Ecotechnology working paper 2016-1c

Energy, emergy, and the city[1]

Erik Grönlund, Morgan Fröling, Torbjörn Skytt
Ecotechnology and Sustainable Building Engineering, Mid Sweden University, 83125 Östersund
Corresponding Author e-mail: erik.gronlund@miun.se

Abstract

In his book "Environment, Power, and Society" (1971) H.T. Odum introduced a picture of the energy metabolism of a city based on Wolman's paper from 1965 (Sci. Am., 213: 179-190). With the development of the emergy analysis--a branch of energy systems accounting--several authors have contributed to develop quantitative measures of HT Odum's picture, which from many perspectives are diverging from traditional energy studies. In this paper, studies using emergy analysis to study cities are reviewed. The research regarding emergy and cities had during the period 1975-1995 its focus on cities in the United States, e.g. Miami, Jacksonville, San Francisco and Chicago. The research during 1995-2005 was almost exclusively focused on Taipei. From approximately 2006 up till 2015 the research focus has been on Chinese cities; Macao, Beijing and 37 other Chinese cities have been investigated. But there are resent also studies made on Rome (Italy) and Montreal (Canada). Studies up to about 2007/2008 were generally concerned with understanding spatial aspects of the cities investigated. After that, evaluating the sustainability of cities has become a main research focus.

Keywords: Emergy assessment, Spatial distribution, Sustainable city

1 Introduction

With half of the world population living in cities, such anthropogenic structures are important to understand. One approach is to extend a more traditional thinking on ecosystems to incorporate also the human society and its technical systems. A central research theme for the systems ecologist H.T. Odum was how ecosystems and general systems can be described from an energy perspective. This was his approach in the seminal research on food webs in Silver Springs, Florida – a cornerstone study in many textbooks on ecology – and in the work with his brother, E.P. Odum, on the coral reefs at the Eniwetok Atoll (Cleveland, 2008). In his book "*Environment, Power, and Society*" (Odum, 1971) he continued and extended his work applying the energy hierarchies found for food webs of natural systems to systems also including humans. Working with this approach, Odum found systems properties of energy hierarchies of systems including many living organisms that were difficult to deal with using only traditional thermodynamic descriptions of energy flows, developed for describing heat engines and later chemical processes (Giannantoni, 2002). H.T. Odum thus started to develop new concepts to describe the situation he observed, that would later be grouped under the heading Emergy. The latest previous overview of this topic is more than 20 years old (Odum et al., 1995). During the

[1] Version 3, 14 April 2016, (version 1 from 30 March 2015 is available in the conference proceedings of the 9th BIWAES conference Energy and Urban Systems, held in Stockholm 4-7 May 2015)

last decade an increasing amount of emergy papers have addressed cities, especially in China. This paper gives a review of how the emergy concept has been used in the context of cities during the whole period of 1971-2015.

In section 2 is explained how energy and emergy are related to each other. Section 3 contains the review of the use of emergy in the context of cities, spatial focus, what quantitative emergy related parameters that has been used and underlying research motivation is analyzed. The section is divided into two periods: 1971-1995, earlier described by Odum et al (1995), and 1996-2015. Section 4 contains the discussion.

2 Methods and concepts

This study is based on a literature search in the databases ScienceDirect and Springer Link, and on publication lists available at the web site Emergy Systems[2]. Search terms have been "emergy", "city", "cities", and "urban". All publications found are reported in Table 3 of this paper, except for a few very short conference papers.

2.1 Energy and emergy

Emergy is a concept developed in systems ecology (Odum, 1994, 1996), and is in some ways similar to the concept of primary energy, sometimes used for understanding human constructed technical systems (Arvidsson et al., 2012). In H.T. Odum's many studies of natural and human ecosystems he had found that describing energy flows by the mass flows and their heating values did not capture all qualitative aspects of the energy hierarchies of the nutrient webs that he could observe. He therefore started to express energy units in terms of the type of energy that generated it. An example used by Odum (1996) was to express coal power plant electricity in terms of how much coal energy was needed to produce it. On average, for the existing technology at that time, it took 4 joules of coal to produce 1 joule of electricity. The electricity from the coal could then be expressed as 4 coal emergy joules (cej). So far this practice is the same as for a primary energy calculation.

However, any hard coal or brown coal that can be mined from the ground are in themselves results of complex biogeochemical processes over long time, and originates ultimately from solar energy captured by photosynthesis creating the biomass that eventually has been converted into coal. Thus the hard coal could in turn be expressed in how many joules of solar energy it took to produce it, solar emergy joules (sej). Solar emergy joules is today the dominating unit to express emergy, but in principle any type of energy carrier can be chosen. The calculation is also here similar to a primary energy calculation, with a main difference in that primary energy seldom is calculated further back than through the man made technical systems, whereas emergy generally takes the calculation back through the bio-geo-chemical transformation in nature to the energy inputs to the biosphere, with the main input being the influx of solar radiation (but also gravitational energy generating tidal flows and geothermal heat). A significant conceptual difference to the conventional primary energy calculations (see Arvidsson et al 2012) emerge from its roots in system ecology, though; if an ecosystem converts solar radiation into different types of energy carriers, the whole biological system is considered needed for each of the output, it is not allocated to different outputs (Odum, 1996).

H.T. Odum (1996) described emergy as the previous energy it took to generate the actual type of joule, and all of them expressed in one type of energy, almost always solar energy, giving the sej unit. Emergy is often said to be an abbreviation of "energy memory". This view is relevant in many cases, but sometimes it can be useful to think of the concept as a steady state equilibrium measure where everything is produced in average amounts within the time frame chosen (Grönlund, 2009). In modeling terms this means that no stocks are changed. This is of course almost never the real situation, where stocks of for example wood, or body fat, are used in cyclic or fluctuating patterns, and stocks sometimes built up, sometimes used up. However, the

[2] www.emergysystems.org

simplified description of 'no change in stocks' can still be helpful to grasp the concept of emergy, since it to some extent diverts from our everyday use of the word energy (where we happily add up different kinds of energies). Odum also introduced the concept Empower, which is the flow of emergy per time unit.

Emergy can be used to understand structures of ecosystems - the different form of energy that flows through an ecosystem, and to describe hierarchical patterns created by the living ecosystems channeling energy flows in different ways. Since humans and the human society can be seen as part of ecosystems, or emerging from ecosystems, emergy studies can potentially reveal similar information on human societal artifacts, like cities. Such application of emery studies, especially when applied to cities, is the focus of this paper.

3 Emergy and the city

3.1 The period 1971-1995

Regarding emergy and the city it was addressed already in H.T. Odum's book "*Environment, Power, and Society*" from 1971. In a picture (Figure 1-3 in that book, based on Wolman's paper from 1965 the similarities between the energy metabolism of an oyster reef and a city were pointed out. No more explicit discussion on cities was presented in "*Environment, Power, and Society*", other than that cities were natural centers, or nodes, higher up in the energy hierarchies of the world. This had not changed in Odum's second book from 1976, the more popular written "*Energy basis for man and nature*" (co-authored with Elisabeth C. Odum). Cities was not further described in emergy terms except that the internal internal structure of the city was sketched in Figure 10-2 in that book.

However, during these years several references reveal that cities were in focus in H.T. Odum's research. A young Mark Brown – Odum's long time coworker for the coming 30 years - wrote a Master's thesis on the subject 1973 (Brown, 1973), and James Zucchetto was also already working on the subject, and his dissertation with an urban focus was presented in 1975 "*Energy basis for Miami, Florida, and other urban systems*" (Zucchetto, 1975a; Zucchetto, 1975b). Mark Brown, during the second half of the 1970s, wrote his doctoral thesis about "*Energy hierarchies in urban and regional landscapes*", presented 1980 (Brown, 1980).

At some point during this period H.T. Odum also introduced a course - Ecological and General Systems - that was taught during one semester (Odum, 1983, foreword), and later published in an extended version: "Systems ecology: An introduction" (Odum, 1983). A separate chapter in this book was assigned to "Cities and regions" presenting several models from the works of James Zucchetto (1975) and Mark Brown (1980).

During the 1990s research using emergy to understand cities was continued with publications by Whitfield (1995), Lopez and Brown (1995), Woithe (1995a, b) and Doherty (1995), all summarized in the 1995 project "*Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society*" (Odum et al., 1995). This project also included an important international cooperation with Dr. Shu-Li Huang, who brought the urban focus in emergy research to East Asia.

3.1.1 The 1995 report

The report "*Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society*" (Odum et al., 1995) was the result of a new cooperation around the fast growing cities in Asia, but it also summarized research on emergy and cities so far. The research summary was the base for the spatial descriptions of cities presented in Figures 1 and 2. In Figure 1, the left hand side of the figure represents the older "agrarian city" with most people living outside the town center, but centered on and around it. The right hand side in Figure 1 represents a newer town structure, with the city built during a period of increased use and high availability of fossil fuels. A theory of emergy and landscape hierarchy was presented; some of the hypothetical outcomes are presented in Figure 2.

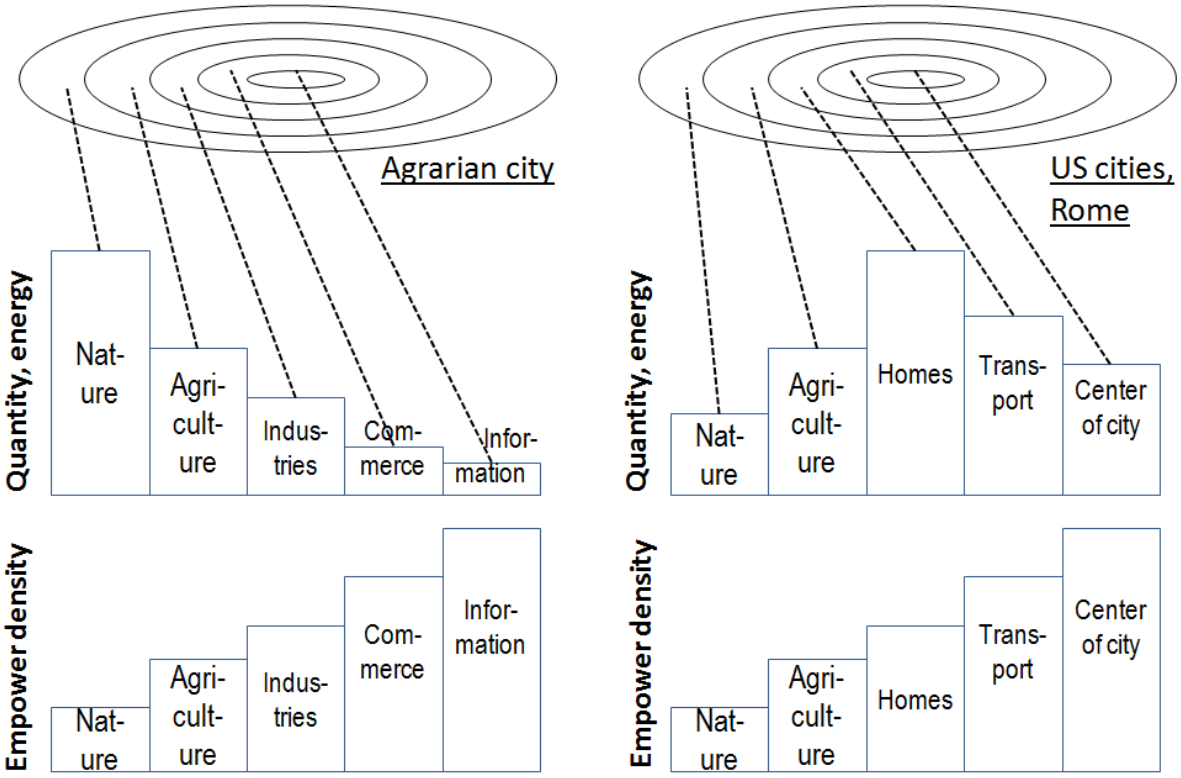

Fig.1. Model of zones of a city in an agrarian landscape and in a city in a fuel-based urban landscape, both with hypothetical distribution of energy and empower (emergy/time). (Redrawn from Figure 1 and 2 in Odum et al., 1995)

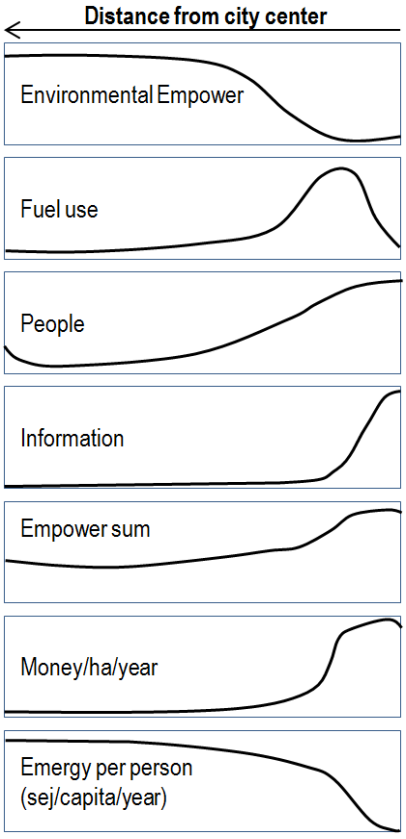

Fig.2. Hypothetical gradients in zonal properties around a city. (Redrawn from Figure 3 and 4 in Odum et al., 1995)

In the report (Odum et al., 1995) a city was considered a natural concentration of information and people, in the energy hierarchy of landscapes. The similarities between cities and ecosystems were pointed out; Lopez and Brown (1995) mentioned succession and metabolism. As in natural ecosystems there are succession phases: growth, homeostasis, regression, renewal and oscillation (Odum, 1983). The metabolism of the city is also similar to natural systems like coral reefs or ant hills in the respect that a city assimilates resources from the surroundings, transforms them within the city structure, and releases waste to the surroundings.

Lopez and Brown (1995) investigated Miami along seven transects and found a clear zonation in the city from the center to the periphery 25 km out. The highest Empower (emergy/time) was found 5-15 km from the center. Whitfield (1995) investigating Jacksonville, Florida, also found structure in the energetic organization. However, here the center of the city had very high Empower, decreasing fast at first and then slower out to east and west. Woithe (1995b) investigated different zones for empower density in Chicago and San Francisco and found gradients in all of them.

3.2 The period 1996-2015

While earlier emergy studies of cities mainly considered cities in the USA, the main body of the scientific publications after 1995 considers cities outside the USA with a main focus on Asia. For several years in the beginning of this period nearly all published emergy studies regarding cities was on the single city Taipei, Taiwan.

3.2.1 Taipei

The earlier mentioned report including the overview of emergy studies on cites published in 1995 (Odum et al., 1995) was a co-project with professor Shu-Li Huang, National Taipei University, Taiwan. Already in 1991, Huang and Odum (1991) published a plan for this project for emergy analysis of Taiwan, and from 1995 up to 2011 Huang and co-workers published many papers on the investigation of Taipei and its hierarchical position in relation to the full island of Taiwan (Chen and Huang, 1998; Huang, 1996, 1998, 2003; Huang and Chen, 2005; Huang et al., 2011b; Huang and Hsu, 2003; Huang et al., 2007; Huang et al., 2001; Huang et al., 2006; Huang et al., 1998; Huang et al., 1995; Huang et al., 2010; Lee et al., 2008, 2009).

In Huang and Chen (2005) was repeated the distribution picture from Odum et al. (1995). Huang et al. (2006) published the time frame from 1936-98 where Taipei showed the same urbanization pattern as other cities studied, and Huang et al. (2007) could verify the spatial picture from the earlier studies of American cities regarding Empower density. Lately Huang and coworkers (Chang and Huang, 2015; Huang et al., 2011a) have tried to develop the emergy concept to be used in addressing urban flooding vulnerability.

3.2.2 Macao

From 2008 a series of emergy papers was published by Kampeng Lei and coworkers at South China University of Technology and the Macao University (Lei et al., 2012; Lei and Wang, 2008a, b, c; Lei et al., 2008; Lei et al., 2011; Lei et al., 2010). In 2014 their research was summarized in the book: "*Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao*" (Lei et al., 2014). A major outcome were the positive Net Emergy Ratio that Macao experiences, since the vast amount of tourists entering the town was found bring with them and spend more emergy than they take with them leaving the town. The net emergy gain from tourists has supported Macao's socioeconomic development for many decades.

3.2.3 Beijing

During the latest years of the period up till 2015, most international journal publications regarding emergy and cities has studied Beijing. Researchers Zhifeng Yang and Bin Chen, Beijing Normal University, seems to be the common denominators for the long list of publications by Yan Zhang et al. (Zhang et al., 2011; Zhang et al., 2009a, b), and Gengyuan Liu et al. (Liu et al., 2011a, b, c, d; Liu et al., 2011e, 2014; Liu et al., 2013; Liu et al., 2012; Liu et al., 2009a; Liu et al., 2009b). Other journal articles on Beijing have been published by

Hu et al. (2010); Cai et al. (2009); Chen and Chen (2011); Li and Wang (2009); Song et al. (2014); Song et al. (2015). Several time scenarios have been published and the amount of emergy data regarding Beijing has been growing fast in resent time.

3.2.4 Other Chinese cities

A number of other Chinese cities have also been investigated, but not with the same intensity as the cities mentioned above Yangzhou city in East China was studied by Hu et al. (2009). Liu et al. (2009a) evaluated 31 Chinese cities regarding emergy and found a pattern where they could divide the cities into six distinctive groups. Based on these groups they proposed an urban ecosystem health evaluation framework describing efficiency, structure, impact and flux with an emergy-based index. In another paper they (Liu et al., 2011d; Liu et al., 2013) proposed an urban emergy loss evaluation framework including human-made capital and loss of natural capital as basis for sustainable policy-making and design of urban sustainable development schemes. Liu et al. (2009b) also made a separate ecosystem health evaluation of Baotou City, located in the west of the Inner Mongolia Autonomous Region. Su (2010) investigated the Yangtze River delta urban cluster, Su et al. (2011) the Pearl River delta, and Su and Fath (2012) investigated Guangzhou. Lou et al. (2015) investigated the regional environmental sustainability based on emergy indicators for the city of Shanwei in the Guangdong region.

3.2.5 Rome and Montreal

A few western cities have also been investigated in recent years. Rome was studied by Ascione et al. (2009), and Montreal by Vega-Azamar et al. (2013). Ascione et al. (2009) used the approach of comparing emergy indices of the city with national averages for the same indices, e.g. for emergy use per person, empower density, and emergy/GDP. The conclusion from the Rome study was that emergy intensity indicators and performance ratios confirmed Rome as a special resource attractor, but also confirmed "…its fragility and unsustainability, due to the excess reliance on non-renewable and outside resources" (Ascione et al. 2009).

3.2.6 Emergy indices

The emergy papers focusing on cities reviewed here show a variety in the choice of indices, but they also to some extent use different names for the same index. Examples are given in Table 1 showing a variety of emergy indices used in selected studies. Emergy density, ED (suggested by Brown, 2009, later to change name to Empower Intensity, since it is a surface measure, not a volume), percent renewable emergy (R/U), emergy per capita (EP), and environmental loading ratio (ELR), are all commonly used indices that also show little variation in names between authors. Emergy yield ratio (EYR), emergy sustainability index (ESI), emergy exchange ratio (EER) and waste to emergy ratio (W/U) are less commonly used, but basically consistent nomenclature vise. Emergy intensity of currency (EIC) is rather commonly used in papers but show under a variation of names (e.g. EMR, EDO). Emergy investment ratio (EIR) and metabolic dependence (ESR) are less common and show variation in names. The most striking example of name change is Liu et al. (2009a) who renamed what many other have called EIR to a modified EYR called NEYR. Table 1 also indicate that it is common to suggest new indices in the emergy literature on cities.

Even though comparison between emergy investigations meet some methodological problems since approaches are not yet standardized, a few have anyhow been made. Lei et al. (2008) compared Macao with Taipei, Zhongshan, Miami-Dade County and San Juan (based on Doherty, 1995; Woithe, 1995a; Huang and Hsu, 2003). Ascione et al., (2009) compared Rome with Macao, Taipei, and San Juan (based on Doherty, 1995; Huang, 1998; Lei et al., 2008). Vega-Azamar et al. (2013) compared Montreal with Miami-Dade County, Zhongshan, Beijing, Guangzhou, Rome, Shanghai, Taipei, San Juan, and Macao (Based on Lei et al. (2008); Ascione et al., 2009; Zhang et al., 2009c; Zhang et al., 2011). Of these Vega-Azamar et al. (2013) made the deepest analysis and found significant correlations between population density and emergy density, between population and total emergy used, and between per capita available space and emergy density. A weaker correlation was also found between population density and emergy per capita, but no significant correlation was found for total population and per capita emergy utilization.

Table 1 An overview of indices used in emergy evaluations of cities.

Article	Cities	EYR	ELR	EIR	ED	ESI	R/U	EIC	EP	EER	W/U	W/R	ESR	Other
Woithe, 1995	Miami-Dade County		(U-R)/R		Use/area	n.a.	R/U	U/GDP	Use/cap					and others
Doherty, 1995	Puerto Rico		Econom./environ.		Use/area	n.a.	%env.		Use/cap					% external economic and others
Huang & Chen, 2005	Taipei			EIR	ED		R/U	EMR	U/P		W/U	W/R	Emergy self-suff.	and others
Lei et al., 2008	Macao	EYR	ELR	EIR	ED	ESI	R/U	EMR	U/P	EER	W/U			F/U and others
Liu et al., 2009a	31 Chinese cities		ELR	NEYR=F/(R+N)	ED			EMR		EER				EUEHI=(NEYRxEERxED)/(ELRxEIC)
Zhang et al., 2011	Beijing		ELR		ED			EDO	EP				ESR	
Ascione et al., 2009	Rome	EYR	ELR		ED	ESI	R/U	U/GDP	Em/cap					$U^{city}/U^{country}$; $(Em/cap)^{city}/(Em/cap)^{country}$; $ED^{city}/ED^{country}$; $EIC^{city}/EIC^{country}$
Vega-Azamar et al., 2013	Montreal	EYR	ELR		ED		R/U	EMR	Ucap		W/U			

Y=U=yield, total emergy used (released)
R=Free renewable emergy of environmental inputs as sun, wind, rain, waves, earth cycle, etc.
N=Free nonrenewable emergy from the local environment, e.g. fossil fuels, minerals, soil, forest wood when used up faster than produced
M=Purchases (imported) minerals, fuels, goods and raw materials
S=Purchased (imported) services and labor, the paid work of people
F=Feedback (imports)=M+S
EYR=Emergy Yield Ratio=Y/F
ELR=Environmental Loading Ratio=(F+N)/R
EIR=Emergy Investment Ratio=F/(R+N)
ED=Empower Density=(R+N+F)/area/year
ESI=Emergy Sustainability Index=EYR/ELR
%R=Renewability=R/U
EIC=Emergy Intensity of currency=EMR=U/GDP
EER=Emergy Exchange Ratio
GDP=Gross Domestic Product
EP=Emergy/capita=U/cap
EUEHI=Emergy-based Urban Ecosystem Health Index
W/U=Waste to emergy ratio
W/R=Waste to renewable
F/U=Emergy use purchased ratio
EmSelf-suff. = (R+N0+N1)/U = Emergy Self-sufficiency (N0= dispersed rural, e.g. soil loss, N1=concentrated use, e.g. hydroelectricity)
ESR=(R+N)/U=Metabolic dependence
EISR=(EYR*EER)/ELR

Table 2 An overview of values for the indices in Table 1#. Values are from the period 1998-2005

Article	Cities	Year	EYR	ELR	EIR	ED sej/m2/ year	ESI	R/U	EIC	EP sej/cap/ year	EER	W/U	W/R	ESR*
Woithe, 1995**	Miami-Dade County	1990	0.082	27.6	2.75	1.31E13	0.00030	3.50%	1.60E12 sej/$	3.41E16	121.90			
Doherty, 1995**	Puerto Rico	1992	0.380	964	9.64	7.01E13	0.00039	0.10%	1.64E12 sej/$	2.20E16	2.63			
Huang & Chen, 2005***	Taipei	1998			70.84	7.59E13		1.4%	1.73E12 sej/$	2.08E16		0.58	41.72	2.4%
Lei et al., 2008	Macao	2004	0.743	743	6.27	8.94E14	0.001	0.13%	2.39E12 sej/$	5.28E16	1.35	0.12		
Liu et al., 2009a	Shanghai	2004		311.39	9.69	5.02E13			n.a.		3.82			
Liu et al., 2009a	Changchun	2004		45.78	1.94	5.48E12			n.a.		125.68			
Liu et al., 2009a	Lhasa	2004		0.05	0.00	3.5E11			n.a.		0.11			
Zhang et al., 2011***	Beijing	2004		531.23		3.88E13			1.22E13 sej/$	4.36E16				34.45%
Ascione et al., 2009	Rome	2005	1.02	60.43		1.0E14	0.02	0.3%	2.43E12 sej/€	5.50E16				
Vega-Azamar et al., 2013	Montreal	2005	1.034	30.321		2.31E14		3.19%	1.54E12 sej/$	6.25E16		8.96%		

abbreviations in this table are explained in the footnotes to Table 1.
* values in this column are produced with similar index composition, but not with exactly the same index composition
** values recalculated by Lei et al., 2008.
*** from the time series presented in the article only the latest values are presented in the table.

Table 1 may be slightly misleading in the listing of evaluation indices since many of the papers rather use the basic variables (Y, R, N, M, S, and F) and the emergy model producing them for conclusions regarding sustainability. Some papers use the emergy model in an explicit way while other only show it in principle in the method section.

Table 2 give examples of quantitative values for the indices in Table 1 from the indicated publications. All the reported figures are average values for the cities studied.

3.3 Overview of investigated cities

Table 3 gives the full list of all cities investigated with emergy accounting in the papers found published during the period 1971-2015. The overview shows the strong development of urban emergy research in China after the millennium shift. The number of references shows that Beijing, Macao, and Taipei are the most investigated cities. It must be remembered, though, that the number of references don't reveal the depth of the individual investigation, some of the references are short conference papers while others are full doctoral dissertations (e.g. Zucchetto, 1975b).

Table 3 Cities investigated with emergy accounting during 1971-2015

City	*References*
America	
Chicago	Woithe, 1995b
Ft. Myers	Brown, 1980
Gainesville	Brown, 1980
Jacksonville	Whitfield, 1995
Miami	Lopez and Brown, 1995; Woithe, 1995a; Zucchetto, 1975a; Zucchetto, 1975b
Montreal	Vega-Azamar et al., 2013
San Francisco	Woithe, 1995b
San Juan	Doherty, 1995
Europe	
Rome	Ascione et al., 2009
Asia	
Baotou	Liu et al., 2009b
Beijing	Cai et al., 2009; Li and Wang, 2009; Liu et al., 2011a, b, c; Liu et al., 2011d; Liu et al., 2013; Liu et al., 2012; Liu et al., 2009a; Song et al., 2014; Song et al., 2015; Su et al., 2013; Su et al., 2009; Zhang et al., 2009a,b; Zhang et al., 2011; Zhang et al., 2009c
Changchun	Liu et al., 2013; Liu et al., 2009a
Changsha	Liu et al., 2013; Liu et al., 2009a
Chengdu	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009
Chongqing	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009; Zhang et al., 2009c
Fushun	Su et al., 2009
Fuzhou	Liu et al., 2013; Liu et al., 2009a
Guangzhou	Liu et al., 2013; Liu et al., 2009a; Su and Fath, 2012; Su et al., 2013; Su et al., 2011; Su et al., 2009; Zhang et al., 2009c
Guiyang	Liu et al., 2013; Liu et al., 2009a
Haikou	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009

Hangzhou	Liu et al., 2013; Liu et al., 2009a; Su et al., 2013; Su et al., 2009
Harbin	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009
Kunming	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009
Lanzhou	Liu et al., 2013; Liu et al., 2009a
Lhasa	Liu et al., 2013; Liu et al., 2009a
Macao	Lei et al., 2012; Lei et al., 2015; Lei and Wang, 2008a, b, c; Lei et al., 2008; Lei et al., 2011; Lei et al., 2010; Lei et al., 2014a, b
Nanjing	Liu et al., 2013; Liu et al., 2009a; Su et al., 2013; Su et al., 2009
Nanning	Su et al., 2009
Qingdao	Su et al., 2009
Shanghai	Liu et al., 2013; Liu et al., 2009a; Su et al., 2013; Su et al., 2009; Zhang et al., 2009c
Shanwei	Lou et al., 2015
Shenyang	Liu et al., 2014; Liu et al., 2013; Liu et al., 2009a
Shenzhen	Su et al., 2013; Su et al., 2011; Su et al., 2009; Zhang et al., 2009c
Shijiazhuang	Liu et al., 2013; Liu et al., 2009a
Taipei	Chen and Huang, 1998; Huang, 1996, 1998; Huang and Chen, 2005; Huang et al., 2011; Huang and Hsu, 2003; Huang et al., 2007; Huang et al., 2001; Huang et al., 1998; Huang et al., 1995b, a; Lee et al., 2009
Taiyuan	Liu et al., 2013; Liu et al., 2009a
Tangshan	Cai et al., 2009; Su et al., 2013; Su et al., 2009
Tianjin	Cai et al., 2009; Liu et al., 2013; Liu et al., 2009a; Su et al., 2013; Zhang et al., 2009c, Zhang et al., 2012
Urumchi	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009
Wuhan	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009
Xi'an	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009
Xiamen	Su et al., 2009; Yang et al., 2012; Yang et al., 2014; Yang et al., 2013
Xining	Liu et al., 2013; Liu et al., 2009a
Yangzhou	Hu et al., 2009
Yinchuan	Liu et al., 2013; Liu et al., 2009a; Su et al., 2009
Zhengzhou	Liu et al., 2013; Liu et al., 2009a
Zhongshan	Lei et al., 2008
Zhuhai	Su et al., 2013; Su et al., 2011

4 Discussion

H.T. Odum and coworkers found zonation in emergy distribution in cities during the period 1975-1995. From this they put up many hypotheses with a spatial focus, considering changes in emergy indices when moving along transects from the city center to the periphery. A total of seven cities were actually studied, all of them in America. In the period after 1995 significantly more emergy evaluations have been performed on cities, mainly but not exclusively on cities in East Asia. The works by Shu-Li Huang maintained a spatial focus and could to some extent confirm the hypotheses and findings from the earlier studies of cities in the United States during 1975-95. However, most of the later studies in East Asia have not had a spatial focus in the same way as the Odum and Huang groups. Instead the focus has been on evaluation of the cities from a sustainability perspective. This has been especially prominent in the works of Kampeng Lei and his group addressing the city of Macao. It seems like H.T. Odum's wish (Odum 1995) to develop predicting models for

spatial organization of cities is still yet to be proved. It is interesting that the newer investigation for Rome (Ascione et al., 2009) did not address the spatial prediction made by Odum et al. (1995).

The research groups in Beijing, with main authors Zhifeng Yang, Bin Chen, Yan Zhang and Gengyuan Lei seem to have moved emergy research on cities in new and innovative directions, suggesting many new indices for evaluation of for example urban ecosystem health. This group has also substantially increased the volume of investigated cities. The significant increase in amount of available data is promising for future new knowledge and hypotheses regarding emergy and cities.

However, even though many new indices are developed, a problem seems to be the interpretation. What do the indices actually tell us? The question of what are "good" or "bad" values often remains unanswered, or answered in a way inconsistent with other emergy investigations.

In the preparation of this paper an attempt was made to verify the energy diagrams in Fig.1 (in Odum et al., 1995) with data from the newer investigations published after the millennium shift. However, published data are generally not available for different zones, thus not allowing for this analysis.

Generating Table 1 from the studies obtained revealed that even though the method of emergy accounting has reached a certain level of standardization (Odum, 1996; Brown and Ulgiati, 2004), the level of standardization is not strong regarding the use of indices. As can be seen in Table 1 the names of some of the indices are varying. Our interpretation is twofold: on the one side a lot of creativity is still invested in the method, on the other side comparisons between investigations are still problematic hampering the possibilities for more generalized conclusions.

Looking into studies to put together Table 1 also revealed that even though indices are used to report results from emergy accounting, conclusions from the studies are often more based on the total picture the authors have from their evaluations than what are captured in the indices reported. This is similar to general experiences from the field of modeling: the value of the modeling procedure often lays more in the process of learning to know the modeled system than what can be revealed in modeling outcomes (Meadows, 2008). Liu et al. (2014) connects to this issue in their model of "…dynamic mechanisms of urban development, resource consumption and environmental impacts". Their outcome was not that one single index or even set of indices could best capture sustainability, rather the model itself showed which important parameters that were necessary to include.

5 Conclusions

During the period 1971-1995 the research on emergy and cities mainly studied cities in the United States The main research during 1996-2005 took place almost only in Taipei. From approximately 2006 up 2015 the main research considers Chinese cities.

The main interest up to 2007/2008 was on the spatial aspect of the city with different emergy signatures for older agrarian cities compared to newer cities. However, data available is still not differentiated enough to conclude anything regarding these hypotheses on spatial aspects of cites. The more recent emergy studies of cities have moved to evaluating sustainability as a main question. Different approaches were used regarding sustainability conclusions, some based to a larger extent on the emergy model, and some based more on a variety of sustainability indices.

Acknowlegdements

We thank a group of anonymous reviewers at the Journal of Environmental Accounting and Management for valuable comments that helped us improve this manuscript further from its original conference version.

References

Arvidsson, R., Fransson, K., Fröling, M., Svanström, M., Molander, S., 2012. Energy use indicators in energy and life cycle assessments of biofuels: review and recommendations. Journal of Cleaner Production 31, 54-61.

Ascione, M., Campanella, L., Cherubini, F., Ulgiati, S., 2009. Environmental driving forces of urban growth and development: An emergy-based assessment of the city of Rome, Italy. Landscape and Urban Planning 93, 238-249.

Brown, M., 1973. Energy indices in the urban pattern. Master's Thesis. University of Florida, Gainesville.

Brown, M.T., 1980. Energy basis for hierarchies in urban and regional landscapes. Dissertation, University of Florida, Gainesville.

Brown, M.T., 2009. Suggestions for an Emergy Nomenclature, in: Brown, M.T., Sweeney, S., Campbell, D.E., Huang, S., Ortega, E., Rydberg, T., Tilley, D., Ulgiati, S. (eds.), Emergy Synthesis 5: Theory and Applications of the Emergy Methodology. . Proceedings of the 5th Biennial Emergy Conference. Center for Environmental Policy, University of Florida, Gainesville. 612 pages.

Brown, M.T., Ulgiati, S., 2004. Emergy Analysis and Environmental Accounting, in: Cleveland, C.J. (ed.), Encyclopedia of Energy. Elsevier, New York, pp. 329-354.

Cai, Z.F., Zhang, L.X., Zhang, B., Chen, Z.M., 2009. Emergy-based analysis of Beijing–Tianjin–Tangshan region in China. Communications in Nonlinear Science and Numerical Simulation 14, 4319-4331.

Chang, L.-F., Huang, S.-L., 2015. Assessing urban flooding vulnerability with an emergy approach. Landscape and Urban Planning 143, 11-24.

Chen, S., Chen, B., 2011. Assessing inter-city ecological and economic relations: An emergy-based conceptual model. Front. Earth Sci. 5, 97-102.

Chen, T.-C., Huang, S.-L., 1998. Towards a symbiosis: Urban development and environmental quality in the Taipei metropolitan region. Journal of Environmental Planning & Management 41, 77-93.

Cleveland, C., 2008. Odum, Howard T. The Encyclopedia of Earth. Retrieved from http://www.eoearth.org/view/article/154996.

Doherty, S., 1995. Emergy evaluation of San Juan, Puerto Rico, in: Odum, H.T., M.T. Brown, D.F. Whitfield, S. Lopez, R. Woithe, S. Doherty. (ed.), Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society. Center for Environmental Policy, University of Florida, Gainesville, pp. 121-132.

Giannantoni, C., 2002. The maximum em-power principle as the basis for thermodynamics of quality. SGEditoriali, Padova, Italy.

Grönlund, E., 2009. Why is emergy so difficult to explain to my environmental science friends?, in: Brown, M.T. (ed.), Emergy Synthesis 5: Theory and Applications of the Emergy Methodology. Proceedings from the Fifth Biennial Emergy Research Conference, Gainesville, Florida, January, 2008. The Center for Environmental Policy, University of Florida, Gainesville, USA, pp. 33-39.

Grönlund, E., Fröling, M., Carlman, I., 2014. Donor values in emergy assessment of ecosystem services. Ecological Modelling 306:95-100.

Hu, D., Wang, R.-S., Lei, K.-P., Li, F., Wang, Z., Wang, B.-N., 2009. Expanding ecological appropriation approach: Solar space method and a case study in Yangzhou city, East China. Ecological Complexity 6, 473-483.

Hu, D., You, F., Zhao, Y., Yuan, Y., Liu, T., Cao, A., Wang, Z., Zhang, J., 2010. Input, stocks and output flows of urban residential building system in Beijing city, China from 1949 to 2008. Resources, Conservation and Recycling 54, 1177-1188.

Huang, S.-L., 1996. Indicators and strategies of sustainable urban development for Taipei City. . Report No. 031644850137. Department or Urban Development, Taipei Municipal Government, Taipei, Taiwan.

Huang, S.-L., 1998. Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. Journal of Environmental Management 52, 39-51.

Huang, S.-L., 2003. Theory of urban energetics and mechanisms of urban development, Advances in Energy Studies, Reconsidering the Importance of Energy. 3rd Int. Workshop, Porto Venere, Italy September 24-28, 2002. SGE Editoriali, Padova.

Huang, S.-L., Chang, L.-F., Yeh, C.-T., 2011a. How vulnerable is the landscape when the typhoon comes? An emergy approach. Landscape and Urban Planning 100, 415-417.

Huang, S.-L., Chen, C.-W., 2005. Theory of urban energetics and mechanisms of urban development. Ecological Modelling 189, 49-71.

Huang, S.-L., Chen, Y.-H., Kuo, F.-Y., Wang, S.-H., 2011b. Emergy-based evaluation of peri-urban ecosystem services. Ecological Complexity 8, 38-50.

Huang, S.-L., Hsu, W.-L., 2003. Materials flow analysis and emergy evaluation of Taipei's urban construction. Landscape and Urban Planning 63, 61-74.

Huang, S.-L., Kao, W.-C., Lee, C.-L., 2007. Energetic mechanisms and development of an urban landscape system. Ecological Modelling 201, 495-506.

Huang, S.-L., Lai, H.-Y., Lee, C.-L., 2001. Energy hierarchy and urban landscape system. Landscape and Urban Planning 53, 145-161.

Huang, S.-L., Lee, C.-L., Chen, C.-W., 2006. Socioeconomic metabolism in Taiwan: Emergy synthesis versus material flow analysis. Resources, Conservation and Recycling 48, 166-196.

Huang, S.-L., Odum, H.T., 1991. Ecology and economy: Emergy synthesis and public policy in Taiwan. Journal of Environmental Management 32, 313-333.

Huang, S.-L., Wong, J.-H., Chen, T.-C., 1998. A framework of indicator system for measuring Taipei's urban sustainability. Landscape and Urban Planning 42, 15-27.

Huang, S.-L., Wu, S.-C., Chen, W.-B., 1995. Ecosystem, environmental quality and ecotechnology in the Taipei metropolitan region.

Ecological Engineering 4, 233-248.
Huang, S.-L., Yeh, C.-T., Chang, L.-F., 2010. The transition to an urbanizing world and the demand for natural resources. Current Opinion in Environmental Sustainability 2, 136-143.
Lee, C.-L., Huang, S.-L., Chan, S.-L., 2008. Biophysical and system approaches for simulating land-use change. Landscape and Urban Planning 86, 187-203.
Lee, C.-L., Huang, S.-L., Chan, S.-L., 2009. Synthesis and spatial dynamics of socio-economic metabolism and land use change of Taipei Metropolitan Region. Ecological Modelling 220, 2940-2959.
Lei, K., Hu, D., Zhou, S., Guo, Z., 2012. Monitoring the sustainability and equity of socioeconomic development: A comparison of emergy indices using Macao, Italy and Sweden as examples. Acta Ecologica Sinica 32, 165-173.
Lei, K., Wang, Z., 2008a. Emergy synthesis and simulation for Macao. Energy 33, 613-625.
Lei, K., Wang, Z., 2008b. Emergy synthesis of tourism-based urban ecosystem. Journal of Environmental Management 88, 831-844.
Lei, K., Wang, Z., 2008c. Municipal wastes and their solar transformities: An emergy synthesis for Macao. Waste Management 28, 2522-2531.
Lei, K., Wang, Z., Ton, S., 2008. Holistic emergy analysis of Macao. Ecological Engineering 32, 30-43.
Lei, K., Zhou, S., Hu, D., Guo, Z., Cao, A., 2011. Emergy analysis for tourism systems: Principles and a case study for Macao. Ecological Complexity 8, 192-200.
Lei, K., Zhou, S., Hu, D., Yu, Y., 2010. Ecological energy accounting for the gambling sector: A case study in Macao. Ecological Complexity 7, 149-155.
Lei, K., Zhou, S., Wang, Z., 2014. Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao. Springer Berlin Heidelberg.
Li, D., Wang, R., 2009. Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: The case of Beijing, China. Ecological Complexity 6, 484-493.
Liu, G., Yang, Z., Chen, B., 2011a. Comparison of different urban development strategy options to the urban metabolism optimal path. Procedia Environmental Sciences 5, 178-183.
Liu, G., Yang, Z., Chen, B., 2011b. Emergy-based Ecological Economic Evaluation of Beijing Urban Ecosystem. Procedia Environmental Sciences 5, 18-24.
Liu, G., Yang, Z., Chen, B., 2011c. Four angle model for the urban metabolism integrated analysis. Procedia Environmental Sciences 5, 81-86.
Liu, G., Yang, Z., Chen, B., 2011d. A spatial comparative analysis of environmental impacts in Chinese urban metabolic processes. Procedia Environmental Sciences 5, 43-50.
Liu, G., Yang, Z., Chen, B., Ulgiati, S., 2011e. Monitoring trends of urban development and environmental impact of Beijing, 1999–2006. Science of the Total Environment 409, 3295-3308.
Liu, G., Yang, Z., Chen, B., Ulgiati, S., 2014. Emergy-based dynamic mechanisms of urban development, resource consumption and environmental impacts. Ecological Modelling 271, 90-102.
Liu, G., Yang, Z., Chen, B., Zhang, L., 2013. Modelling a thermodynamic-based comparative framework for urban sustainability: Incorporating economic and ecological losses into emergy analysis. Ecological Modelling 252, 280-287.
Liu, G.Y., Yang, Z.F., Chen, B., 2012. Emergy-based urban dynamic modeling of long-run resource consumption, economic growth and environmental impact: conceptual considerations and calibration. Procedia Environmental Sciences 13, 1179-1188.
Liu, G.Y., Yang, Z.F., Chen, B., Ulgiati, S., 2009a. Emergy-based urban health evaluation and development pattern analysis. Ecological Modelling 220, 2291-2301.
Liu, G.Y., Yang, Z.F., Chen, B., Zhang, Y., Zhang, L.X., Zhao, Y.W., Jiang, M.M., 2009b. Emergy-based urban ecosystem health assessment: A case study of Baotou, China. Communications in Nonlinear Science and Numerical Simulation 14, 972-981.
Lopez, S., Brown, M.T., 1995. Organisation and distribution of urban structure in metropolitan Miami, Florida, in: Odum, H.T., M.T. Brown, D.F. Whitfield, S. Lopez, R. Woithe, S. Doherty. (ed.), Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society. Center for Environmental Policy, University of Florida, Gainesville, pp. 64-94.
Lou, B., Qiu, Y., Ulgiati, S., 2015. Emergy-based indicators of regional environmental sustainability: A case study in Shanwei, Guangdong, China. Ecological Indicators 57, 514-524.
Meadows, D., 2008. Thinking in systems : a primer. Chelsey Green Publishing Co, White River Junction, Vermont, USA.
Odum, H.T., 1971. Environment, power and society. John Wiley & Sons, New York.
Odum, H.T., 1983. Systems ecology: An introduction. John Wiley & Sons, New York.
Odum, H.T., 1996. Environmental accounting. Emergy and environmental decision making. John Wiley & Sons, New York.
Odum, H.T., Brown, M.T., Whitfield, D.F., Lopez, S., Woithe, R., Doherty, S., 1995. Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society. Center for Environmental Policy, University of Florida, Gainesville.
Odum, H.T., Odum, E.C., 1976. Energy basis for man and nature. McGraw-Hill, New York.
Pulselli, F.M., Coscieme, L., Bastianoni, S., 2011. Ecosystem services as a counterpart of emergy flows to ecosystems. Ecological Modelling 222, 2924-2928.
Song, T., Cai, J.-m., Chahine, T., Xu, H., Niu, F.-q., 2014. Modeling urban metabolism of Beijing city, China: with a coupled system dynamics: emergy model. Stoch Environ Res Risk Assess 28, 1511-1524.
Song, T., Cai, J., Xu, H., Deng, Y., Niu, F., Yang, Z., Du, S., 2015. Urban metabolism based on emergy and slack based model: A case study of Beijing, China. Chin. Geogr. Sci. 25, 113-123.
Su, M., 2010. Emergy-based urban ecosystem health evaluation of the Yangtze River Delta urban cluster in China. Procedia Environmental Sciences 2, 689-695.
Su, M., Fath, B.D., 2012. Spatial distribution of urban ecosystem health in Guangzhou, China. Ecological Indicators 15, 122-130.

Su, M., Yang, Z., Chen, B., 2011. Limiting factor analysis of urban ecosystems based on emergy—A case study of three cities in the Pearl River Delta in China. Procedia Environmental Sciences 5, 131-138.

Vega-Azamar, R.E., Glaus, M., Hausler, R., Oropeza-García, N.A., Romero-López, R., 2013. An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada. Landscape and Urban Planning 118, 18-28.

Whitfield, D.F., 1995. Emergy analysis of the spatial resource distribution of urban land uses for the city of Jacksonville, Florida, in: Odum, H.T., M.T. Brown, D.F. Whitfield, S. Lopez, R. Woithe, S. Doherty. (ed.), Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society. Center for Environmental Policy, University of Florida, Gainesville, pp. 31-63.

Woithe, R., 1995a. Emergy indices of Dade County (Miami), Florida, in: Odum, H.T., M.T. Brown, D.F. Whitfield, S. Lopez, R. Woithe, S. Doherty. (ed.), Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society. Center for Environmental Policy, University of Florida, Gainesville, pp. 105-120.

Woithe, R., 1995b. Zones of Empower density in American cities, in: Odum, H.T., M.T. Brown, D.F. Whitfield, S. Lopez, R. Woithe, S. Doherty. (ed.), Zonal Organization of Cities and Environment - A Study of Energy Systems Basis for Urban Society. Center for Environmental Policy, University of Florida, Gainesville, pp. 95-104.

Wolman, A., 1965. The metabolism of cities. Scientific American 213, 179-190.

Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011. Emergy analysis of the urban metabolism of Beijing. Ecological Modelling 222, 2377-2384.

Zhang, Y., Yang, Z., Yu, X., 2009a. Ecological network and emergy analysis of urban metabolic systems: Model development, and a case study of four Chinese cities. Ecological Modelling 220, 1431-1442.

Zhang, Y., Yang, Z., Yu, X., 2009b. Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China). Ecological Modelling 220, 1690-1696.

Zhang, Y., Zhao, Y.W., Yang, Z.F., Chen, B., Chen, G.Q., 2009c. Measurement and evaluation of the metabolic capacity of an urban ecosystem. Communications in Nonlinear Science and Numerical Simulation 14, 1758-1765.

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

Zucchetto, J.J., 1975b. Energy basis for Miami Florida and other urban systems. Dissertation, Dept. of Environmental Engineering Sciences, University of Florida, Gainesville