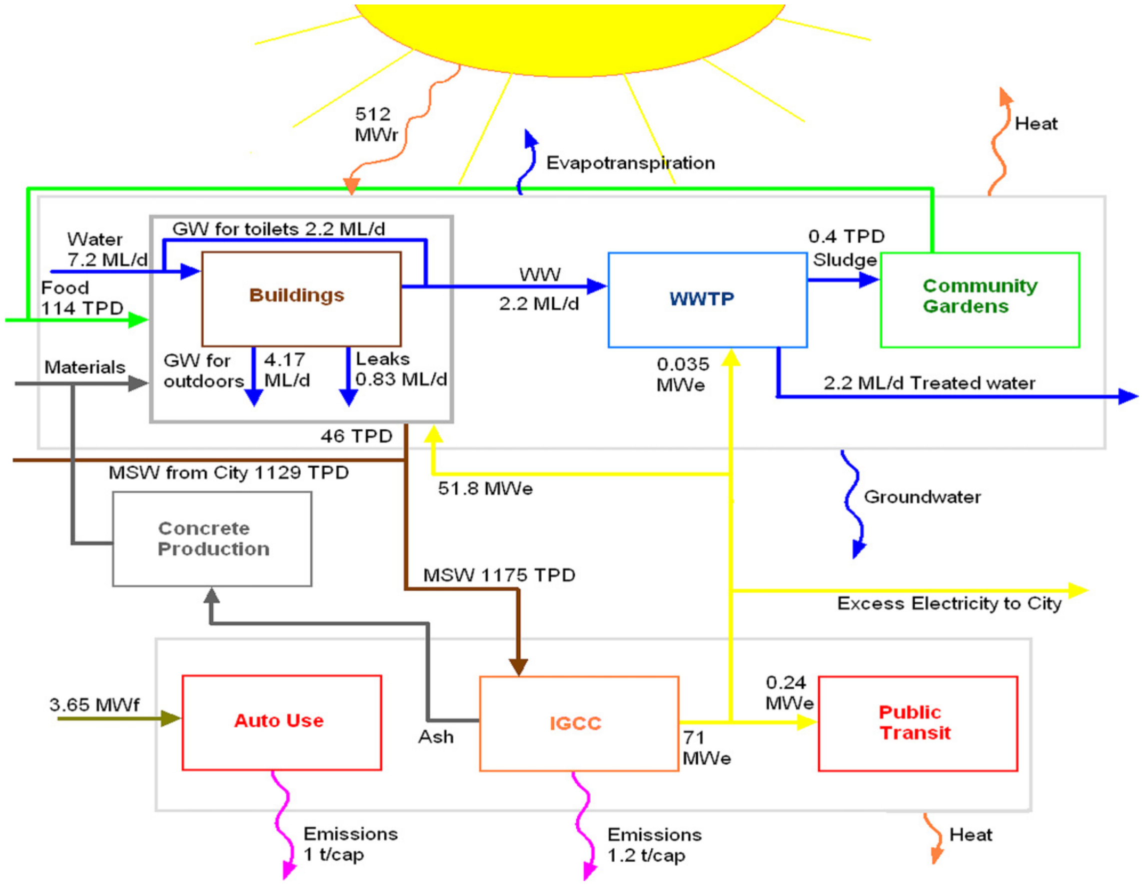

Fig. 3. The urban metabolism of the Toronto Port Lands shows reduction in inputs of energy, water, materials, and nutrients due to the partial closing of these loops (designed by a second group of graduate students at the University of Toronto).

- development of a standard classification system for stocks and flows in the urban metabolism.

Another important future direction is fuller integration of social, health and economic indicators into the urban metabolism framework. While others, such as Newman (1999), have previously proposed that social indicators be included in the urban metabolism, such indicators have tended to be *added on*. Social, heath and economic impacts are, however, inherently related to the urban metabolism. For example, high consumption of gasoline and high rates of obesity are both related to an auto dependent lifestyle. Hence, a framework for sustainable city/community indicators, developed for the Public Interest Energy Research Program (PIER) of the California Energy Commission, links social, health and economic indicators to the urban metabolism in the form of a matrix.

The advantages of using an urban metabolism framework as a unifying research theme are that it (Pincetl and Bunje, 2009):

1. explicitly identifies of the system's boundaries;
2. accounts for inputs and outputs to the system;
3. allows for a hierarchical approach to research;
4. includes decomposable elements for targeted, sectoral research;
5. necessitates analysis of policy and technology outcomes with respect to sustainability goals;
6. is an adaptive approach to solutions and their consequences; and
7. integrates social science and biophysical science/technology.

While there is much interest in the science of urban metabolism, great efforts are still required to get it established in the practice of urban planning and design. The need to do so has been clearly articulated. For example, in contemplating what is required to approach sustainability, Oswald and Baccini (2003) suggest that it will require no less than the reconstruction of our cities. They write:

> "*Reconstruction … means launching an intelligent experiment in a democratic society in order to ensure the survival of the contemporary city. We cannot foresee the final state of this process. We are defining the quality goals of a new regionally customized urban life*"
> "*Customization means that every society consisting of several million people must, for instance, develop concrete ideas on where they will obtain water, food, material and energy over the long term, without depleting regional or global resources; ideas on how they will renew experiential knowledge, promote creative capabilities and create symbols, without poisoning their relationship to their own origins or disrupting global communication*"

Significant progress has been made over the past decade by the green/sustainable building industry in tracking energy and material flows at the building scale. There is arguably a need for the planning and design community – specifically architects, engineers and planners – to step up to higher level. Studies of resource flows for neighborhood developments or entire cities needs to become mainstream practice, rather than just a rare exercise for experimental Dongtan-like developments. This requires the design community to become much more numerate in energy and material flows. The challenge ahead is to *design the urban metabolism* of sustainable cities.

Please cite this article in press as: Kennedy, C., et al., The study of urban metabolism and its applications to urban planning and design, Environmental Pollution (2010), doi:10.1016/j.envpol.2010.10.022

Acknowledgment

The authors are grateful for the support of the California Energy Commission, PIER Program.

References

Baccini, P., 1997. A city's metabolism: towards the sustainable development of urban systems. Journal of Urban Technology 4 (2), 27–39.
Baccini, P., Brunner, P.H., 1991. Metabolism of the Anthroposphere. Springer Verlag, Berlin.
Baccini, P., Bader, H.-P., 1996. Regionaler Stoffhaushalt, Spektrum Akad. Verlag.
Baker, L.A., Hope, D., Xu, Y., Edmonds, J., Lauver, L., 2001. Nitrogen balance for the Central Arizona-Phoenix (CAP) ecosystem. Ecosystems 4, 582–602.
Baker, L.A. (Ed.), 2009. The Water Environment of Cities. Springer, US.
Barles, S., 2007a. Feeding the city: food consumption and flow of nitrogen, Paris, 1801–1914. Science of the Total Environment 375 (1–3), 48–58.
Barles, S., 2007b. A material flow analysis of Paris and its region. Renewables in a changing climate-innovation in the built environment. In: Proceedings of the International Conference CISBAT 2007. École Polytechnique Fédérale de Lausanne, Lausanne, pp. 579–584. 4–5. September 2007.
Barles, S., 2009. Urban metabolism of Paris and its region. Journal of Industrial Ecology 13 (6), 898–913.
Barles, S., 2010. Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues. Journal of Environmental Planning and Management 53 (4), 439–455.
Barrett, J., Vallack, H., Jones, A., Haq, G., 2002. A Material Flow Analysis and Ecological Footprint of York. Technical Report. Stockholm Environment Institute, Stockholm, Sweden.
Bettencourt, L., Lobo, J., Helbing, D., Kuhnert, C., West, G.B., 2007. Growth innovation scaling and the pace of life in cities. Proceedings of the National Academy of Sciences of the United States of America 104, 7301–7306.
Bohle, H.G., 1994. Metropolitan food systems in developing countries: the perspective of urban metabolism. GeoJournal 34 (3), 245–251.
Boyden, S., Millar, S., Newcombe, K., O'Neill, B., 1981. The Ecology of a City and its People: The Case of Hong Kong. Australian National University Press, Canberra.
Browne, D., O'Regan, B., Moles, R., 2009. Assessment of total urban metabolism and metabolic inefficiency in an Irish city-region. Waste Management 29 (10), 2765–2771.
Brunner, P.H., Rechberger, H., 2001. Anthropogenic metabolism and environmental legacies. In: Munn, T. (Ed.), Encyclopedia of Global Environmental Change, vol. 3. Wiley, UK.
Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis. CRC Press, Boca Raton, Florida.
Burstrom, F., Frostell, B., Mohlander, U., 2003. Material flow accounting and information for environmental policies in the city of Stockholm. Workshop Quo vadis MFA? Material Flow Analysis-Where Do We Go? Issues Paper presented at the, Trends and Perspectives of Research for Sustainable Resource Use, 9–10 October, Wuppertal, Germany
Cencic, O., Rechberger, H., 2008. Material flow analysis with software STAN. Journal of Environmental Engineering and Management 18 (1), 3–7.
Chartered Institute of Wastes Management, 2002. A Resource Flow and Ecological Footprint Analysis of Greater London. Best Foot Forward, London.
Chrysoulakis, N., 2008. Urban metabolism and resource optimisation in the urban fabric: the BRIDGE methodology. In: Proceedings of EnviroInfo2008: Environmental Informatics and Industrial Ecology, September 10–12, vol. 1. Leuphana University of Lüneburg, Germany, pp. 301–309.
Codoban, N., Kennedy, C.A., 2008. The metabolism of neighbourhoods. ASCE Journal of Urban Planning and Development 134 (1), 21–31.
Decker, H., Elliott, S., Smith, F.A., Blake, D.R., Sherwood Rowland, F., 2000. Energy and material flow through the urban ecosystem. Annual Review of Energy and the Environment 25, 685–740.
Deilmann, C., 2009. Urban metabolism and the surface of the city. In: German Annual of Spatial Research and Policy, Guiding Principles for Spatial Development in Germany. Springer, Berlin Heidelberg.
Duvigneaud, P., Denayeyer-De Smet, S., 1977. L'Ecosystéme Urbs, in L'Ecosystéme Urbain Bruxellois, in Productivité en Belgique. In: Duvigneaud, P., Kestemont, P. (Eds.), Traveaux de la Section Belge du Programme Biologique International, Bruxelles, pp. 581–597.
Emmenegger, M.F., Frischknecht, R., Cornaglia, L., Rubli, S., 2003. Métabolisme des activités économiques du Canton de Genève –Phase 1 Rapport final.
Engel Yan, J., Kennedy, C.A., Saiz, S., Pressnail, K., 2005. Towards sustainable neighbourhoods: the need to consider infrastructure interactions. Canadian Journal for Civil Engineering 32 (1), 45–57.
European Environment Agency, 1995. Europe's Environment: The Dobris Assessment. Earthscan, London.
Færge, J., Magid, J., Penning de Vries, F.W.T., 2001. Urban nutrient balance for Bangkok. Ecological Modelling 139, 63–74.
Fischer-Kowalski, M., Krausmann, F., Smetschka, B., 2004. Modelling scenarios of transport across history from a socio-metabolic perspective. Review – Fernand Braudel Center 27, 307–342.
Folke, C., Jansson, Å, Larsson, J., Costanza, R., 1997. Ecosystem appropriation by cities. Ambio 26, 167–172.
Forkes, J., 2007. Nitrogen balance for the urban food metabolism of Toronto, Canada. Resources, Conservation & Recycling 52 (1), 74–94.
Fung, M., Kennedy, C.A., 2005. An integrated macroeconomic model for assessing urban sustainability. Environment and Planning, B 32 (5), 639–656.
Gandy, M., 2004. Rethinking urban metabolism: water, space and the modern city. City 8 (3), 363–379.
Gasson, B., 2002. The ecological footprint of Cape Town: unsustainable resource use and planning implications, SAPI International Conference: Planning Africa, Durban South Africa.
Girardet, H., 1992. The Gaia Atlas of Cities. Gaia Books Limited, London.
Hammer, M., Giljum, S., 2006. Materialflussanal- ysen der Regionen Hamburg, Wien und Leipzig. (Material flow analysis of the regions of Hamburg, Vienna and Leipzig) NEDS Working Papers #6 (08/2006), Hamburg, Germany.
Hanya, T., Ambe, Y., 1976. A study on the metabolism of cities. In: Science for a Better Environment. HSEC, Science Council of Japan, pp. 228–233.
Hermanowicz, S.W., Asano, T., 1999. Abel Wolman's the metabolism of cities' revisited: a case for water recycling. Water Science & Technology 40 (4), 29–36.
Heynen, N.C., Kaika, M., Swyngedouw, E., 2005. In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism. Routledge.
Hendriks, C., Obernosterer, R., Muller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. Material flow analysis: a tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands. Local Environment 5, 311–328.
Huang, S., 1998. Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. Journal of Environmental Management 52, 39–51.
Huang, S.-L., Hsu, W.-L., 2003. Materials flow analysis and energy evaluation of Taipei's urban construction. Landscape and Urban Planning 63 (2), 61–74.
Kaye, J.P., Groffman, P.M., Grimm, N.B., Baker, L.A., Pouyat, R.V., 2006. A distinct urban biogeochemistry? Trends in Ecology & Evolution 21 (4), 192–199.
Kennedy, C.A., 2007. Applying industrial ecology to design a sustainable built environment: the Toronto Port Lands challenge, In: Engineering Sustainability Conference, Pittsburgh, USA, April 15–18.
Kennedy, C.A., Cuddihy, J., Engel Yan, J., 2007. The changing metabolism of cities. Journal of Industrial Ecology 2007 (11), 43–59.
Kennedy, C., Steinberger, J., Gasson, B., Hillman, T., Havránek, M., Hansen, Y., Pataki, D., Phdungsilp, A., Ramaswami, A., Villalba Mendez, G., 2009a. Greenhouse gas emissions from global cities. Environmental Science and Technology 43, 7297–7302.
Kennedy, C.A., Ramaswami, A., Carney, S., Dhakal, S., 2009b. Greenhouse gas emission baselines for global cities and metropolitan regions. In: Plenary paper presented at the World Bank's Fifth Urban Research Symposium, Marseille, France, June 28–30.
Kennedy, C., Steinberger, J., Gasson, B., Hillman, T., Havránek, M., Hansen, Y., Pataki, D., Phdungsilp, A., Ramaswami, A., Villalba Mendez, G., 2010. Methodology for inventorying greenhouse gas emissions from global cities. Energy Policy 37 (9).
Lennox, J., and Turner, G., 2004. State of the environment report on human settlements: stocks and flows indicators. In: Technical report CSIRO Sustainable Ecosystems. Prepared for the 2006 Australian State of the Environment Committee.
Maclaren, V., 1996. Developing Indicators of Urban Sustainability: A Focus on the Canadian Experience. Intergovernmental Committee on Urban and Regional Research, ICURR Press, Toronto, ON.
Newcombe, K., Kalma, J., Aston, A., 1978. The metabolism of a city: the case of Hong Kong. Ambio 7, 3–15.
Newman, P.W.G., Birrell, R., Holmes, D., Mathers, C., Newton, P., Oakley, G., O'Connor, A., Walker, B., Spessa, A., Tait, D., 1996. Human settlements. In: Australian State of the Environment Report. Department of Environment, Sport and Territories, Canberra, Australia.
Newman, P.W.G., 1999. Sustainability and cities: extending the metabolism model. Landscape and Urban Planning 44, 219–226.
Niza, S., Rosado, L., Ferrão, P., 2009. Urban metabolism: methodological advances in urban material flow accounting based on the Lisbon case. Journal of Industrial Ecology 13 (3), 384–405.
Ngo, N.S., Pataki, D.E., 2008. The energy and mass balance of Los Angeles County. Urban Ecosystems 11, 121–139.
Nilson, J., 1995. A phosphorus budget for a Swedish municipality. Journal of Environmental Management 45, 243–253.
Obernosterer, R., 2002. Urban metal stocks: future problem or future resource? Substance flow and stock analysis as a tool to achieve sustainable development. In: International Conference Regional Cycles: Regional Economy Towards Sustainability, 31 October–2 November, Leipzig, Germany.
Obernosterer, R., Brunner, P.H., 2001. Urban metal management the example of lead. Journal Water, Air, & Soil Pollution: Focus 1 (3–4), 241–253.
Odum, H.T., 1983. Systems Ecology, an Introduction. Wiley-Interscience, New York, NY.
Oswald, F., Baccini, P., 2003. Netzstadt: Designing the Urban. Birkhäuser.
Pares, M., Pou, G., Terradas, J., 1985. Descobrir el Medí Urba; Ecología d'una ciutat: Barcelona. Centre del Medi Urba, Barcelona.
Pincetl, S., Bunje, P.M.E., 2009. Potential Targets and Benefits for Sustainable Communities Research, Development, and Demonstration Funded by the PIER Program, prepared for California Energy Commission, UCLA Institute of the Environment.
Quinn, D., 2007. Urban Metabolism: Ecologically Sensitive Construction for a Sustainable New Orleans. http://web.mit.edu/djq/Public/Thesis/Holcim_April_07_David_Quinn.pdf.

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

Sahely, H.R., Kennedy, C.A., 2007. Integrated systems flow model for quantifying environmental and economic sustainability indicators: case study of the City of Toronto urban water system. ASCE Journal of Water Resources Planning and Management 133 (6), 550–559.

Schremmer, C., Stead, D., 2009. Sustainable urban metabolism for Europe (SUME). In: Paper Presented at the World Bank's Fifth Urban Research Symposium Marseille, France June 28–30, 2009.

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

Sörme, L., Bergbäck, B., Lohm, U., 2001. Century perspective of heavy metal use in urban areas. a case study in Stockholm. Journal Water, Air, & Soil Pollution: Focus 1 (3–4), 197–211.

Stanhill, G., 1977. An urban agro-ecosystem: the example of nineteenth-century Paris. Agro-Ecosystems 3, 269–284.

Stimson, R.J., Western, J., Mullins, P., Simpson, R., 1999. Urban metabolism as a framework for investigating quality of life and sustainable development in the Brisbane-Southeast Queensland Metro region. In: Yuen, B.K.P., Löw, C., Low, C. (Eds.), Urban Quality of Life: Critical Issues and Options. Springer Chapter 9.

Svidén, J., Jonsson, A., 2001. Urban metabolism of mercury turnover, emissions and stock in Stockholm 1795–1995. Journal Water, Air, & Soil Pollution: Focus 1 (3–4), 79–196.

Tarr, J.A., 2002. The Metabolism of an industrial city: the case of Pittsburgh. Journal of Urban History 28, 511.

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

Warren-Rhodes, K., Koenig, A., 2001. Escalating trends in the urban metabolism of Hong Kong: 1971–1997. Ambio 30 (7), 429–438.

White, R., 2002. Building the Ecological City. Woodhead, Cambridge.

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

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

Zhang, Y., Yang, Z., Yu, X., 2009. Evaluation of urban metabolism based on energy synthesis: a case study for Beijing. Ecological Modelling 220 (13–14), 1690–1696.

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

Please cite this article in press as: Kennedy, C., et al., The study of urban metabolism and its applications to urban planning and design, Environmental Pollution (2010), doi:10.1016/j.envpol.2010.10.022