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Landscape and Urban Planning 63 (2003) 61–74

LANDSCAPE
AND
URBAN PLANNING

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Materials flow analysis and emergy evaluation of Taipei's urban construction

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Received 22 March 2001; received in revised form 11 March 2002; accepted 8 July 2002

Abstract

The metabolism of a city can be seen as the process of transforming all the materials and commodities for sustaining the city's economic activity. This paper attempts to incorporate resource and material flow analysis to investigate Taipei area's urban sustainability due to urban construction. The material flows (sand and gravel, cement, asphalt, and construction waste) during the past decade for constructing major urban engineering projects such as roads, bridge, MRT, flood prevention projects, storm drainage and sewerage pipes, and buildings are analyzed for Taipei metropolis. In order to evaluate the contributory value of material flows to the ecological economic system, emergy (spelled with an M; previously known as embodied energy) evaluation is incorporated in this research. A framework of indicators including categories of: (1) intensity of resource consumption; (2) inflow/outflow ratio; (3) urban livability; (4) efficiency of urban metabolism; and (5) emergy evaluation of urban metabolism is developed for measuring the effect of urban construction on Taipei's sustainability. The consumption of sand and gravel is approximately 90% of the total construction material used, and the generation of construction waste in Taipei exceeds 30×10^6 ton per annum. The emergy value of construction materials in Taipei is equivalent to 46% of total emergy use. Although the livability in Taipei has improved, the significant amount of construction waste remains an important environmental issue. The recycling and reuse of construction waste can not only create circular pattern of urban metabolism but is also vital to the sustainable development of Taipei.

Keywords: Urban metabolism; Material flows; Emergy evaluation; Urban construction; Sustainability indicators

1. Introduction

Human society is increasingly becoming urban, but it continues to rely on nature for its resource intake and disposal of wastes. The philosophy of traditional towns was mainly characterized by labor power for transport and production. Fossil fuel powered transport has caused many cities to stop relying on resources from their local regions. The philosophy of modern cities is characterized by their routine use of energy as a driving force for power production, transportation of goods, construction of building and infrastructure as well as domestic comfort. Cities have to rely on the ecosystems beyond the city limits. As cities draw more and more resources from far off areas, they also accumulate large amounts of materials within themselves.

If compared with other ecosystems, the urban systems are relatively immature due to rapid growth and inefficient use of resources. Odum (1989) observes that cities are one of the heterotrophic ecosystems in the biosphere; the good parasites do not destroy their host, rather, remain in symbiotic relationship

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PII: S0169-2046(02)00152-4

with each other. From point of view of system ecology, cities are self-regulating systems and may be seen as super-organisms, created for the benefit of human beings and for sustaining their livelihood. Cities can not be self-regulating without maintaining stable links with the hinterland from which they draw energy, food, and materials and into which they release their wastes.

The concern to make urban life more sustainable in the global context has increased the attention paid to the ecological footprints of cities (Wackernagel and Rees, 1996). Girardet has calculated the resource use in greater London and estimated its ecological footprint as 125 times the area it occupies (Sustainable London Trust, 1996). The approach of urban metabolism has been proposed by quite a few academics over the past 30 years (Wolman, 1965; Boyden et al., 1981; Douglas, 1983; Girardet, 1990). However, it has rarely been used for urban policy making. Wolman (1965) defines the metabolism of a city as all the materials and commodities needed to sustain the city's inhabitants at home, at work, and at play. Extending from the concept of urban metabolism, the requirements to sustain the city include even the construction materials needed to build the city's structure over a period of time. Lawson and Douglas (1998) have suggested that deliberate human activity, in terms of excavating and filling of sectors of the earth's surface, is the most efficient geological agent on the earth at present.

Although there has been growing concern about the physical characteristics of cities in recent years, the effort of "greening of the cities" has mainly meant creating more green spaces just to improve the visual appearance of the cities. Much more radical changes in the urban metabolism are required to make the cities ecologically viable, not just environmentally pleasant. This approach to sustain urban development is implicitly understood by environmental planners and resource managers but is not inherent to conventional economists and urban planners.

How can we use systematic approach to assess a city's sustainability to fulfill the agenda of urban sustainability? This paper attempts to apply material flow and ecological energetic analyses to investigate Taipei area's urban sustainability in the context of urban construction. It concentrates on the analysis of materials flows and evaluation of indicators. Section 2 provides background concept on material flows and urban metabolism, and its implication to urban sustainability; this is followed by a brief description of the methodology for the case study. The approach adopted in this paper is based on the experience of previous research (Huang et al., 1995, 1998). The next two sections elaborate upon material flows analysis of urban construction of Taipei. Each material flow is converted into a common energy unit—emergy (spelled with an M; previously known as embodied energy) to evaluate their contributory value to the ecological economic system. Thereafter the sustainability of Taipei due to its consumption of construction would be discussed.

2. Urban metabolism, material flows and sustainability

The major environmental problems and associated social costs of an urban ecosystem are related to the rapid increase of resource inputs for urban consumption and the disposal of construction wastes, which are of nuisance to urban dwellers. To make urbanization sustainable, we must first understand how our cities function in the context of resource consumption. Like human metabolism, the physical and biological processes of a city system transform inflows of energy and materials into useful products, services and wastes. They are based on the laws of thermodynamics and a balance sheet of inputs and outputs can be analyzed. The materials, energy, and food supplies brought into cities, transformed within them and the products and wastes sent out from the cities are often referred to as the urban metabolism, a concept first suggested by Wolman (1965). The complete metabolism of a city comprises of many inputs such as food, fuel, clothing, durable goods, electric energy, construction materials, and services. The metabolic cycle is not completed until the residues of daily consumption have been removed and disposed of adequately with minimum nuisance and hazard to life. Wolman (1965) has pointed out that provision of adequate water supply, effective disposal of sewage and control of air pollution are the three metabolic problems that have become more acute as a result of urban growth. Boyden et al. (1981) used Hong Kong for a case study and applied urban metabolism approach to study its urban ecology and relationships with Hong Kong's social characteristics.

Our present urban-industrial civilization is vastly accelerating the process of entropy with unpromising resolution for the future of life on earth. The most profound problem the cities are up against lies in the linearity of the material flows. Girardet (1990) shows that the linear processes by which cities transform environmental resources into waste products is disruptive of the planet's life support systems. Nutrients are taken out of the land as crop is grown, and never returned to the land. Raw materials are extracted and processed as consumer goods, which end up as rubbish and can not be reabsorbed for future use. Fossil fuels are either mined or pumped out from geological strata and burned and released into the atmosphere. The linear metabolic system of the modern cities is different from nature's circular metabolism, where every output by an organism is also an input that renews and sustains the living environment. The linear pattern of production, consumption and disposal in our cities is not at all concerned about the sustainability of cities. Inflows and outflows are not considered as related. The present urban metabolism is definitely different from the circular pattern of nature's metabolism.

Material flows analysis can provide a framework for analyzing the urbanization process and the way cities are transforming the earth's ecosystems as a consequence of human activities. Rapid transfer of materials from the natural environment to the urban and industrial environment will change both geomorphology and urban morphology. Lawson and Douglas (1998) take into account the exploitation of the earth's resource to investigate the geo-environmental perspective of urban metabolism on sustainable development. They suggest that the account and quantification of material flow, reuse and recycling should be important components in the development of indicators that would help in identifying as to which country or city is becoming more sustainable in its behavior. The materials needed to develop urban areas play an important role in sustainable development. Any consideration of sustainable urban development would have to take into account the growing material demands, and the consequential effects of the disposal of construction wastes. The demands of cities for earth materials for construction have caused so much movement of rock and sedimentary matter that its rate is higher by two or three-orders than magnitude of the rates of erosion and sedimentation.

The way cities function and their standard of living determine their amounts and types of resource use. There is no point to simply criticize a large city's huge amount of inflows and outflows of energy and materials. The question is what a city should do to conserve and recycle metabolic flows and whether the metabolism has enhanced its urban sustainability. Newman (1999) expanded the concept of urban metabolism to include aspects of livability for demonstrating the practical meaning of sustainability. It is suggested that in addition to the reduction of the city's use of natural resources and production of wastes, the livability should also be taken into consideration as an important goal of urban sustainability.

3. Methodology

The main task of this research is to establish the volumes of materials shifted in major urban construction projects, the material inputs to, and waste outflow from Taipei metropolis. The urban construction projects include road, bridge, mass railway transit, dike and levee for flood prevention, and storm drainage and sewerage pipes, and buildings. The construction materials include sand and gravel, cement, and asphalt. Data for major urban construction projects were gathered from the statistics or annual reports of public agencies. The quantities of construction materials required per unit length or area for different projects were based on the estimates made by Chang (1998). From these estimates an overall figure for materials movement by each major urban construction project can be obtained.

In order to evaluate the contributory value of material flows due to urban construction to the urban ecological economic system, a new accounting system is required that can assure the contribution of biophysical value of resources to the economic system. For the purpose of taking into account the varied qualities of energy inherent in the hierarchy of system components, two terminologies—*transformity* and *emergy*—are introduced in this paper. Emergy is defined as *all the available energy that was used in the work of making a product and expressed in units of one type* *of energy*. Transformity is *the emergy of one type required to make a unit of energy of another type* (Odum, 1996). After the energy content (e.g. joule) of a flow has been estimated, it can be multiplied by its solar transformity to obtain its solar emergy, with the unit of solar emergy joule (sej). Emergy indices such as ratio of resource emergy used to total imported emergy can be calculated to illustrate the relative worth of material flows within the urban ecological economic system. Further details on the procedure of emergy analysis can be found in Huang and Odum (1991) and Odum (1996).

Past research on urban metabolism has placed emphasis on the increase of resource flows and per capita consumption due to urbanization. In order to study the effects of resource flow for construction activities on urban sustainability, a framework of indicators is developed in the present paper. It includes following five categories: (1) intensity of resource consumption; (2) inflow/outflow ratio; (3) urban livability; (4) efficiency of urban metabolism; and (5) emergy evaluation of urban metabolism (please refer Table 1).

Table 1
Urban metabolism indicators of Taipei's urban construction

Intensity of resource consumption
Density of construction material use (ton/km^2)
Per capita construction material use (ton per person)
Per capita construction waste generated (ton per person)
Inflow/outflow ratio
Ratio of construction material use to urban productivity (ton/US$)
Ratio of construction waste to urban productivity (ton/US$)
ratio of increase rate of construction material use to increase rate of construction waste (ton/ton)
Urban livability
Road density (m^2/m^2)
Per capita road area (m^2 per person)
Service ratio of sewage treatment (%)
Ratio of material flows to soil loss (ton/ton)
Ratio of material flows to net soil loss (ton/ton)
Ratio of increase of sediment yield to increase of material flows (ton/ton)
Ratio of increase of air pollutant to increase of material flows (ton/ton)
Efficiency of urban metabolism
Ratio of increase of construction material use to increase of urban construction (%/%)
Ratio of increase of construction waste to increase of urban construction (%/%)
Emergy evaluation of urban metabolism
Ratio of construction material used to total emergy use (%)
Ratio of construction material import to total emergy import (%)
Ratio of construction waste emergy to total waste emergy (%)
Ratio of construction waste emergy to total emergy use (%)
Ratio of construction waste emergy to renewable emergy (%)

4. Background of study area

During the past decades, Taiwan has experienced a rapid growth in the economy with associated expansion of urban areas and high rates of per capita consumption. As a result of rapid urbanization, currently, nearly 80% of the population in Taiwan live in urban areas. The urban population has grown by four million people in just 15 years between 1980 and 1995, and the urban area has increased >40% for the same period of time. Despite a great expansion of the financial and commercial sectors in Taiwan, more investment in urban infrastructure is needed for sanitation and improving transportations. The west coast of Taiwan has become a visibly unsustainable environment due to the rampant urban growth. In addition, they are increasingly polluted with both sewage and air. Since sophisticated sewage works, which can cope with all types of water pollutants are very expensive and the traffic explosion has not been alleviated effectively, it is likely to take a long time before these environmental problems afflicting urban areas are tackled. The examination of the demands on resources and disposal of urban wastes is critical to the evaluation of trends towards future sustainability.

The city of Taipei is located in the northern part of Taiwan, which is also the key urban center of the island. The study region, an area of about 2325 km^2, consists of Taipei city and the outlying areas of Taipei County. Currently, the total population in the study region is approximately 6.2 million, having increased

Table 2
Summary of urban construction in Taipei area

Category	Year			
	1981–1985	1986–1990	1991–1995	1996–1998
Road (m^2)[a]				
New road	457,275	236,156	795,352	453,956
Widening	237,572	260,211	270,496	137,726
Maintenance	438,273	390,441	517,736	1,604,550
MRT (km)[b]	–	22	7	3
Bridges (m^2)[c]				
RC	52,097	10,394	27,426	2,026
Steel	9,170	11,844	23,631	57,537
Storm drainage (m)[d]				
Arterial pipes	13,605	8,982	11,435	58,204
Branch pipes	17,973	13,232	13,611	53,868
Sewerage (m)[a]				
Arterial pipes	5,308	3,901	9,066	6,912
Branch pipes	14,182	95,998	13,643	45,881
Flood prevention (m)[a]				
Dike/levee	16,673	7,870	4,730	2,620
Bank protection	4,569	5,439	14,170	3,518
Buildings (10^3 m^2)[e]	9,608	8,115	9,899	10,440

[a] The Statistical Abstract of Taipei Municipality (1982–1999); The Statistical Abstract of Taipei Prefecture (1982–1999).
[b] Data provided by Department of Rapid Transit Systems, Taipei City Government, Taiwan (http://www.dorts.gov.tw).
[c] Data provided by Department of New Construction Projects, Taipei City Government, Taiwan (http://www.ncp.tcg.gov.tw); The Statistical Abstract of Taipei Prefecture (1982–1999).
[d] Data provided by Department of Maintenance Engineering, Taipei City Government (http://www.med.tcg.gov.tw).
[e] Construction and Planning Statistical Year Book of Taiwan Area, ROC (1982–1998).

by about 25% during the past decade. On an average, approximately 2×10^6 m^2 floor area of building per annum were constructed between 1981 and 1998 in Taipei, mainly in response to the rapid urbanization during the past decades (Table 2). Road construction has been the major civil engineering project in Taipei area since 1980. During the period 1991–1995, nearly 800,000 m^2 of new roads have been built. In addition, the widening and maintenance of existing roads, with the figures of over 900,000 and 3,000,000 m^2 during the period 1981–1998, also has contributed to the improvement of transport infrastructure in Taipei (see Fig. 1a). However, the main growth in transport infrastructure since 1980s in Taipei has been the construction of over 30 km of MRT (see Fig. 1b).

Due to the low lying topography of Taipei, the construction of storm drainage pipes and dike and levee for flood prevention should also be considered as major civil engineering projects in Taipei. The dike and levee, with height exceeding 3 m, were constructed along Tamsui and Keelung Rivers to prevent floods with 200 year return interval. The total length of dike and levee, which has been built in Taipei area since 1981 is approximately 32 km, and the length of arterial storm drainage pipes constructed during this period exceeds 90 km (see Fig. 1c). The construction of sewerage for collecting household wastewater in Taipei area has continued to be a major civil engineering project since 1980s for the protection of surface water quality. In all, the total length of the arterial and branch sewerage constructed during the past decades is approximately 195 km (see Fig. 1d).

The one-way traffic of energy and materials from rural areas to a metropolis like Taipei is causing severe

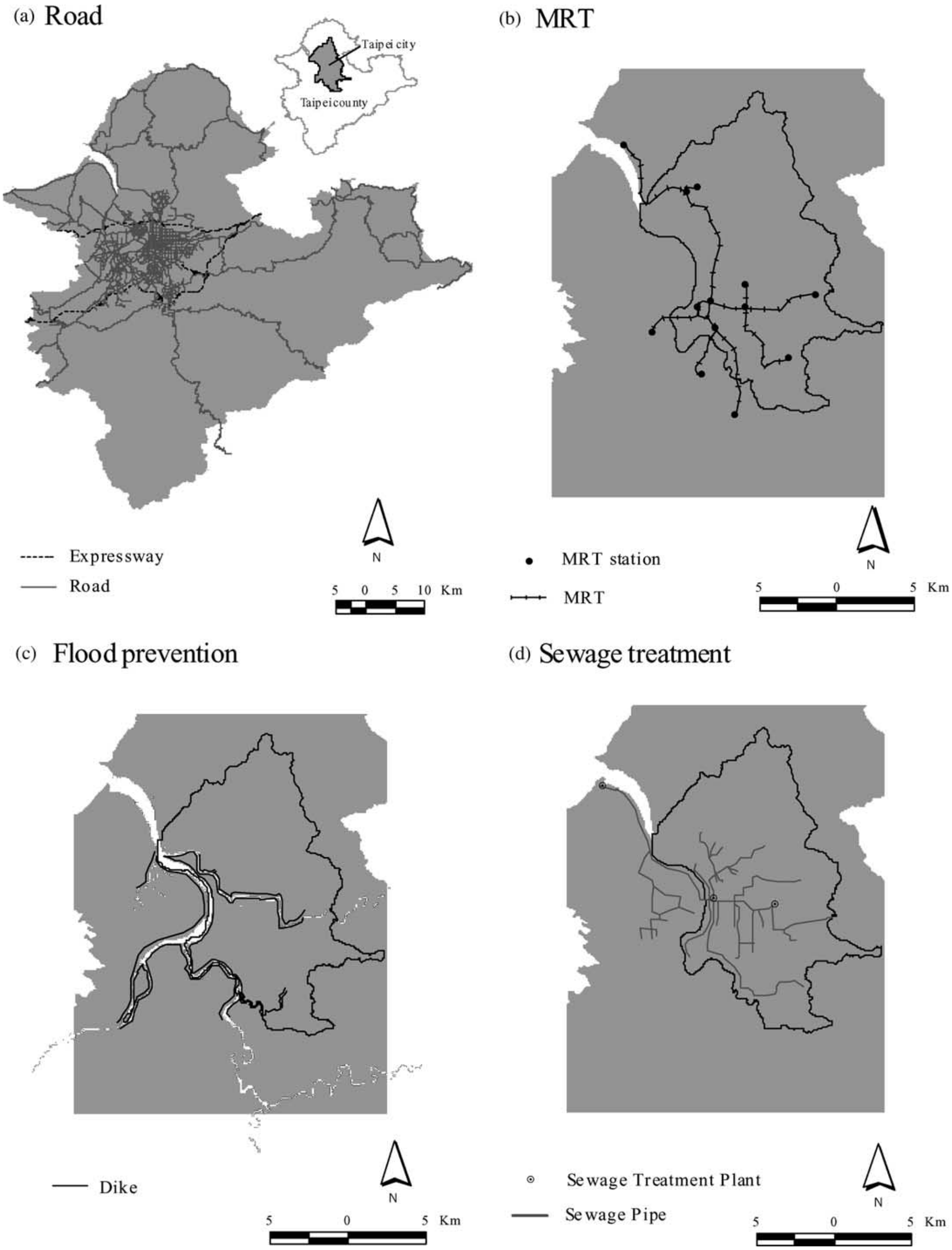

Fig. 1. Major civil engineering projects in Taipei.

depletion of resources and degradation of the environment. The case study of Taipei area is an attempt to investigate the urban sustainability as a result of earth material flows for urban construction.

5. Material flows accounting of resource use for urban construction

5.1. Resource flows

Calculation of the earth moving involved in all the urban construction is difficult as each individual project involves a different set of structural and resource requirements. Per unit requirements of materials for each type of construction is used as a basis for estimating material flows during the past decades (see Table 3). As a result, ever since 1991, the consumption of sand and gravel in Taipei area has exceeded 1.0×10^7 ton per year. The main consumption of sand and gravel is for the construction of civil engineering projects such as MRT system and road construction, which reached its peak in 1993 and gradually decreased afterwards (Fig. 2A). Similar to the pattern of sand and gravel consumption, the consumption of cement in Taipei area also reached its maximum of 4.1×10^6 ton in 1993, and the major consumption of cement is for buildings (Fig. 2B). Because most of the major urban engineering projects are nearly completed, the total demand for sand/gravel and cement have gradually decreased since 1995. As for asphalt, the major use for its consumption is road construction and maintenance, and there is a tendency of increasing the volume of consumption. In summary, sand and gravel are the major materials required for urban construction, which amounts to approximately 90% of the total demand. In spite of the completion of flood prevention projects and MRT system, the material consumption for the rest of construction projects such as buildings and roads, are still increasing.

Table 3
Per unit requirements of construction materials

Category	Material		
	Sand/gravel	Cement	Asphalt
Road (m^2)	0.591 m^3	0.01 pack	22.8 kg
Bridges (m^2)			
RC	2.988 m^3	0.2 pack	81.96 kg
Steel	0.394 m^3	0.326 pack	15.17 kg
Storm drainage (m)			
Arterial pipes	6.49 ton	0.998 ton	–
Branch pipes	1.3 ton	0.2 ton	–
Sewerage (m)			
Arterial pipes	6.430 m^3	1.446 ton	–
Branch pipes	0.480 m^3	0.122 ton	–
Flood prevention (m)			
Dike/levee	135 ton	20.77 ton	–
Bank protection	90 ton	13.85 ton	–

Data on construction waste are inevitably incomplete due to the lack of site for dumping and illegal fly tipping. The most recent estimate of construction waste in Taipei area shows production of 20×10^6 to 40×10^6 ton per annum (see Table 4), which is equivalent to approximately 30–40% of the total construction waste in Taiwan. Judging from the statistics of material flows during the period of 1996–1998, the volume of construction waste produced is much higher than the resource consumed for construction. Fig. 3 summarizes the comparison of material flows between 1991 and 1998. In addition to local sources, the supply of sand and gravel has to rely on domestic sources outside Taipei area. The source of cement is from domestic supply and asphalt must rely on foreign import. The consumption of sand/gravel and cement in 1998 was decreased by 40% as compared to 1991. However, the consumption of asphalt increased by 130% due to the maintenance of road. As for the resource flows for building, the consumption of sand and gravel decreased by 17%, but the consumption of cement increased nearly four times due to the structure requirement of high-rise buildings.

5.2. Emergy evaluation

Further evaluation of principal emergy flows of materials used due to urban construction can provide a preliminary understanding of their relative worth and contribution to ecological economic system of Taipei. Further more, the emergy flows can also be used for the subsequent calculation of emergy indices to measure the ecological economic interface of rapid urban development.

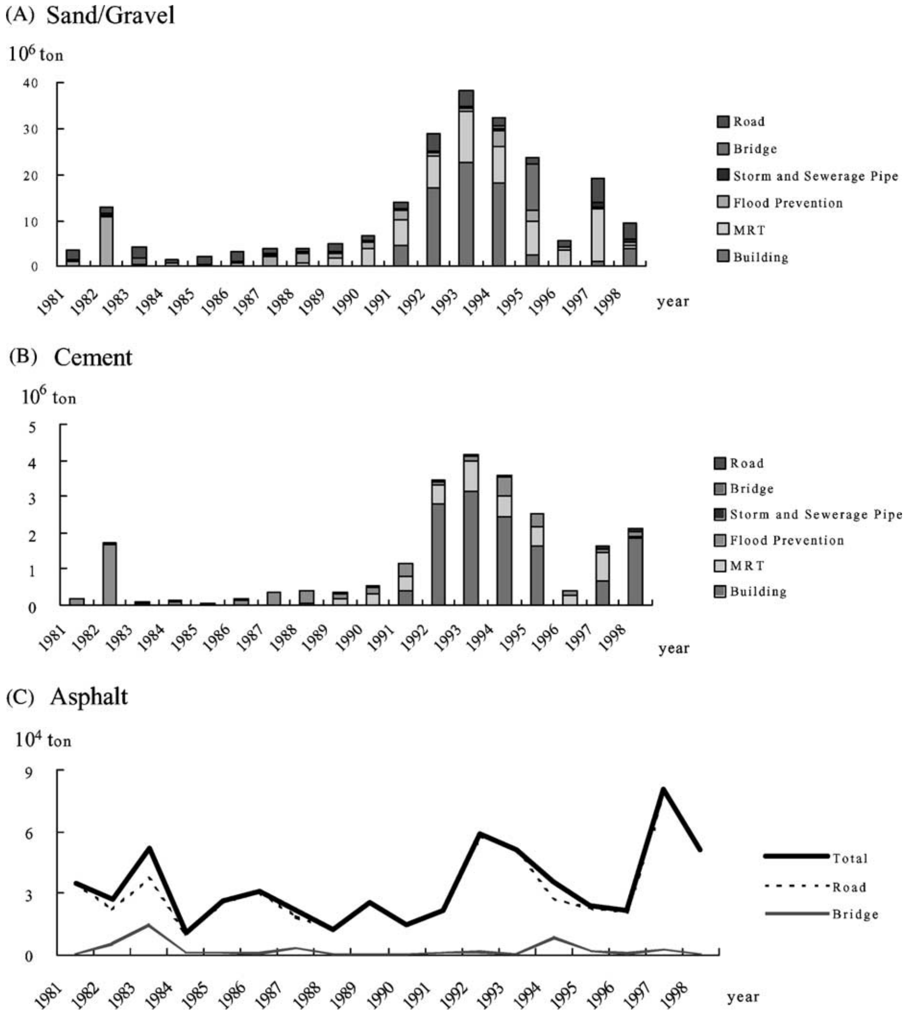

Fig. 2. Trends of resource consumption for urban construction in Taipei.

The estimated material flows for the periods of 1991–1995 and 1996–1998, presented in the previous section, are converted into emergy units and analyzed within the framework of Taipei's ecological economic system. Due to its limited natural resources and relatively urbanized land uses, the emergy flows from renewable sources (R) and locally non-renewable sources (N) to the urban economy in Taipei area are relatively small (please refer Table 5 and Fig. 4). Imported fuels and goods and services are the principal sources of urban activities in Taipei. Specifically, in Taipei area 95% of its activity operates on imported fuels and goods and services. Because most of the major civil engineering projects are nearly completed, the demand for construction materials has decreased, therefore, the average emergy used per year (U) during 1996–1998, 1.77×10^{23} sej, is less than the emergy used during 1991–1995, 2.23×10^{23} sej. The urban construction in Taipei has to rely on imported materials (M), the amount of which during the period 1991–1998, is even higher than the imported fuels emergy (F). Owing to its low transformity, the emergy value of sand and gravel from local sources (N3) is only 2.23×1017 sej per year. The emergy

Table 4
Construction waste produced in Taipei area[a]

Type	Year			
	1995	1996	1997	1998
Civil projects				
Taipei city	14.58	4.31	5.61	11.49
Taipei county	5.87	6.86	9.80	8.70
Subtotal	20.45	11.16	15.41	20.19
Buildings				
Taipei city	1.38	1.33	2.02	11.07
Taipei county	9.61	9.27	5.70	8.84
Subtotal	10.99	10.60	7.72	19.91
Total	31.44 (42%)[b]	21.76 (34%)	23.13 (24%)	40.10 (45%)

[a] The unit in 10^3 ton.
[b] The value in parenthesis represents the percentage of Taiwan area.

of construction material is mainly from sources outside Taipei area (M). Although the volume of the imported sand and gravel for construction in Taipei area is 10 times higher than that of cement, but due to the higher transformity of cement, the emergy value of cement used dominates the total emergy flows of materials used for urban construction (see footnote "M" of Table 5). The waste flows in Taipei area have greatly increased during the past decades. It is estimated that the waste emergy flow comprises approximately 70–75% of construction waste. However, the reuse and recycle of construction waste is still minimal.

6. Sustainability of Taipei's urban construction

Based on the material flows analysis and emergy evaluation of Taipei's urban construction, the proposed sustainability indicators (please refer Table 1) are calculated to measure the effect of urban construction on Taipei's sustainability. The intensity of resource consumption for urban development reached its maximum in 1993 due to the construction of MRT and flood prevention projects (please refer Fig. 5). The ratio of construction material use to urban productivity also declines, representing its decreasing contribution to urban economic activity (please refer Table 6). Although the per capita consumption of construction materials has been steadily decreased, but the generation of construction waste shows no sign of decrease because of the increasing excavation for high rise buildings in Taipei. As a result, the ratio of construction waste to urban productivity also increases, and shows negative sign on the ratio of increase rates of construction material use to construction waste.

The livability in Taipei has improved to some extent during the past decade due to the increased provision of infrastructures such as road density and service ratio of sewerage (Table 7). However, the ratio of material flows to soil loss shows the negative effect of urban construction on natural environment. When we compare natural rates of erosion with surface material shifted as a result of urban construction, we are examining the similarity of people-accelerated natural process activity to deliberate shifting of materials. The comparison brings out the magnitude of the materials fluxes involved. Making this comparison for Taipei area, the ratio of 70.19 in 1995 and 88.6 in 1998 reveal the contrast between human-induced materials shifted with the natural process of soil loss. Furthermore, the ratio of increase rate of sediment yield to increase rate of material flows signifies the impact of urban construction to surface water.

The results of emergy evaluation show that the material flows for urban construction is equivalent to 44% of total emergy used in Taipei area in 1995, representing its high contribution to the ecological economic

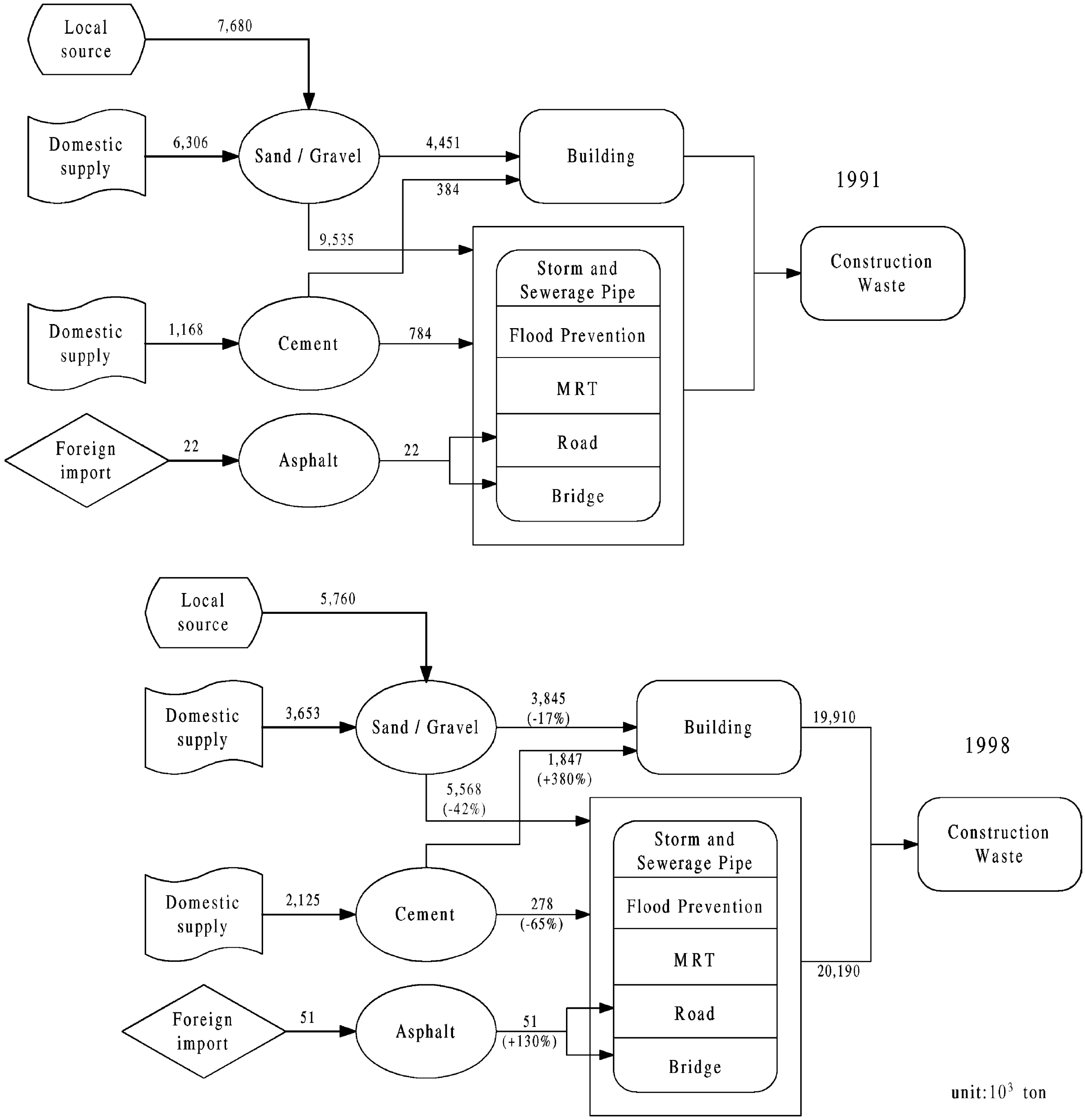

Fig. 3. Summary of resource flows of Taipei's urban construction.

system of Taipei (see Table 8). Despite the decreasing ratio of construction material used to total emergy use in 1998 (26%), 70% of the total waste emergy still contributed by construction waste emergy, which is equivalent to 29% of the total emergy use. The ratio of construction waste emergy to renewable emergy can be seen as an index of environmental loading, and the ratio of 26.63 in 1995 and 22.7 in 1998 shows the pressure of construction activity on the natural environment of Taipei.

Table 5
Summary of principal emergy flows of Taipei area

Expression	Emergy flow	Solar emergy (sej per year)	
		1991–1995	1996–1998
U[a]	Total emergy used	2.23×10^{23}	1.77×10^{23}
R[b]	Renewable emergy flows	2.21×10^{21}	2.27×10^{21}
N[c]	Indigenous nonrenewable flows		
	N0 Dispersal rural	9.54×10^{20}	9.54×10^{20}
	N1 Concentrated use	5.39×10^{20}	5.51×10^{20}
	N2 Direct export	0.00×10^{00}	0.00×10^{00}
	N3 Construction materials	2.23×10^{17}	1.67×10^{17}
F[d] & M[e]	Imported fuels and materials		
	F: imported fuels	3.75×10^{22}	4.41×10^{22}
	M: imported construction materials	9.83×10^{22}	4.61×10^{22}
P2I[f]	Imported good and services	8.39×10^{22}	8.30×10^{22}
P1E[g]	Exported goods and services	1.33×10^{23}	1.05×10^{23}
W[h]	Waste emergy flows	7.78×10^{22}	7.26×10^{22}
	Wc Construction waste	5.63×10^{22}	5.07×10^{22}
X[i]	Urban productivity	7.36×10^{10} (US$)	7.31×10^{10} (US$)
P1	Ratio of emergy used to GDP (Taipei)	3.03×10^{12} (sej per US$)	2.42×10^{12} (sej/US$)
P2	World emergy/dollar ratio	1.98×10^{12} (sej/US$)	1.98×10^{12} (sej/US$)

[a] U: total emergy used (R + N + F + M + P2I).

[b] R: renewable emergy flows (wind + tide + upstream flow): wind: (3.30×10^{18} J) (623 sej/J) = 2.06×10^{21} sej per year; tide: (1.63×10^{13} J) (23,564 sej/J) = 3.84×10^{17} sej per year; upstream flow (1991–1995): (2.76×10^{8} m^3) (10^6 g/m^3) (5 J/g) (41,068 sej/J) = 5.67×10^{19} sej per year, 1996–1998: (1.04×10^{9} m^3) (10^6 g/m^3) (5 J/g) (41,068 sej/J) = 2.14×10^{20} sej per year.

[c] N: indigenous non-renewable flows (N0 + N1). N0: dispersal rural (soil loss + wood + sand). Soil loss (1991–1995): (240 ton/km^2) (2324.37 km^2) (1.71×10^{15} sej/ton) = 9.54×10^{20} sej per year, wood: (589.09 m^3) (7×10^{5} g/m^3) (3.8 kcal/g) (4186 J/kcal) (34,900 sej/J) = 2.29×10^{17} sej per year, sand: (7.68×10^{6} ton) (10^6 g/ton) (29,000 sej/g) = 2.23×10^{17} sej per year. Soil loss (1996–1998): (240 ton/km^2) (2324.37 km^2) (1.71×10^{15} sej/ton) = 9.54×10^{20} sej per year, wood: (148.57 m^3) (7×10^{5} g/m^3) (3.8 kcal/g) (4186 J/kcal) (34,900 sej/ton) = 5.77×10^{16} sej per year, sand: (5.76×10^{6} T) (10^6 g/ton) (29,000 sej/g) = 1.67×10^{17} sej per year. N1: concentrated use (hydro electric + coal). Hydro electric (1991–1995): (5.34×10^{8} kwh) (3606 J/kwh) (159,000 sej/J) = 3.06×10^{20} sej per year, coal: (2×10^{5} ton) (7.0×10^{6} kcal/ton) (4186 J/kcal) (39,800 sej/J) = 2.33×10^{20} sej per year; hydro electric (1996–1998): (7.59×10^{8} kwh) (3.606 J/kwh) (159,000 sej/J) = 4.35×10^{20} sej per year, coal: (9.91×10^{4} ton) (7.0×10^{6} kcal/ton) (4186 J/kcal) (39,800 sej/J) = 1.16×10^{20} sej per year. N2: direct export. N3: construction materials (included in N0). Sand (1991–1995): 2.23×10^{17} sej per year; Sand (1996–1998): 1.67×10^{17} sej per year.

[d] F: imported fuels (petroleum and petroleum product + coal). Petroleum and petroleum product (1991–1995): ($43,156 \times 10^{6}$ l) (9000 kcal/l) (4186 J/kcal) (66,000 sej/J) = 2.91×10^{22} sej per year, coal: (5607×10^{6} l) (9000 kcal/l) (4186 J/kcal) (39,800 sej/J) = 8.41×10^{21} sej per year; Petroleum and petroleum product (1996–1998): ($47,500 \times 10^{6}$ l) (9000 kcal/l) (4186 J/kcal) (66,000 sej/J) = 3.29×10^{22} sej per year, coal: (7446×10^{6} l) (9000 kcal/l) (4186 J/kcal) (39,800 sej/J) = 1.12×10^{22} sej per year.

[e] M: imported construction materials (sand and gravel + cement + asphalt). Sand (1991–1995): (1.78×10^{7} ton) (10^6 g/ton) (29,000 sej/g) = 5.17×10^{17} sej per year, cement: (2.98×10^{6} ton) (10^6 g/ton) (3.3×10^{10} sej/g) = 9.83×10^{22} sej per year, asphalt: (13,889 ton) (10^6 g/ton) (347,000 sej/g) = 4.82×10^{15} sej per year; 1996–1998: sand: (6.55×10^{6} ton) (10^6 g/ton) (29,000 sej/g) = 1.90×10^{17} sej per year, cement: (1.40×10^{6} ton) (10^6 g/ton) (3.3×10^{10} sej/g) = 4.61×10^{22} sej per year, asphalt: (51,113 ton) (10^6 g/ton) (347,000 sej/g) = 1.77×10^{16} sej per year.

[f] P2I: imported goods and services (P2 × I). P2: world emergy/dollar ratio = 1.98×10^{12} sej/US$; I: dollar paid for imported goods and services. Imported goods (1991–1995) 3.59×10^{10} US$ + imported services 6.41×10^{9} US$ = 4.24×10^{10} US$; imported goods (1996–1998) 3.55×10^{10} US$ + imported services 6.54×10^{9} US$ = 4.19×10^{10} US$.

[g] P1E: exported goods and services (P1 × E). P1: Taipei's emergy dollar ratio (U/X). 1991–1995: 3.03×10^{12} sej/US$; 1996–1998: 2.42×10^{12} sej/US$.

[h] W: waste emergy flows (solid waste + waste water + construction waste). Solid waste (1991–1995): (3.52 ton per day) (365 day per year) (4×10^{6} BTU/ton) (1055 J/BTU) (1.8×10^{6} sej/J) = 2.01×10^{22} sej per year, waste water: (1.19×10^{6} m^3 per day) (365 day per year) (10^6 g/m^3) (5 J/g) (665,714 sej/J) = 1.44×10^{21} sej per year, construction waste: (3.14×10^{7} ton) (10^6 g/ton) (1.79×10^{9} sej/g) = 5.63×10^{22} sej per year; solid waste (1996–1998): (3.724 ton per day) (365 day per year) (4×10^{6} BTU/ton) (1055 J/BTU) (1.8×10^{6} sej/ton) = 2.04×10^{22} sej per year, waste water: (1.22×10^{6} m^3 per day) (365 day per year) (10^6 g/m^3) (5 J/g) (665,714 sej/J) = 1.48×10^{21} sej per year, construction waste: (2.83×10^{7} ton) (10^6 g/ton) (1.79×10^{9} sej/g) = 5.07×10^{22} sej per year.

[i] X: urban productivity. 1991–1995: 7.36×10^{10} US$; 1996–1998: 7.31×10^{10} US$.

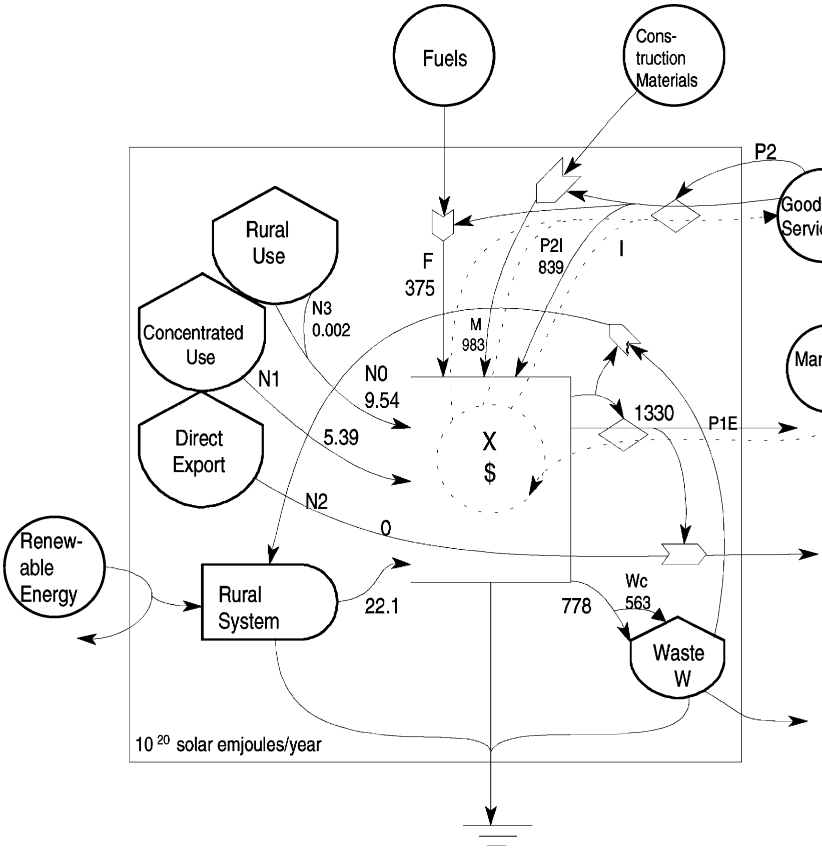

Fig. 4. Aggregated diagram of emergy flows for Taipei area in 1995.

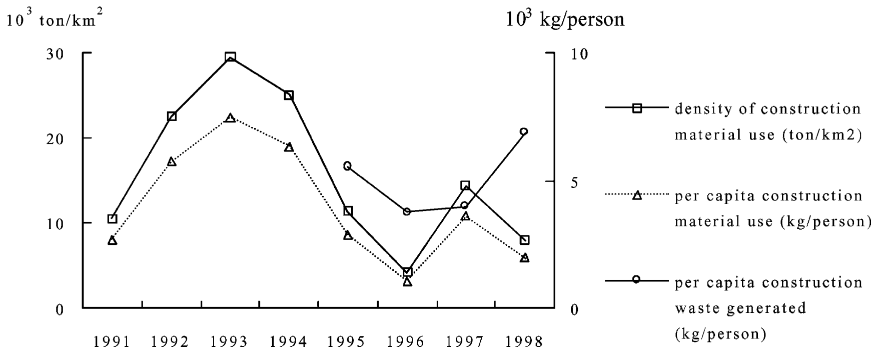

Fig. 5. Trends of indicators of intensity of resource consumption for Taipei's urban construction.

Table 6
Indicators of inflow/outflow of urban construction in Taipei

Indictors	1991	1995	1998
Ratio of construction material use to urban productivity (ton/US$)	1.06×10^{-5}	8.40×10^{-6}	4.74×10^{-6}
Ratio of construction waste to urban productivity (ton/US$)	NA[a]	1.61×10^{-5}	1.64×10^{-5}
Ratio of increase rate of construction material use to increase rate of construction waste (ton/ton)	–	NA	−0.94[b]

[a] Data of construction not available till 1995.
[b] Value represents the ratio between 1995 and 1998.

Table 7
Indicators of urban livability in Taipei due to urban construction

Indicators	1991	1995	1998
Road density (m^2/m^2)	0.0183	0.0217	0.0234
Per capita road area (m^2/person)	4.72	5.52	5.84
Service ratio of sewage treatment (%)	21.16	24.55	41.37
Ratio of material flows to soil loss (ton/ton)	NA[a]	70.19	88.60
Ratio of material flows to net soil loss (ton/ton)	NA	717.77	1061.34
Ratio of increase of sediment yield to increase of material flows (ton/ton)	NA	NA	3.38[b]
Ratio of air pollution to increase of material flows (ton/ton)	NA	NA	−0.31[b]

[a] Data of construction waste not available until 1995.
[b] Value represents ratio between 1995 and 1998.

Table 8
Emergy index of material flows of urban construction

Index	1995	1998
Ratio of construction material use to total emergy use (%)	0.44	0.26
Ratio of construction material import to total emergy import (%)	0.45	0.27
Ratio of construction waste emergy to total waste emergy (%)	0.72	0.70
Ratio of construction waste emergy to total emergy use (%)	0.25	0.29
Ratio of construction waste emergy to renewable emergy (%)	26.63	22.70

7. Conclusions

Over 10×10^6 ton of materials were extracted per year for construction and 30×10^6 ton of construction waste per year was dumped without recycling in Taipei area in the process of urban development. This material transfer is not only modifying the landscape at a rapid pace but also causing severe damage to hydrological properties elsewhere in Taiwan. Despite the ongoing construction of expressway and development of industrial sites on coastal area, the construction wastes produced in urban area have not been recycled to refill the project sites.

In order to cope with rapid expanding of urban areas, sand and gravel extraction either causes changes to rivers, which can have severe impacts on transportation infrastructure further down stream, or takes land out of food production, and forces greater energy consumption to bring production from farms farther away. The significance of 80–90-fold difference between natural soil erosion and the deliberate shifting of material for urban construction lies in the recognition that the overall rate of change of land surface in Taiwan is now more rapid than at any time before colonization (i.e. 300 years ago).

The process of urbanization is likely to continue but how can its profound destructiveness of ecosystem be reversed? The urban development might continue to displace and relocate earth surface materials. Usually the market does not resolve these geomorphic and environmental impacts. Mitigation of the effects of urban construction requires investment of materials, energy and labor, which then become external costs to the public. Waste dumps represent one of the most serious environmental problems due to the lack of treatment facility in Taiwan. Probably the greatest impact of the process is in the river valleys, where landfills have raised the height of ground level and blocked natural drainage pattern. Despite the shortage of landfill sites for construction waste, construction waste dumping will continue to be a highly significant aspect of serious environmental problem in Taiwan for the next 10 years at least. In order to develop a self-regulating relationship with the biosphere, cities will need to adopt circular metabolic systems that ensure the continuing viability of the environment on which they depend. Adopting circular resource flows will help cities to reduce their footprint, and thus, their impact on the biosphere. The rate of geomorphic transformation by construction materials used and disposed could be reduced by greater reuse and recycling of construction waste.

It is vitally important to recognize the pattern of urban metabolism, the throughput of energy, materials, goods, and the generation and treatment of waste from the perspective of sustainable development. This paper presents a preliminary investigation on the material flows due to construction activity. The materials flow accounting approach and emergy evaluation to urban construction have important implications for evaluating the sustainability of urban development. Much more work needs to be done to find ways of recycling and reuse of construction waste and of reducing the impact of mineral extraction on the landscape. In the future, the materials flow accounting and emergy evaluation can be extended to include: (1) the assessment of the energy used in the material flows, from extraction and processing to transportation and waste dumping; and (2) the impacts of urban construction on the geomorphic landscape and aquatic ecosystems.

Acknowledgements

Financial support was provided by the National Science Council, Executive Yuan of the Republic of China (Grant nos.: NSC89-2415-H-005-A-009, NSC89-2415-H-305-005). Prof. Ian Douglas and Nigel Lawson of University of Manchester gave many useful comments on the development of indicators.

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