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Contributions of Material and Energy Flow Accounting to Urban Ecosystems Analysis: Case Study Singapore

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Abstract

Sustainable development requires to stabilize the extraction of resources at levels that can be provided into the long term future and also reduce emissions to a degree that they don't threaten the integrity of our planet's life support systems. At the same time economic activity needs to flourish to meet development targets such as laid out in the millennium development goals. While the objectives of sustainability have been formulated at the global level it is challenging to define measure of progress more regionally.

Since our population, our resource use and emissions are increasingly concentrated in urban centers we need a better understanding of their functioning. Material and energy flow accounts are suggested as a method to study variations in volume and composition of resource use among different societies. They enable to link the appropriation of ecosystem services for socioeconomic activity across various scales from the local to the global level. A first and preliminary material flow account for the overall throughput of resources and energy consumption for the urban economy of Singapore is presented, describing the city as an urban ecosystem with characteristic inputs and outputs. This paper has three components. 1) It documents changes in resource input and consumption over 40 years of economic growth and restructuring of Singapore. 2) For a recent year it balances material inputs and emissions. 3) It compares how the volume and composition of resource inputs into Singapore differs from other countries.

Results show that the volume of traded material dominated direct material input (DMI) and exceeded domestic material consumption (DMC) throughout the time series. Per year the direct material input (DMI, excluding air and water) grew from about 10 tons per capita up to 75 tons in 2000, which is exceptionally high. Domestic material consumption (DMC) rose from values between 3- and 4- to more than 50 tons per capita between 1965 and 2000. In the most recent period more than 20 tons of material per capita was added each year to the physical infrastructure of the city of Singapore.

In comparison to other socioeconomic systems, the consumption of biomass was exceptionally low. Fossil fuel consumption was very high and the use of construction minerals even higher, with considerable inter-annual variation. It is suggested that those features are characterizing the metabolic profile of a city during a phase of urban restructuring.

While total GDP grew at a factor of 20 in the observed time period, so did material consumption. A trend of de-linking of resource throughput and economic growth (referred to as dematerialization) was not observed.

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1. Introduction

The global trend of urbanization is ongoing. We are currently passing the point were half of the human population lives in cities and it is projected that over the coming 25 years the number of urban dwellers will grow by another 2 billion people due to migration and natural increase (UNSWPP 2004). Most of the urban growth will occur in low income countries.

Worrying trends are increases in the urban-rural income discrepancy[1], lagging rates of job creation and urban poverty. Concerns include the fragmentation of traditional social security networks, exposure to health risks from unsafe living and working conditions, lacking sanitation, exposure to air pollution and improper waste treatment (McGranahan et al 2001). The limited ability of low income countries to proactively address those problems makes urbanization a particular challenge for sustainable development.

On the other hand cities offer potentials to effectively supply large segments of the population with basic needs such as health care, access to education and infrastructure. As centers of economic activity and consumers they provide opportunities of employment, economic investment and social mobility. They often are entry points into an increasingly denser network of market integration of the global economy.

In a similar way that there is ambiguity about the social and economic consequences of urbanization, also the environmental impact of urban settlements has been subject to discussion.

On the global level cities cover only 3% of the total land area. Considering that they accommodate half of the population they are an efficient form of settlement possibly enabling the conservation of natural ecosystems at other places. Their impact on the surrounding environment through resource depletion and emissions although clearly exceeds the immediate urban boundary: As centers of population cities rely on a hinterland of rural and extractive economies. They depend on area-intensive agricultural systems converting sunlight and nutrients into biomass for food production. Together with air and water these are the vital resources to sustain the population. Additionally cities import a wide range of goods, depending on effective transport systems: non-food biomass such as wood and fibers,

[1] Since the urban-rural income gap is one driver of urbanisation it provides a positive feed back.

minerals for construction- and industrial use and growing volumes of technical energy carriers like fossil fuels. After the consumption of those materials, refuse and waste is released as emissions into the environment. Formally this process of inflows and outflows resembles that of a biotic organism and has been described as urban metabolism (Wolman 1965). An analytical description would be a mass balances: what goes in must go out, after corrections for changes in stock. Environmental impacts are associated on both sides of this equation: the input of resources into cities is depleting deposits of renewable and non-renewable resources all over the world; also the outputs from cities are affecting the environment on an increasingly global scale.

It had been highlighted by resource economists that the process of resource use described above is a complementary biophysical description of the socio economic process, mirroring stages of adding value over the supply chains of commodities (Ayres and Kneese 1969), (Georgescu-Roegen 1971). Other authors referred to the concept as cradle-to grave analysis.

In sustainable development research there is need for methods that can expand our understanding of the interaction between urbanization, economic development and environmental degradation. This paper argues that physical flow accounts (Material and Energy Flow Accounts: MFA, EFA) provide integrating capacity in this context.

Urbanization itself is a central element of economic development and modernization, since it implies large segments of the workforce are disengaging from agricultural activity and are shifting to work in other fields such as the industry-, service- or public sector. The impact of industrialization and economic restructuring on the environment at the next step does strongly depend on the technology in use, which is subject to policy regulations and consumption levels.

Research on the general interactions of those variables over time of economic development has been conducted in the field of resource- and environmental macro economics (Auty 1985), (Daly 1991). One line of thought about this interaction was formulated during the early 1990s and publicized as 'Environmental Kuznets hypothesis' (IBRD 1992). It states that there are regularities between per capita income and environmental degradation. While early stages of development would be characterized by an increase in the output of waste and environmental degradation the hypothesis argues that with growing economic activity, this correlation will decline once a certain threshold of wealth is reached. Further on the correlation would even turn negative since richer societies are able to invest more in waste abating technologies. As economies develop and mature the relative importance of the service sector would rise. As 'knowledge based economies' they would then require less resource consumption and also produce less pollution to generate a unit of income. The relation between per capita income and environmental degradation over the long run would then follow an inverted U-shape.

Critics point out that this relation empirically holds true only for a limited number of environmental problems such as water quality and certain types of indoor or urban air pollution. Other consumption related pollutants, such as solid waste production, CO2 - emissions, household energy use and transport emissions are either not declining with increasing wealth or are showing more complex relations (De Bruyn and Opschoor 1997). Such explanations include the effect of trade and the possible outsourcing of environmental risks into 'pollution haven' that are less able to enforce regulations. They stress the importance to distinguish between trends in emissions per unit of wealth generated, emissions per capita and total emissions, since only changes in the latter of the three units is mediating effects on the environment. Trends such as relative decoupling per unit of GDP can mask a 'rebound effect' where increases in technologic efficiency are still more than compensated by increases in consumptive behavior (Binswanger 2001).

To increase our understanding about the relation between resource use and development and the regional variation at the urban scale, this study applies a time series approach to Singapore as an example of a fully urbanized economy with considerable dynamics of industrial transformation over the past 40 years.

1.1. Research Questions

The general approach of society's metabolism reasons that the interaction of society and natural systems can be better understood by monitoring material flows through the socio-economic system on the input- as well as on the output side. Many traditional research projects have been focusing on the release of waste since they impose various risks for the human population and the environment. In a wider view although, already the input of material flows into the socio-economic system can be described as a driver of outputs such as emissions and other pollution. Furthermore they are often documented more comprehensively

than outputs. This approach follows the idea of material balancing based on the conservation of mass: everything that goes into the system must go out or reside somewhere within the system. Based on those considerations the central questions this paper addresses are: How did the direct material input and energy consumption of Singapore change over the past 40 years? How did inputs and outputs balance during one year in the most recent history?
How did the trends in biophysical resource use relate to demographic and economic trends?
The variations in the volume and composition of resource use of the fully urbanized system of Singapore were then compared with several other cases on larger, national scale studies.

1.2. Background of the Concept 'Urban Metabolism'
The metaphor of urban metabolism has first been brought forward by the sanitary engineer Abel Wolmann in 1965 in a Scientific American article titled 'The Metabolism of Cities'. He calculated the demand of fossil energy, food and water, and balanced several of the resulting emissions (sewage, refuse and air pollutants) for a hypothetical US city of 1 million. A further development in accounting for the physical economy of cities was achieved by a team of Australian researchers who conducted a case study on Hong Kong (Newcombe 1975a, Newcombe 1975b, Newcombe 1976, Newcombe et al 1978), synthesized in (Boydon et. al. 1981) with support of the UNESCO Man and Biosphere Program and from UNEP. Among the results were an overall material balance and a regionalized account of energy use by economic sector and end use, impact of nutrition on larger, geochemical nutrient flows (Newcombe 1977) and 'indirect' (externalized) land-use patterns of area demand outside the city to feed the population of Hong Kong. This study had a holistic focus recognizing a range of cultural and historic details. It took into account 'physio-chemical, biotic, societal and cultural components of the situation, and considered the dynamic interrelations between them'. It was a pioneering study for a large number of following research projects that all applied an 'ecosystem approach' to urban environmental studies. Another important human ecosystem study on the urban scale was published in 1983 by Ian Douglas (Douglas 1983). The term 'ecosystem approach' was increasingly redefined and widened to include larger numbers of parameters and broader systemic and holistic approaches (Machlis et al 1997), (Decker et al. 2000).

The second half of the 1980s and early 1990s witnessed the synthesis of several streams of theoretical and empirical developments by foundation of the societies and journals of Ecological Economics (Martinez Alier 1987, van den Bergh 2000) and shortly afterwards

Industrial Ecology (Jelinski et al 1992, Ayres and Simonis 1994). Both fields of research are devoted to a systemic understanding of society-nature interaction. Material and Substance Flow Accounting is one of the methodologies of operationalization. (Baccini and Brunner 1991).

1.2.1. Recent national and urban case studies

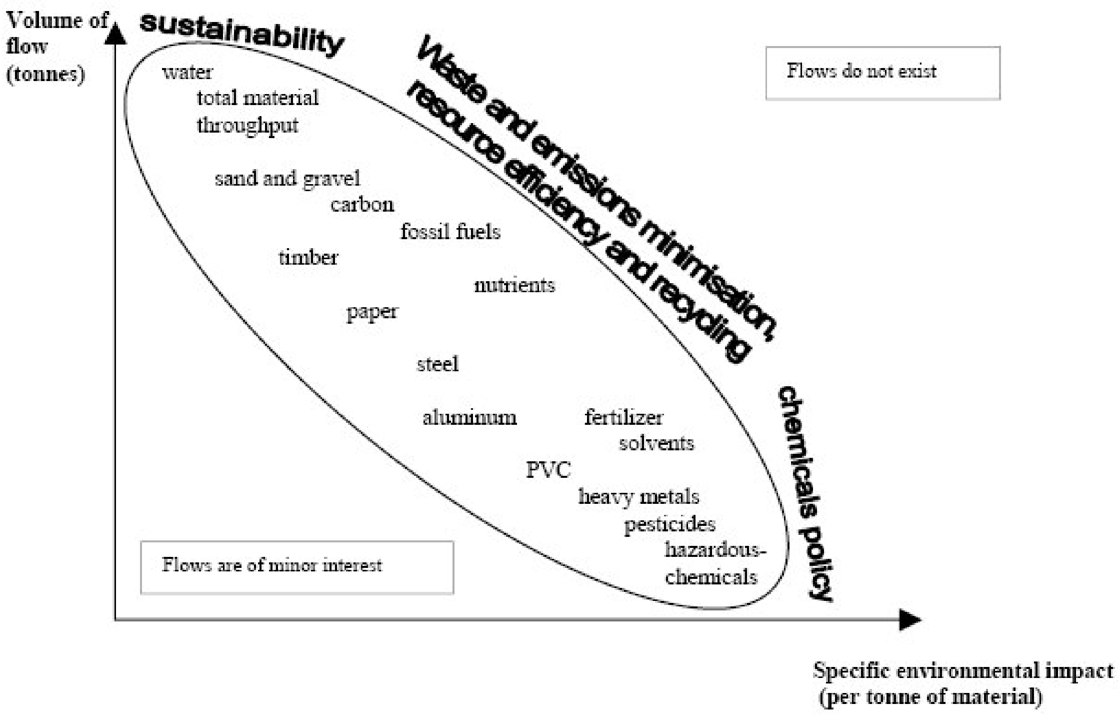
The demand for physical flow accounts on a national level as strategic reporting tool for resource consumption has been recognized in a number of agencies and countries (Steurer 1992, Stahmer 1993, Adrianse et al 1997, Matthews et al 2000, National Research Council 2004). In the past 10 years those accounts have been established as satellite accounts of integrated economic- environmental reports (UNDESA 2000). Eurostat, the statistic agency of the European Union, started reporting material flows in 2001, which have since been updated and expanded (Eurostat 2002). Additionally Eurostat did recently release a methodological guide for harmonized MFA accounting procedures (Eurostat 2001). This project has been following those guidelines. Physical Flow Accounts are also proposed as satellite account to a System of Integrated Environmental and Economic Accounts (SEEA) in a recent revision of the Handbook of National Accounting, endorsed by the Statistical commission of the United Nations (UN), jointly published and revised with the European Commission, the International Monetary Fund (IMF), the Organization for Economic Cooperation and Development (OECD) and the World Bank (UNDESA 2003).

Additional to the national case studies a number of projects developed methods for physical flow accounts on a regional and city level. Examples of such regional studies, adding to the cases mentioned earlier include Amsterdam (Goree et al 2000), the lower Buenz valley (Brunner et al 1994), London (Best Foot Forward 2002), Vienna (Brunner 1995, Brunner et al 1996) and York (Barrett et al 2002).

1.2.2. Policy implications

Traditional approaches to urban environmental management and policy development have been criticized for being only reactive and focusing on laws for isolated processes. They are usually limited to prohibitions, technical regulations and requirements and therefore lack integrative capacity and flexibility (UNU-IAS 2003). Formulating preventing environmental policies requires a change of perspective towards a systemic or holistic view to environmental reporting. (Ayres 1994) points out that the resulting change in perception already has implications on policy formulation. The proposed method of physical flow accounts follows the precautionary reasoning, that all human induced alterations of biogeochemical flows are potentially harmful and need recognition in environmental accounting. Since this method monitors resource inputs as well as outputs it expands the scope of environmental sustainability assessments beyond the narrow paradigm of waste and toxicity. It also addresses problems of resource depletion and scarcity, which are relevant in the context of inter- and intra generational resource distribution. The following graph indicates the relation between various categories of material flows and some policy fields.

Figure 1 Material flows: volume versus impact and policy field



Source: Steurer 1996

The method is capable of addressing long term effects such as accumulation of toxins in the environment over time, even when historic data on emissions is not available. Metabolic flow studies have repeatedly been used to locate pools of toxins (such as heavy metals or persistent organic pollutants) for effective remediation (Tarr and Ayres 1990), (Brunner et al 1996), (Tarr 1996), (Palm and Osterlund 1996), (Guinee et al 1999). Conventional, narrow focused approaches often address only point source pollution (such as emissions of stationary industrial facilities). Diffuse, non point-source emissions from mobile emissions sources, or which are typically occurring at the end of the life cycle of commodities after consumption have been more difficult to regulate.

For example a traditional single-issue approach to the regulation of pollutants has been to establish maximal levels for the concentration of toxic emission by media (into the water, release towards the air or into the soil as landfill). Such approaches encourage to simply add volume to dilute the efflux from a drain[2] or a chimney but not to change the process and abate the production of the problematic substance per se. Building higher smokestacks or longer sewage pipes to transport waste further offshore is expensive and protects the immediate environment but is not a genuine solution. It just buys time and delays the moment until pollutants reach the economic system again via bioaccumulation in food chains. An intermediate growth of the production system then requires a larger effort to address the problem in a fundamental way. One common result of the above mentioned narrow approach can be to transfer the burden of emissions from one media to the other. Dissolved liquid or gaseous waste products can be filtered out and transferred into a sludge which is than buried in a landfill or incinerated. Landfills in turn can produce leaching back into the hydrosphere; incineration can release toxic fumes into the atmosphere. Interactions and translocations like these can be understood by input side accounts. A systemic view towards resource use has implications on the assessment of innovations and new technology: Further concerns are that that traditional 'end of the pipe fixes' can dis-encourage innovation and maintain a 'locked in' situation of old technology by widespread adoption (Ayres and Simonis 1994).

Implications of systemic accounting for policymakers are the potential advantages of limiting the traditional, segmented approach to environmental policy making and to introduce cross-analytical tools of monitoring. Physical flow accounts would be a central component of such integrated environmental and economic accounts (UNDESA 2003) which are characterized by congruent boundary definitions to the monetary system of natural accounting (SNA). Integrated accounts have the potential to overlap monetary flows such as value of resource stocks, value added by their use in specific economic sectors and consequential costs to clean up the resulting environmental damage. Such links might be established by environmental Input-Output analysis which has been developed in structural economics (Duchin 1992,

[2] Following the short sighted reasoning 'the solution to pollution is dilution'.

Duchin 1998, Hendrickson et al 1998, Suh et al 2004). Other tools in this context are provided by means of substance flow- and life cycle analysis (Guinee et al 1999), (van der Voet et. al. 2003). Most of those tools are still in development or are used on a case to case basis. Research on environmental reporting systems has just begun to use such an integrative and comprehensive approach despite a longer history of that paradigm (Fischer-kowalski 1998). This study aims to contribute a case study in this context. The following section introduces the case of Singapore and aims to provide an overview on some of the macroeconomic and macro-ecologic trends.

1.3. Introducing the Case: Geographic Position and Economic Development of Singapore

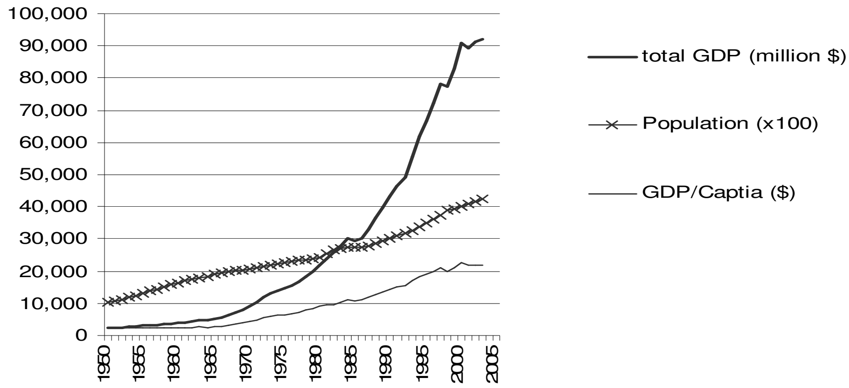
The modern city of Singapore was founded as a trading post for the East Indian Company in 1819 by Sir Stamford Raffles. He recognized the strategic location in the Street of Malacca which forms the shortest passage between the Pacific and the Indian Ocean. In 1867 Singapore joined the straits settlement, a British crown colony, together with Malacca, Penang and Labuan. The Straits colony flourished as a free port especially after opening of the Suez Canal in 1867 and the rise of steam shipping. It was connected to Britain via telegraph line in 1870 and in 1909 a trunk railway connection via Johor Bahru on the Malaysian side of the Johor strait connected Singapore up to Kuala Lumpur and further to Prai. From 1922 onwards it was possible to reach Bangkok by rail. Important freight transports on rail in that period included rubber, tin and increasingly kerosene (Dick and Rimmer 2003). The Straits colony was occupied by Japan during World War II and broken up in 1946 when Singapore became a separate crown colony. It acquired self governing status in 1959 soon after the demise of British Malaysia and joined the federation of Malaysia in 1963. In 1965 Singapore seceded from the federation of Malaysia and became an independent republic within the Commonwealth. It was among the five founding members of the Association of Southeast Asian Nations (ASEAN) in 1967.

At the time of its independence in 1965 the GDP of Singapore was 2,700 $ per capita, about 20% below the world average.[3] By the year 2000 its GDP had risen to more than 22,000 $ per capita, which corresponded to almost 4 times the world average. The speed of Singapore's

[3] GDP measures in this study are unless otherwise stated in purchasing power parity (ppp) US $ of 1990 value (Geary Khamis $), as published in (GGDCCB 2005 - Groningen Growth and Development Centre and the Conference Board, Total Economy Database, January 2005, http://www.ggdc.net). The same source was used for population figures.

transition from a developing country depending largely on warehouse trade towards a manufacturing and service based economy and a transport hub for the South East Asian (SEA) region is exceptional.

Figure 2 Economic and population growth, 1950-2000 (GGDCCB 2005)



After the withdrawal of the last British troops in 1971 the economy of Singapore was initially challenged by a situation of chronically high levels of unemployment of a largely unskilled labor force. The initial strategy of industrialization continued to depend on entrepot trade of regional products, such as timber form the archipelago and simple manufacturing. Additionally refineries and other petrochemical industries were attracted by tax exemptions and a range of other incentives. In 1970 Singapore become the largest petroleum refining centre in the Southeast Asian region. The surge for oil in Southeast Asia allowed Singapore to establish itself as a regional centre for petroleum related activities such as geophysical surveying and manufacture of oilrigs and drilling equipment for firms operating in Indonesia and elsewhere in Southeast Asia. Due to its strategic location on the route between East Asia and the Persian Gulf and European and American markets, it became a leading bunker port. Ship building and ship repair was an important contributor to the value added in manufacture in the early 1970s. Singapore also gained from structural changes in the shipping industry, such as the development of super tankers and the steep rise in containerization of freight since the early 1960s.

The free trade policy of Singapore attracted foreign direct investment and the number of people employed in manufacturing more than doubled between 1970 and 1980. Between 1960 and 1980 the annual volume of GDP generated through manufacturing and construction rose about the factor of 10.

Figure 3 Total employment by economic activity (LABOSTA)

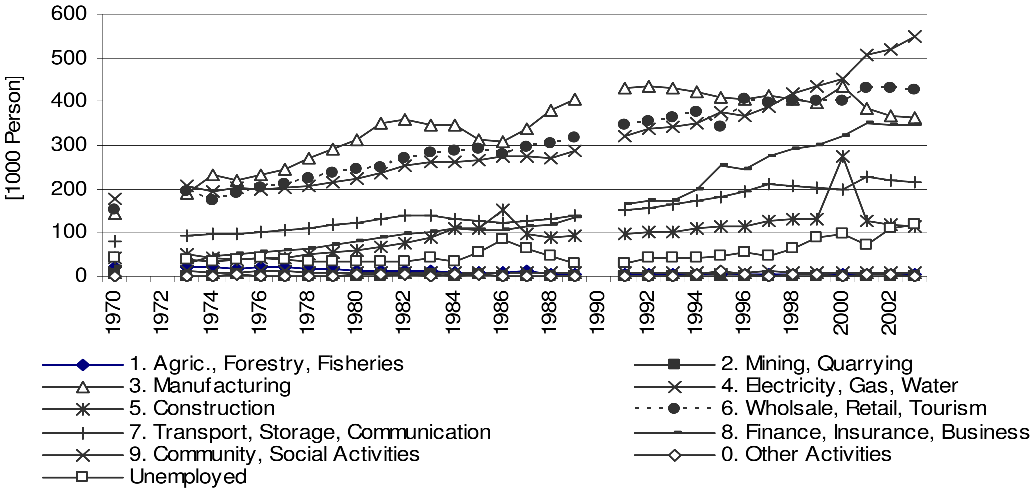


Figure 4 Composition of GDP (Mitchell 2003, 1990 US$, Maddisson 2003)

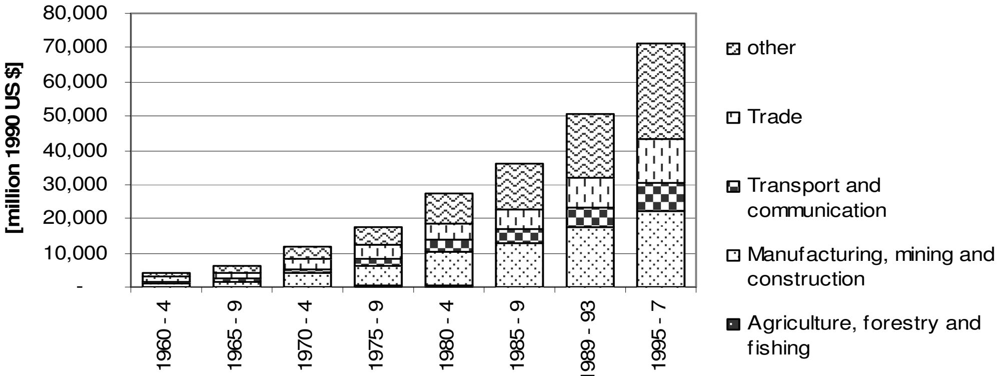
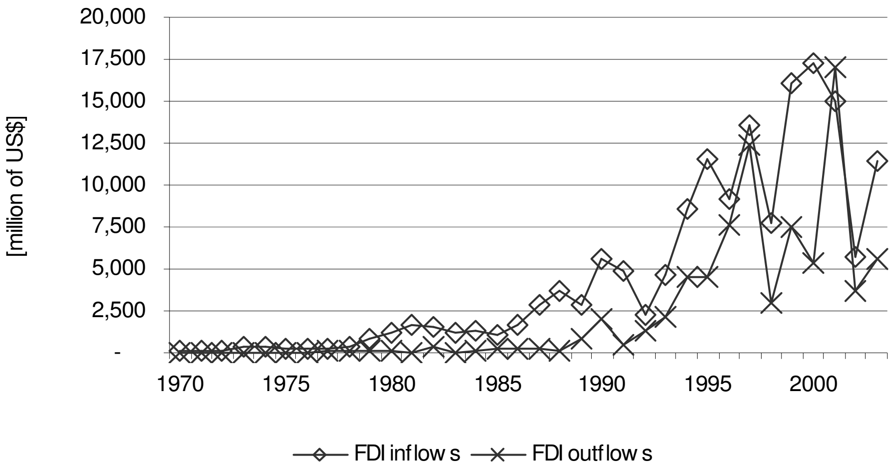
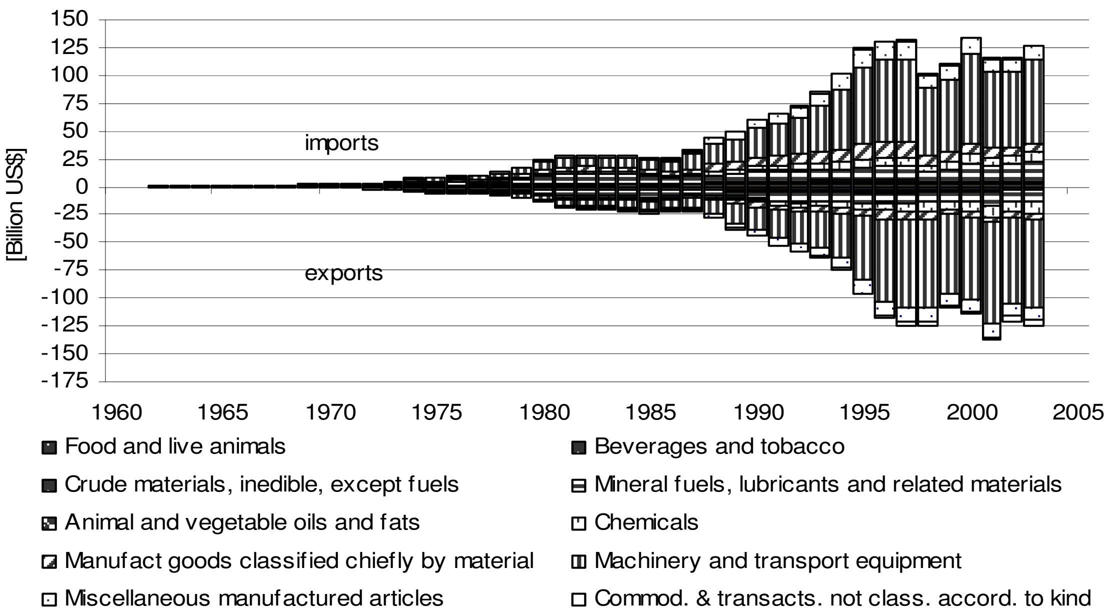


Figure 5 Foreign Direct Investment FDI (US $ in current value, FDISTAT)



After 8 years of double digit growth rates between 1966 and 1973, the economy of Singapore was affected by the global impacts of the first oil crises during the mid 1970s. Foreign demand for electrical and electronic goods nevertheless sparked an increase in investment and three forth of new manufacturing jobs in the following years were located in the electronics industry. Export oriented and labor intensive manufacturing of electronic products became the leading sector of industrial production, followed by petroleum refining.

Figure 6 Total trade, current value US $



Source: COMTRADE

During the 1960s the Statutory Board replaced the colonial Singapore Improvement Trust, which together with the Singapore City Council and the Singapore Rural Board has put forward a diagnostic survey and Master Plan in 1958 (see Appendix 1). During that time still an estimated 250,000 people were living in slums and 300,000 in squatter areas around the cities periphery. In the 1960s a number of satellite towns in a radius of 8 km of the city centre were constructed. Following advice from United Nations consultants in 1971, a number of larger, self sufficient New Towns, each holding 250,000 to 300,000 settlers were erected in greater distances from the city. By 1974 the board's powers of urban renewal were handed over to the Urban Redevelopment Authority (URA), which in the following 30 years built about 750,000 home units in over 20 New Towns (Dick and Rimmer 2003).

Governmental projects between 1973 and 1979 included several expansions of the main island, construction of the international airport at Changi and a connecting expressway system. These projects demanded massive investments of about 6% of the GDP during those years. In 1976 the decision was taken to build the Mass Rapid Transit System (MRT) and construction started in 1983. Funding for the 2.2 billion US$ project was mobilized by the sale of reclaimed land. The train network connected 42 stations via 67 km of tracks and started operating in 1987.

The early 1980s brought a change in government policies towards raising wages and incentive schemes to increase labor skills. In a 'second industrial revolution' it was attempted to attract technology intensive industries, such as audiovisual- and computer equipment in 'high technology parks' and a 'Singapore science park'.

The reductions in global oil demand during the global recession in the early 1980s required adjustments in the refinery sector for changing patterns of supply and demand. In 1985 and 1986 Singapore did sled into recession, which caused in reaction the repatriation of 200,000 foreign workers. During the end of the 1980s the economy caught up and the government engaged in plans to expand the service sector and to develop Singapore to a regional hub for finance and insurance activities, a position formerly held by Hong Kong. Since production costs and living standards had increased substantially, labor intensive work was starting to being transferred to neighboring countries such as Indonesia, Malaysia and Thailand. In 1992 the Singaporean electronics sector produced 18 million units of disk drive for data storage, equal to 50% of the world total output. The electronics sector accounted for 40% of the countries total manufacturing output. The refinery capacity had been expanded to more than 1 million barrels a day, making Singapore the world 3rd largest refinery location after Huston and Rotterdam. It became the most versatile and technologically advanced refinery location in the Asian and Pacific region and a preferred place of oil trading. Additional to plans of further expansion of refinery capacity, companies from the petrochemical sector invested several billion US$ into plants to produce plastics like styrene, propylene and other derivatives often used for household appliances, as well as capacity for the production of annually more than 900,000 tons of benzene. In 1997 Singapore was hit by the Asian crisis, which drove it into recession in 1998 for the first time since 13 years. In comparison with the other nations of the 'Asian tiger states' it consolidated its position after that disturbance relatively fast. Singapore continued to diversify its economic bases and besides significant income from tourism also innovation based economic sectors such as biotechnology were attracted. The openness of its economy and its strong position in information technologies led to a reduction in foreign direct investment following the burst of the 'new economy-bubble' in 2000, a trend that was further accentuated by the financial insecurity following the 2001 attacks on the world trade centre in New York. During the first half of 2003 Singapore's Economy was impacted by the outbreak of Severe Acute Respiratory Syndrome (SARS) which affected the passenger numbers of air travel.

Despite the above mentioned challenges to its economy, Singapore engaged in a number of large infrastructure projects. Of central importance is the expansion of the 3rd passenger terminal of the Chiangi international Airport, commissioned in October 2000 and projected for completion by 2006, an investment of 1.5 billion US$. The Economic Development board began a land reclamation program to expand Jurong Island, as a base for further industrial development. This project is organized in 4 phases and aimed at the amalgamation of seven islands. It was estimated to cost about 4.2 billion US $ already the first phase aims to increase the land area from 1,000 to 2,800 hectares. Further reclamation projects are also planned for the western tip of the mainland for the expansion of Tuas and for expansions of the most east island of Pulau Tekong (see **Appendix 1**).

Summarizing one can conclude that Singapore managed to develop from an impoverished island in Southeast Asia, lacking natural resources into one of the richest economies in that region. It transformed its economy from low-technology manufacturing to highly skilled commercial activities and expanded on its strategic position at a bottleneck of global trade

(50,000 vessels carrying more than 20% of world trades are passing through the street of Malacca). It diversified its economic activity and is among the world leading places for manufacturing of electronic products, petrochemical production, financial transactions, transport services and tourism. [4]

2. Material and Methods

As described earlier, material flow accounts for the socio-economic process are a relatively recent development in environmental reporting (Ayres 1978), (Jelinski et al. 1992) (Adriaanse et al. 1997), (Matthews et al. 2000), (Klein 2001), (UNDESA 2003). They aim at an overall cradle to grave description of resource flows through the socioeconomic process on a certain area over time (Fischer Kowalski 1998), (Fischer Kowalski and Huettler 1998). Environmental pressures are associated to input flows and associated resource depletion as well as to output flows such as emissions.

The methodological documentation in this section refers mainly to the material flow aspect of society's metabolism. The documentation of energy consumption in physical units such as joules or tons of oil equivalents has a longer tradition. Due to the importance of energy for the economic process, its strategic relevance and commodity value most countries are providing energy balances in physical units in their national statistics. Additionally there are a number of international agencies such as the International Energy Agency (IEA), the World Energy Council (WEC) and private companies which are monitoring and publishing fluctuations in the global supply and demand of energy carriers. There also is a wide literature base with estimates covering earlier periods (Putnam 1953), (Smil 1995). In this study the accounts of energy use have been obtained from a publication of the International Energy Agency (IEA) "Energy Balances of non-OECD Counties" which offer data on Singapore starting from 1971. A documentation of IEA methods is provided in (OECD/IEA 2004).

Regarding material flow accounts, the time series presented in this paper is limited to input flows (excluding air and water), and to direct material use. For the most recent period (years

[4] Sources: Compiled from US Geological Survey Mineral yearbook, various years, Economist Intelligence Unit, country report Singapore, various years, Encyclopedia Britannica, online edition, Wickipedia online encyclopedia.

2000-2003) an average annual balance of material inputs and -outputs and recycling rates is presented, including balancing items such as water and oxygen. In the following section the data sources and conversion factors are explained and at which points estimates were necessary to fill existing data gaps.

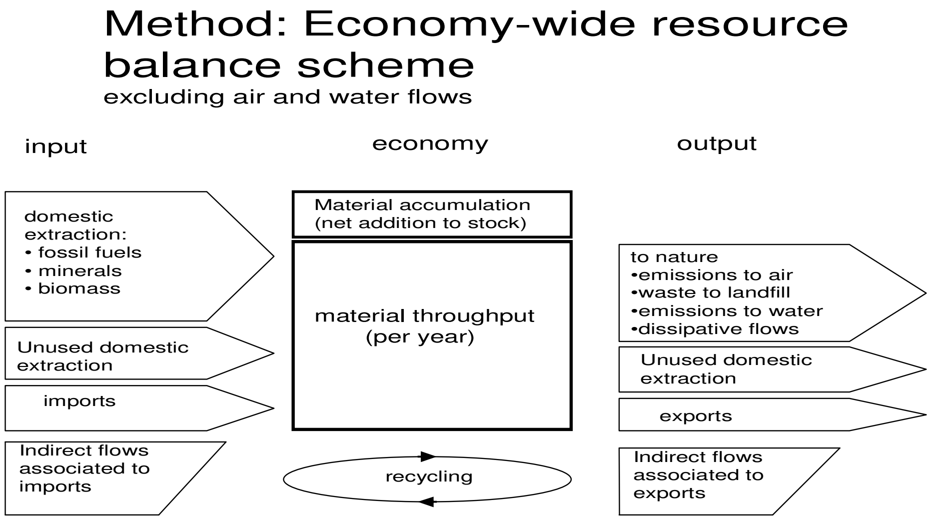
2.1. Methods

Material inputs are distinguished according to their principle pathways entering society:

- Material extracted from the domestic environment and
- Traded materials (Imports and Exports) originating from- or being send to- the rest of the world (ROW).

For a schematic overview see **Figure 7**.

Figure 7 Economy – wide resource balance scheme.



Source: Eurostat 2001, page 16

A detailed description of the nomenclature and accounting procedures for national material flows have been compiled in a recently published methodological guidebook (Eurostat 2001), (UNDESA 2003).

2.1.1. Boundary definitions

The study at hand is presenting a nationwide bulk-flow material flow account (MFA). This is a similar approach like life cycle accounts (LCA) which aim to trace the resource requirement to generate one specific product (or its respective service function) ‘from the cradle to the grave’. In contrast to LCA it has a clear spatial definition and a temporal resolution by year. It is broader in scope than substance flow analysis (SFA), which focuses on the fate of one specific element, or substance within the economic system and the environment. The underlying reasoning is nevertheless similar and the concept aims to enable the aggregation from lower level data to the regional totals (Klein and van der Voet 2000), (Bouman et al 2000) and from substance flows to bulk flows. The system under investigation is the anthroposphere (Baccini and Brunner 1991) which comprises of the entire socio-economic system, all economic sectors including subsistence household- and governmental activities.

For any accounting framework it is crucial to be exact on the definition of boundaries and flows through the respective system under investigation, since congruent definitions are a condition for comparative analysis. This refers to comparisons with other (e.g. monetary) accounts of the socio-economic system as well as to comparisons with case studies from other nations. While the natural flows of material and energy through the ecosystems on the geographical territory are omitted, those flows related to socio-economic activity are highlighted. The biophysical stocks of society include its population and all artifacts. In economic terms this corresponds to man made fixed (tangible) assets such as roads, buildings, infrastructure, machines, vehicles and technical products in general. All flows required to construct and maintain such structures are considered inputs. The waste generated during the production process and especially after consumption and release back into the environment are accounted as outputs. Outputs can be classified according to the transport media and the ecosystem component where they are released as emissions to the atmosphere, -to the hydrosphere or in the case of solid waste -to the geosphere. The basic reasoning of this exercise is based on the conservation of mass: all inputs have to balance outputs, after correction for changes in stock. Since Inputs are usually better documented than outputs, these accounts provide a more complete picture on the environmental pressure imposed by economic activity.

Growing plant material for example (e.g. cultivated forest, arable land and pastures) is considered part of the external environment. The harvest of biomass from such areas is accounted as biomass input into society (domestic extraction). Agricultural activities such as seeding, fertilizing, applying pesticides, etc. are considered dissipative outflows from society. Domesticated livestock is considered part of society’s biophysical stock. Animal grazing for fodder is considered an input into the system. The subsequent fabrication of animal products (meat, milk, eggs, etc.) is consequently accounted as an internal flow, since the feed requirements for the animals have already been accounted for. If one would account for animal products as input, it would lead to a double counting of such material.

Besides the characterization by origin (domestic or rest of the world) there are two more distinctions in material flow terminology, which are: direct-indirect flows and used-unused flows (Eurostat 2001).

- *Direct-indirect* refers to the life-cycle dimension of a flow. It classifies whether the material is directly integrated into a product and is physically entering the national economy, or if it did occur upstream of a production process and can only be approximated from the product. An example of indirect flows would be the volume of ore extracted in another country to produce the metal that has been imported. Another example would be the fuel necessary to transport resources to the point of entry in the national economy ('from the cradle to the border'). All imports in contrast are direct flows.

- *Used-unused* indicates whether the input flow is entering any economic system and acquires the status of a product or not. Used and unused flows can occur within the system or abroad, upstream of the consumption process. Used flows in contrast are always direct flows (see above). Examples for unused flows would be: excavations for construction activity (where the product is the absence of material, e.g. for a tunnel or a foundation) or overburden moved for the process of mining, soil erosion associated to agriculture, or unused biomass by-products from the harvest of crops. Essential is that the extracted material did not enter into a product. While the term used-unused refers to material *inputs*, the equivalent terminology regarding *outputs* is processed versus non-processed (flows originating from an economic system or not).

Adding the sum of indirect and unused flows with direct flows, allows calculating the indicator 'total material requirement'. Some authors named the indirect and unused flows as 'ecological backpacks' (defined as total material requirement minus weight of the final product). On the product level this principle is applied in the concept of material inputs per service unit – MIPS (Schmidt-Bleek 1993). It requires data on the physical resource intensity of all production chains for each input flow. For all those production chains comparable cut-off criteria[5] would need to be applied. Furthermore those factors would need to be dynamic over time to reliably show changes in material intensity.

[5] Cut-off criteria in LCA give information on the attribution and allocation of resource requirements for capital investments (e.g. construction of a new factory) and intermediate sectors as for example the transport industry,

Such data bases for accounts of total material flows have not been available for this study and would need to be extensive for Singapore, since it manufactures very complex products and obtains material from a large number of supply countries. For practical reasons indirect and unused flows have therefore been excluded from this account.

For bulk flow accounts referring to a national total scale, the unused and indirect flows have been shown to be in the order of magnitude of the direct flows (Mathews et al.1997). For individual flow categories especially metal products they can be magnitudes higher. While recognizing that the concept of total flows is more comprehensive and captures a wider range of environmental pressures domestically and abroad, it should be noticed that the data quality of direct flow accounts is considerably more exact since the majority of flows relies on actual measurements instead of extrapolations from proxies.

2.2. Material Flow Accounts

For both principle material input categories (domestic, rest of the world), the materials are classified chiefly by material property, as biomass, construction minerals, industrial minerals, fossil fuels, or as products.

2.2.1. Domestically extracted material

Data on the domestic extraction of biomass was primarily derived from the FAO-stat data base of the United Nations Food and Agriculture Organization. This source reported land use area, harvest from arable land, from forests, and also the landings of fish. Extraction of biomass due to grazing of domestic animals (ruminants) was estimated based on livestock numbers and average values for consumption per animal. Numbers of animals were provided by FAO-stat, demand per animal per day was estimated according to coefficients reported in (Eurostat 2001).

The principle source for the domestic extraction of minerals was the annually published USGS Mineral yearbook. This source provided also general background information on construction activity and restructuring of the manufacturing- and petrochemical industry.

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which is contributing to a large number of products and services. Also the public- and the household sector are missing in most product based LCAs.

Singapore does not own reserves of industrial minerals, such as metal ores or abrasives. And although the metal processing industry had been important in the period between 1970 and 1990, it depended entirely on imports of concentrates and scrap. The mining industry of Singapore was limited to the provision of construction minerals through quarrying and sand extraction. The number of quarrying operations was reported to have decreased over time, to about 4 in 1990. Those operators were extracting sand and producing crushed granite to use as aggregates in concrete production. The extraction of granite had been reported in the USGS mineral yearbook sporadically for 15 of the 41 years between 1962 and 2003. The extraction of sand in contrast was not documented at all.

To estimate the extraction of granite during the years not reported and to approximate the use of sand for construction activity, those volumes were modeled based on the consumption of cement. This is a conservative estimate, since it does not cover the use of sand and crushed stone as filling material for land reclamation or landscaping. A short description of reclamation activity in Singapore with an estimation of the potential material extraction associated is given in **Appendix 1**.

It was assumed that for the production of concrete cement has to be mixed with sand and aggregates (crushed stone or gravel) at the ratio 1:2:4 by weight to gain concrete of average strength and durability (CP20). The apparent consumption of cement (production + imports - exports) was documented in production and trades statistics. Based on the apparent consumption of cement, the demand for sand and aggregates was calculated, and a possible deficit between material demand and net imports of those minerals was assumed to have been domestically extracted without documentation. In the period between 1980 and 1990 there has been more granite reported as having been mined than required for production of concrete. In total this was about 40 million tons, which is plausible since there are many other uses of granite, e.g. as dimension stones. After 1990 there were no further records on quarrying activities, but it is plausible to assume they were halted, since resources were exhausted and some quarries were abandoned as natural protection sites. Regarding sand, the method described above provided an inverse picture: in the period before 1992, the volume reported as imports were below the demand calculated by the demand for concrete. In the total period between 1963 and 1992, the demand for sand for concrete mixing alone amounted to 84 million tons. After that period, between 1993 and 2003 in contrast, the net trade by far exceeded the demand of sand for concrete. In those 10 years about 345 million ton of sand were imported, mainly from Indonesia. This order of magnitude is nevertheless plausible and possibly an understatement considering the massive demand for filling material for the reclamation projects, as documented in Appendix 1.[6] Regarding other minerals or fossil fuels there was no extraction activity, since Singapore does not own such resources.

2.2.2. Traded material

Information on traded material was derived from the United Nation COMTRADE database, which was accessed through the WITS system hosted by the World Bank. The COMTRADE database covers transactions between more than 130 countries, some of which started reporting in 1962. For each country it reports the value of trade in US $ and the physical quantity traded. The data can be accessed in six different trade classifications. This study used the Standard International Trade Classification, revision 1 (SITC 1). While later revisions are covering more details due to a larger number of categories, revision 1 was chosen, since it covered trade over the longest time period (more than 40 years) in a constant classification starting in 1962.

Trade data was used at the 3 digit level, which distinguishes 179 commodities. In total about 15,000 commodity flows from and to Singapore were considered. Not all of these flows were reported in tons of weight. Conversion factors from other units (such as kilogram, cubic meter, number) were applied. After conversion into weight units, the aggregation into the 4 categories (biomass, fossil fuels, construction minerals, industrial minerals) was conducted on the 2 digit level distinguishing 59 groups of commodities.

The data quality of the COMTRADE database is problematic. Some of the entries to the database are incomplete others not plausible. This includes wrong units (e.g. imports of electricity reported in tons, cubic meters, or kilograms) in other cases the reported volume exceeded the global annual production of the respective commodity by orders of magnitude, which hints towards entry errors or use of wrong units. To cope with such apparently erroneous entries, the trade data for Singapore was filtered and such distorting outliers were

[6] A number of newspaper articles in the period between 2000 and 2005 reported unofficial and undocumented cases of illegal sand mining in Indonesia for land reclamation in Singapore. Impacts of those activities included habitat destruction, uncompensated impacts on regional fisheries and losses of royalties for the Indonesian government.

identified.[7] In a following step the plausibility of such values was examined by comparison with the sum for the respective commodity on sub- aggregate level (4 digit code) and other sources. A similar strategy of data clearing had been documented by (Moriguchi 2003) in a study for the Japanese National Institute for Environmental Studies (NIES). The NIES study provided a global trade matrices of principle resource flows (excluding final products and construction minerals) for 37 geographic units over 4 points in time (1983, 1988, 1993, 1998). Since Singapore was one of those geographic units, the results of both studies could be compared, and showed a close overlap. Slight differences were observed, especially in the biomass categories, but they can be explained by methodological differences. Among them the fact that in the NIES study used the SICT2 classification and the level of commodity disaggregating had been more detailed.

This study relied entirely on trade activity reported by the harbor of Singapore. It is probable that additional to the reported trade also unreported transactions occurred.

An additional problem with the COMTRADE reports on Singapore was that for a number of transactions no reports in physical quantities were reported but only reports in value units. This was mainly the case for some final products, such as machines and electronic products. For those cases an approximation of the total physical inflows- and outflows was conducted based on the monetary trade information. Assumptions on the price of those commodities in the respective year were derived from the world average level, since on the global level there was information on weight-value rations available for all commodity groups. This procedure assumed that the prices at Singapore are considerably close to the world average prices. This procedure concerned only a small number of transactions.

2.2.3. Indicators

Based on those categories and for each of the material category, the following indicators were calculated:

Direct Material Input (DMI) = Domestic Extraction (DE) + Imports (I)

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[7] We looked for changes in the ratio tons of goods per dollar. When this ratio changed by more than an order of magnitude for a single year, the reliability of the price fluctuation was compared with other sources. If it was implausible we looked up which of the two records (weight or value) deviated from the time series and changed it according to an average weight/value ratio of the bordering years. In total this procedure affected less 1% of the entries.

Domestic Material Consumption (DMC) = DMI – Exports (E)

Domestic Processed Output (DPO) = Emissions, waste + Dissipative use of products and losses

Net Additions to Stock (NAS) = DMC – DPO

For a graphical representation of the accounting scheme please see **Figure 7**.

The output indicators were only calculated for the most recent period, between 2000 and 2003, while the material inputs were calculated in annual steps from 1961 to 2003.

To establish a physical material balance of -inputs and -outputs, it is necessary to recognize the input of 'balancing items', such as water and air since they are part of the metabolic process and incorporated in the outputs[8]. Those inputs were not included in the time series of inputs, but are reported separately for the balance in the most recent period.

The so derived indicators are highly aggregated measures of resource use. They describe the principle exchange of materials and the environment during the socioeconomic process and provide a total overview on the scale of resource consumption, and quantify the intensity of exchange with the global trading system.

The different components of societies' material inputs and consumption indicate pressures and potential threats to various ecosystems: Biomass consumption has a clear relation to land use and threats to terrestrial ecosystems. It furthermore includes the consumption of aquatic organisms from aquaculture and wild catch. The consumption of fossil fuels imposes immediate pressures to air quality (smog, acid rain, soot and other particulates etc) and more subtle threats to the stability of the climate system. Additional there are threats of terrestrial and aquatic ecosystems associated to the extraction, transport and refining of fossil fuels (such as oil spills). Since minerals are derived from mining activities, those often interfere with terrestrial and aquatic ecosystem function (acidic runoff, contamination of ore and slag containing heavy metals, problematic solvents, siltation, etc.). A number of studies aimed to establish a framework to relate bulk flow accounts to environmental pressures (UNDESA 2003). This connection might be established by use of input-output tables and attempts to

[8] The combustion of technical fuel requires oxygen and it results in the generation of carbon-dioxide and water. More than 72% of the weight of CO2 is comprised of the oxygen input.

integrate land use into such accounts- the basic ideas of ecological footprinting (Hubacheck and Giljum 2003, Suh 2004) . A central challenge in this context is the qualitative evaluation of the hazard imposed by certain material flows (van der Voet et al 2003) and of lack of a general classification of waste (Duchin 1998).

2.3. Energy Flow Accounts

Energy flow accounting has been at the heart of ecosystem studies since the first half of the 20th century (Lotka 1922, Odum 1971). The flow of energy through separate compartments of ecosystems proved to reveal insights in much of their functioning, hierarchy and on regulatory mechanisms (Lindeman 1942). Studies of energy flows proved to be an integrating unit of analysis, when comparing human socio-economic systems and natural ecosystem dynamics (Pimentel 1979). This has also been exemplified in the classic study on the urban metabolism of Hong Kong (Newcombe 1975a, Newcombe 1975b, Newcobe 1976, Newccombe 1979). A more comprehensive system of energetic resource accounting should include the metabolism of biomass by the human population and its livestock sector to establish compatibility with ecologic energy flow accounts (Haberl 2001). A number of methods use energy flow accounts to integrate socio-economic variables into sustainability analysis and to bridge spatial scales of analysis (Giampietro 2003), (Pastore et al 2000).

This study focused on the flows of commercial energy. It used the detailed energy balances published by the international energy agency (IEA), which reports the supply of energy carriers, and losses during conversion stages into final energy (such as refined petroleum products, electrical energy, etc.). They also report final use of energy by sector, which reflects much of the economic structure. Those accounts are comparable to a large number of national supply and end-use accounts. The unit of IEA accounts is the ton of oil equivalent, defied to equal 41,8 Gigajoules. Details on accounting framework are described in (OECD/IEA 2004).

Compared to the accounting rules for material flows (Eurostat 2001) the main difference in the IEA balances is the recognition of changes in stock which is reflected in the terminology. While in MFA accounts the term ‘consumption’ refers to domestic extraction plus net trade, the IEA energy balances additionally subtract changes in stock, as well as the sale of bunker fuel for international shipping as distinct accounting items. The resulting volume is then referred to as total primary energy supply (TPES). In a following step the energy balances are recognizing conversion losses to final energy, due to consumption within the energy sector (energy use for electricity production, transport and distribution losses of energy, refinery losses).

3. Results

3.1. Material Flows

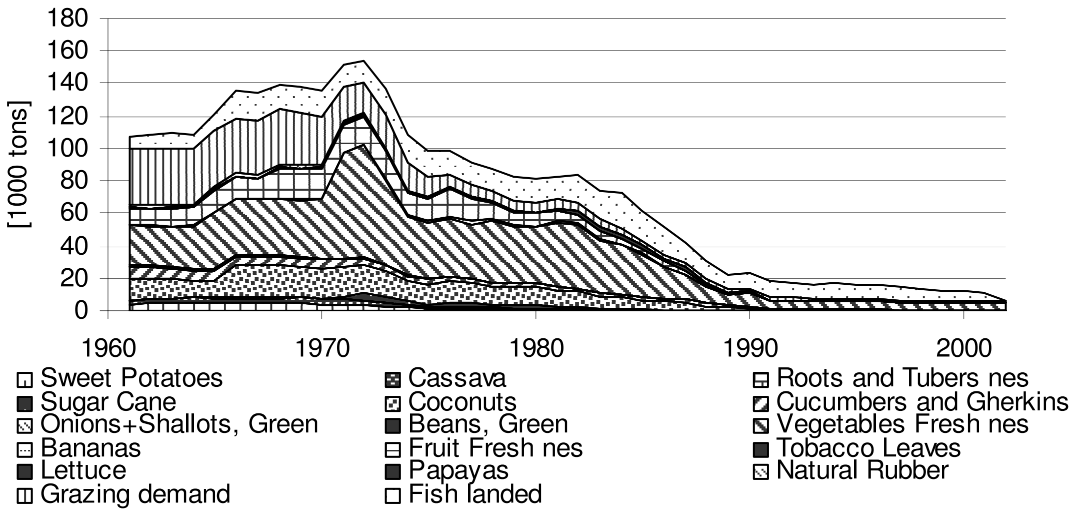
3.1.1. Domestic extraction of material

As an island without significant natural resources, except for its natural deepwater harbor and its geographic location, Singapore had always depended on a very open economy.

Although it imported most of its staple commodities already in the 1960s it still had considerable agricultural activity.

The domestic extraction of biomass included production from rubber plantations, coconut and cassava, a significant livestock sector and the production of fruit and vegetable. Per capita extraction of biomass was nevertheless very low already in the early years. The trend of biomass extraction was decreasing throughout the time series and became insignificant by end of the 1970s when the livestock sector was shut down at least partly for reasons of hygiene and environmental security.

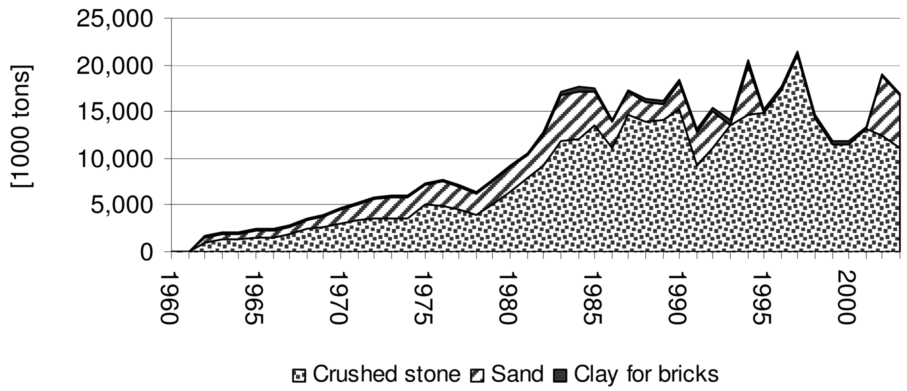
Figure 8 Domestic Extraction of Biomass



The domestic extraction of minerals described here refers to the extraction of sand and gravel for the production of concrete and the extraction of clay for bricks. The additional extraction of sand through sand mining and dredging for land reclamation within as well as outside of Singapore's territory has most probably be significant, although no central documentation on its volume could be found. Crude estimations of this activity are described in **Appendix 1**. The production of bricks had been documented in the Singapore yearbook of statistics and was converted to weight assuming 2.5 kg per brick.

The trend in mineral demand for concrete production was inverse compared to biomass extraction: During the initial period the extraction was low, around 1.6 tones per capita and year. This increased to about annually about 8 tones per capita in the late 1990s. The low value of domestic extraction of minerals during the early period might partly reflect underreporting of construction activity, as discussed in **Appendix 1**.

Figure 9 Domestic extraction of construction minerals

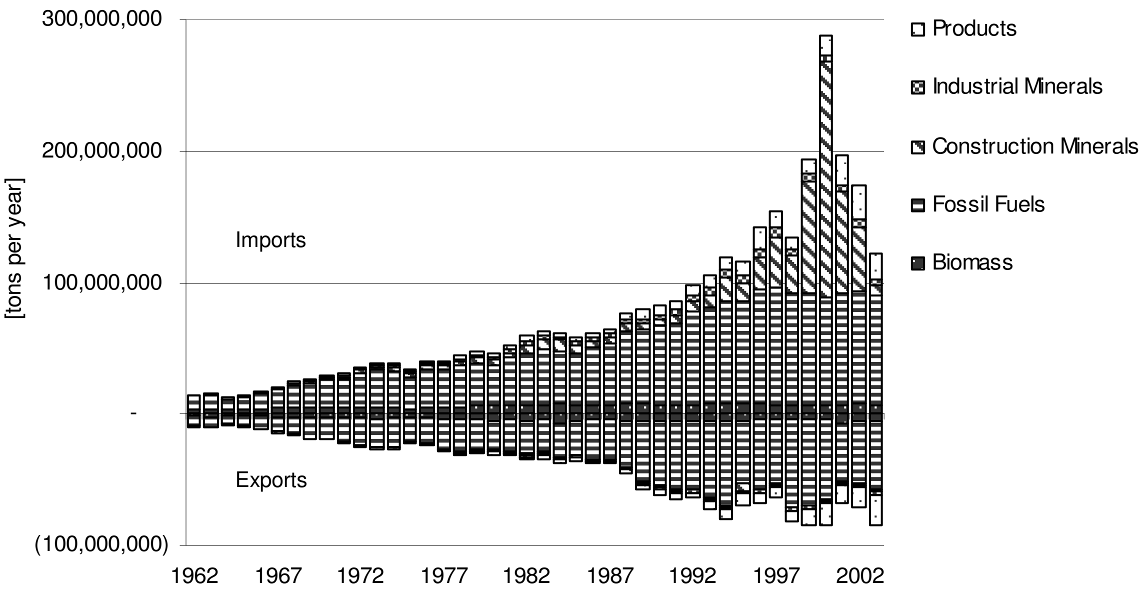


3.1.2. Trade

Trade has been the most significant component of Singapore's metabolism throughout the time series. In the initial period before the end of the 1970s biomass (such as wood, rubber agricultural products) still provided 15% of total trade by weight. Nevertheless fossil fuels were also during that point in time the main traded material category, providing more than 80% of all traded material, the rest being mainly products of complex material composition. The weight share of biomass continued to decrease, the significance of intermediate and final products in contrast increased and it was only from the 1990s onwards that the trade of construction minerals became significant. Especially striking is the period between 1994 and

2003 during which the weight of imported construction minerals rose to about 60% of all traded material. The peak in this period was in the year 2000, when Singapore imported over 170 million tons of sand, practically all of it from neighboring Indonesia. For a more detailed description of the trade with sand and gravel, see **Appendix 1**.

Figure 10 Singapore: Import and Export, physical flows.



3.1.3. Extraction, trade and consumption

The aggregated weight of imports during the early 1960's was more than 8 times the weight of domestically extracted materials. Together both components of societies metabolism are referred to as direct material input (DMI =DE+I). On a per capita basis, DMI increased about 4 times from just about 10 tons per capita and year to almost 50 tons of material per capita and year.

In the early 1960s, more than 60% in weight of the direct material input was exported again. This dynamic indicates entrepot (warehouse) trade. Nevertheless that period was still characterized by large volumes of agricultural extraction of biomass, partly from export oriented plantations. Singapore was still providing an important amount of its nutrition. The following increase in trade volume and decline in biomass extraction coincides with emergence of Singapore in the network of global cities. These data displays how cities are strong attractors of materials and products from huge distances, they are generally weaker in dispersing the products of their metabolism, and depend on the immediate environment to absorb those outflows (Douglas 1983), (Graedel 1999).

Subtracting the weight of exports from direct material input generates the measure domestic material consumption (DMC).

Domestic material consumption started at very low values, around 4 tons per capita in the early 1960s, it rose even faster than DMI by a factor of 7 to about 30 tons per capita at the end of the century. The ratio of DMC to DMI decreased throughout the time series. In the period 2000 to 2003 63% (in weight) of domestic material input were consumed, the weight of exports dropped to 37% of DMI.

Figure 11 Extraction, Trade and Consumption

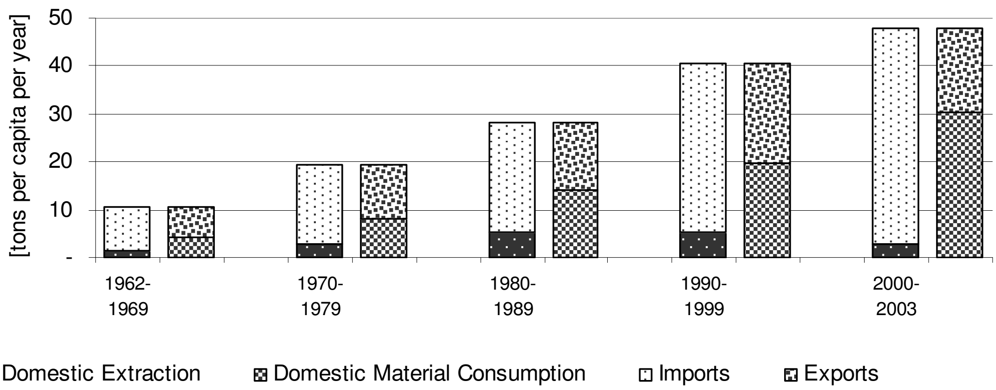
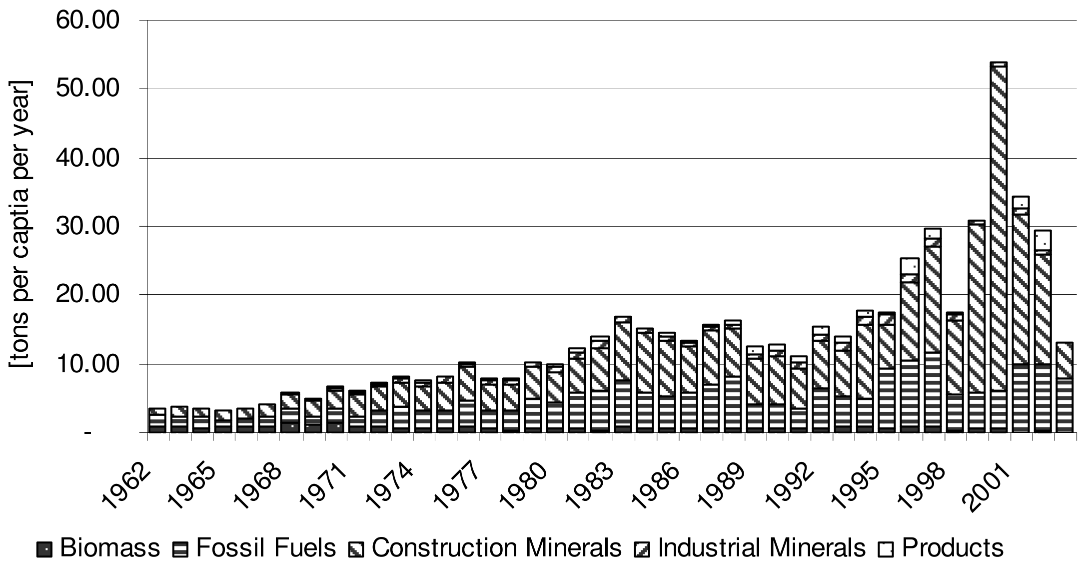


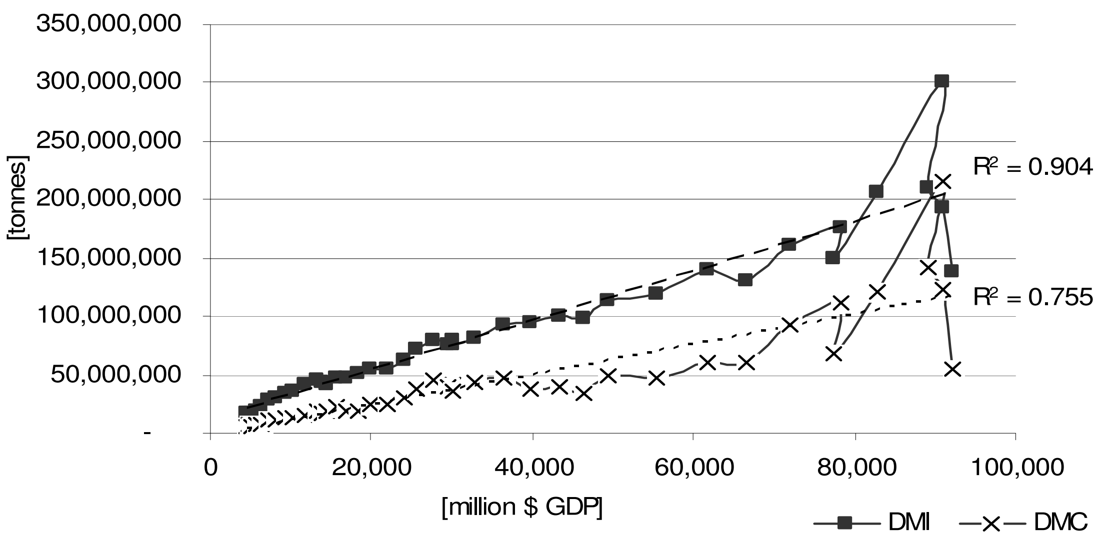
Figure 12 Domestic material Consumption (DMC), Singapore



The composition of domestic material consumption was characterized by a very low share of biomass, a high share of fossil fuels (more than 10 tons per capita at the end of the time series) and a continually increasing share of construction minerals (more than 40 tons in 2000).

3.1.4. Time series analysis of inputs, comparison with economic trends

Figure 13 Correlation between GDP, DMI and DMC, Singapore 1962-2003



For both measures, DMI and DMC, over most of the period no reversion of the growth trend had been observable that would indicate some degree of 'dematerialization'. Only during the past 7 years there have been a number of fluctuations after a sharp downturn in 1998 (Asian crisis of 1997) and another decline after the year 2000 (burst of the 'dot-com' or 'new economy' bubble in March 2000, followed by insecurity of investment and traders after the 9/11 attacks in the US in 2001). During 2003 South East Asia was affected by the SARS epidemic, which led to sharp reductions in air travel.

Over the past 40 years a persistent coupling between trends in GDP and both measures of material use was apparent. The close correlation of both, direct material input as well as domestic material consumption with GDP is plausible, considering the relevance of trade for the economy of Singapore. Crude oil and refinery products continue to dominate the trading of goods by far in units of weight. Since refinery capacity had been increased throughout the period of growth in GDP. This increase in scale had been hiding possible structural changes (the relative importance of electronic products and other manufacturing or the rise of the service sector, which potentially could both lead to exports of lower weight) are not visible at this level of aggregation. The remaining discrepancy between the planned surface area as laid out in the Concept Plan 2001 (Urban Redevelopment Authority 2001), and the present suggests that the downturn in DMI and DMC between 2000 and 2003 is only temporary (compare **Appendix 1**).

3.2. Balancing Items and Outputs

For the period 2000-2003, data for waste generation and recycling rates were available for a number of materials and pathways (NAE 2005). For those years a basic balance of inputs and outputs was established. Since both physical and monetary flows fluctuated considerably during those years, only one average annual value of the three years period was calculated.

As described earlier, for a balance of inputs and outputs it is necessary to include balancing items (inputs and outputs of oxygen and water) since they are part of the metabolic conversion process and necessary to close the balance.

Again the definition of boundaries is crucial in this context: The value of DMC of fossil fuels in this table was calculated from Energy Statistics of the IEA. As emission statistics were reported according to IPCC criteria, they excluded international bunker fuels, and fuel for international air transport. For the balance it was chosen to exclude those fuels from the documented inputs. If those volumes for international transport would be included, DMC of fossil fuel would be about 8.2 tons of oil equivalents per capita. Accordingly the oxygen input and CO_2 emissions would be more than 50% higher.

The input of oxygen was calculated as a least amount estimate: It describes the volume required for the combustion of fuel, assuming 99% oxidation of carbon and hydrogen, and the biological oxygen demand of wastewater emissions (Worldbank 2005).

A number of other oxygen consuming activities were not recognized, for example this calculation did not account for the generation of carbon-monoxide, volatile organic carbon, Nitrogen and sulfur oxides or Ozone (O_3), since direct emission data, have not been reported and those quantities are much dependent on the technology in place (Haq et al 2002). This table also omits the release of aerosols and particulate matter (e.g. lead from gasoline and industry use, black carbon, soot, etc.)

In a strict sense also the oxygen demand of the human and livestock population would need to be included with other biotic processes (such as waste water treatment, food and biotech industry) and other processes (petrochemical industry, leather and fiber industry, etc.)

Other sources of CO_2 emissions excluded from this study are those related to land-cover change, since plants and soil are not considered a physical part of society. Some sources are reporting emission due to cement production (about 3% of total emissions in 2000, according to (Marland et al 2003)) but since Singapore's cement production is based on the processing of imported clinker those emissions should be allocated to the country of clinker fabrication.

Figure 14 Resource input, processing and output, tons per capita per year, average 2000-2003

	Balancing items		Material flows					
	Water	Oxygen	Biomass	Fossil fuels	Minerals (construction)	Minerals (industrial)	Products	total
Domestic Material Consumption (DMC= DE+I-E)	111.49	14.81	0.29	5.24	22.50	0.63	1.02	155.98
Water vapor from combustion	3.67			(CO_2)				3.67
Primary Waste (W)	115.15	-	0.27	16.33	0.10	0.32	0.50	132.68
Recycling (R)	-	-	0.04	-	0.09	0.29	0.12	0.54
Domestic Processed Output (DPO=W-R)	115.15	-	0.23	16.33	0.01	0.03	0.37	132.13
Potential Net Addition to Stock (NAS= DMC-DPO)	-	-	0.06	-	22.49	0.60	0.64	23.80

The results of the balance above show that per capita consumption of materials was about 156 tons per year. More than 70% of the DMC was water, 14% were construction materials and about 9% was oxygen. Recycling was most efficient in the category industrial minerals, where more than 90% of the primary waste was recycled. In the categories fossil fuels and water, no recycling was documented. For the category water, this figure would need to be changed for more recent years, since Singapore engaged in a large scale project for purification and recycling of 'Newater', which is then fed again into the network, aiming to partly close the domestic water cycle.

Regarding fossil fuels it is apparent that they are mainly used as energy carriers and thereby oxidized and finally emitted. Nevertheless the use of by-products (e.g. refinery gasses) for industrial purposes and even the incineration of plastic products for heat generation could be described as 'energy recycling'. In fact it is probably better described as 'cascade use' or 'down-cycling'.

Outputs are clearly dominated by water and the second most voluminous material output is carbon-dioxide from the combustion of technical energy carriers.

The subtraction of domestic processed outputs (DPO, those volumes of primary waste not recycled) from DMC allows to calculate the potential net additions to stock (NAS). Here they are named *potential* net additions to stock since they include recycled goods that are in flow. The calculation was done by material group, which ignores lateral flows from the distinct material groups into the category products (of complex material composition). This procedure can lead to an overestimation of NAS up to the level of NAS in the category products (products made up 2% of the potential NAS).

About 95 % of the potential NAS (more than 22 tons per capita) are construction minerals. This figure reflects the massive investments in infrastructure and construction activity that are currently on going. As infrastructure requires maintenance also in physical terms, these flows are likely to trigger further mineral flows in the future. Also since for example growing road infrastructure can encourage the use of cars, other flows (such as fossil fuels, import of products) are likely to increase in the future as well. The high rate of biomass recycling in comparison to biomass DMC is possibly related to differences in boundary definitions: While the waste statistics reports outputs largely of horticultural waste, those flows are possibly not reported as domestic extraction in the input side of the table (if they are just unused byproducts they would be categorized as indirect flows). Biomass flows are also very sensitive to changes in water content: When dry biomass is reported on the input side and humid or water-saturated weights are reported on the output side, apparently a disproportional loss in mass is recorded. Improvements in this context would be reporting in standardized water contents (Eurostat 2001). Industrial minerals and products each contribute to about 3% NAS. With an addition of about 600 kilo per capita per year, these two categories impose considerable environmental risks and should require careful stock management and disposal since they comprise of complex material compositions. (e.g. household- and industrial products, organic and inorganic chemicals, etc.)

3.2.1. Comparison with urban data on material flows

The following table has been compiled from a number of publications on urban metabolism. For each case study the scope of accounting and the availability of data at the urban level varied and accordingly the methodology differed. This is most obvious when comparing the reports on balancing items (oxygen and air inputs, outputs of water and other combustion products). Therefore the total of all material consumption categories has been reported twice in this table: once including water and oxygen, once excluding those items. The terminology used in this table is not strictly comparable with the rest of this study, since many of those studies were conducted without attempts of methodological harmonization (Eurostat 2001). It has been aimed to arrange the data in a way that the terminus ‘consumption’ is possibly comparable with ‘domestic material consumption’ (extraction plus net trade, sometimes also referred to as domestic supply). All data has been converted to tons per capita per year. Other methodological differences and further limits to comparability will be described further onwards by case and material category.

Figure 15 Comparison of literature values on urban metabolism (converted to tons per capita per year)

Singapore 2000	Water	Oxygen	Biomass	Fossil fuels	Minerals (construction)	Minerals (industrial)	Products	total in (=apparent material consumption),	total in (=apparent material consumption), excluding water and oxygen		
consumption	111.49	14.81	0.29	5.24	22.50	0.63	1.02	155.98	29.68		
waste	115.15	-	0.27	16.33	0.10	0.32	0.50	132.68			
Recycling	-	-	0.04	-	0.09	0.29	0.12	0.54			
DPO		-	0.23		0.01	0.03	0.37	132.13			emission:
										115.15	to water
										16.33	to atmosphere
										0.65	solids
NAS			0.06		22.49	0.60	0.64			23.80	NAS
US City of 1.000.000, 1963 (Wolman 1965)	2,335										
consumption	228		0.73	3.46				231.85	4.2		
waste	182						0.73				emission:
										182	to water
										0.40	to atmosphere
										0.73	solids
Hong Kong 1971 (Newcombe et al 1978)											
consumption	432.55		0.69	1.00	0.33	0.18	1.00	435.75	3.2		
waste	76.47		0.06			0.02	0.26				emission:
										76.47	to water
										0.06	to atmosphere
										0.34	solids
London 2000 (Best Foot Forward 2000)											
consumption	120.28	3.85	1.29	1.84	3.86	0.41	1.25	132.78	8.7		
waste	87.08		0.16	5.69	2.05	0.24	1.21	96.42			
stock change			0.26		1.81	0.18	0.51	2.75	2.8		
											emission:
										87.08	to water
										5.69	to atmosphere
										3.65	solids
Region Lower Buenz-Valley, 1986 (Brunner et al 1994)											
consumption	166	36	4	2	18	12	2	240.00	38.0		emission:
waste										166	to water
										36	to atmosphere
net export of products							18				
										20	NAS
Swedish city of 100.000, 1986 (Hultman 1993)											
consumption	254.98	?	0.73	3.46	7.29			266.45	11.5		
waste	182.13										emission:
										182.13	to water
										23.68	to atmosphere
										0.72	solids
Amsterdam 1998 (Goerre et. al. 2000)											
consumption	91.55	7.17		2.56	1.47	4.18	0.79	107.72	9.0		
waste	93.88			7.34			0.41	101.63			emission:
										93.88	to water
net export of products							3.13			7.34	to atmosphere
										0.41	solids
										2.14	NAS

The total values for annual material consumption varied between 108 and 436 tons per capita if water and air was included. Reported water consumption varied between 432 and 91 tons per capita. The highest figure was reported in the Hong Kong study of (Newcombe et al 1978), although it included the use of 334 tons of seawater for cooling and flushing, uses that were possibly not covered in other studies. The study of (Wolman 1965) reported the national use of water in the US 1960 at annually 2,335 tons per capita, about 10 times of what is used for municipal use on city level. This example illustrates how much the scale of analysis and the definition of accounting boundaries affects the result of a seemingly unambiguous question like ‘level of water consumption’ (Giampietro 2003). On the national scale 44% was used in agriculture, 31% by steam electric utilities, 19% industry and only 8% as urban. The London study reported that leakage consumed 28% of water inputs, more than is used for commercial use (23%), Household use was about 50% of the reported value. The figures of the Singapore study are based on the reported water sales. About 55% of water use was for domestic purpose, transport losses are reported below 5% in Singapore.

The methods for reporting consumption of oxygen or air is even less harmonized among the studies then in the case of water use. While some studies reported inputs of air (Brunner et. al. 1994), others did not report atmospheric inputs at all or they only reported the oxygen content. If for example NOx emissions are reported as outputs, consequentially air should have been the reported on the input side, as it is the principal source of N2.

To solve the problem of limited comparability due to different methods, material consumption was also aggregated excluding water and air in row 10. Those values that are most comparable to the figure of DMC in national studies and to the time series on Singapore presented earlier, varied between 3.2 and 38 tons per capita per year.

Again the case studies varied in comprehensiveness of coverage of material categories. The study of (Wolman 1965) for example did not report construction minerals, industrial minerals or the consumption of products. Also the Study of (Hultman 1993) was restricted in coverage excluding industrial minerals and products, therefore probably underreporting the actual resource consumption.

In comparison to the other urban case studies, the metabolic profile of Singapore is characterized by high inputs of fossil energy carriers, as well as by high inputs of construction minerals, both values are nevertheless within the range of other studies (compare Brunner et al 1994) and (Hultman 1993), (Wolman 1965).

Three more aspects will be highlighted and compared in the following text: 1) the composition of emissions, 2) data on net additions to stock and 3) the net export of products.

1) While water is the most voluminous transport media for outflows, the actual volume of emissions contained in it is probably relatively small (the Hong Kong study reports about 0.6 tons of sewage solid contained in the 334 tons of water per capita per year). The emissions transported in the water are either dissolved, or dispersed as suspension, but do usually not change the molecular composition of the water used (except for water generated as byproduct of combustion).

This is different in the case of emissions to the atmosphere that are most voluminous and weighty. In the case of atmospheric emissions it is the metabolic byproduct itself (mostly carbon dioxide) that is contributing the largest part of the weight. Worldwide average per capita CO2 emissions are currently around 4 tons (OECD/IEA2003). Several of the older studies although did not report CO2 emissions. The lowest value was reported for London, at 5.7 tons per capita, the highest for Singapore at 13.6 tons per capita. As highlighted earlier, if a broader definition of consumption would be applied (production and all imports minus exports to other countries) and Singapore would be responsible for emissions from international transport by ship and air its emissions would be close to 20 tons per capita.

Regarding solid waste, the highest reported value was 3.6 tons per capita for London (dominated by construction waste, which is possibly missing in many other accounts). Solid waste reported for Singapore 2000 was around 0.65 tons per capita. Regarding the comparison of various case studies it needs to be mentioned that the congruence of boundaries of input-output flows in each of these studies is not given and would need closer investigation.

2) Calculations of net additions to stock have been done in the study of the Buenz valley and the Amsterdam study. Those accounts can either be conducted based on flow accounts, like in the case of Singapore, or they can be based on inventories of each separate production process under investigation. Here again the definition of functional and temporal[9] boundaries affects the result a lot (Eurostat 2001). In the case study of the Buenz valley for example the landfill was considered part of the economic system, so depositions there were accounted as internal flows (only seepage or off-gas from the landfill are then emissions).

[9] In the long view most of the ‘stocks’ are in fact flowing due to erosion, corrosion, abrasion, diffusion etc.

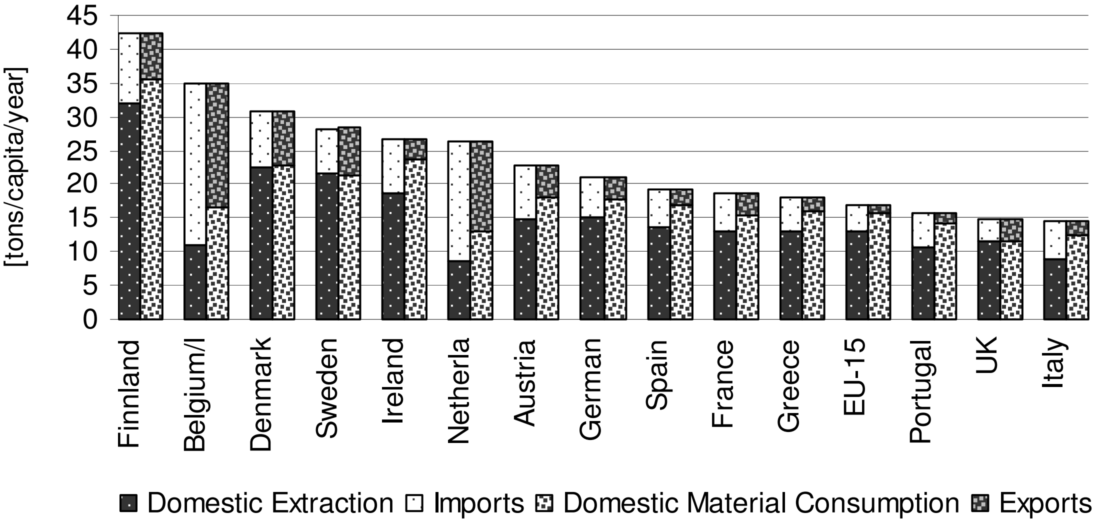
In the Singapore study, it was chosen to account waste depositions to landfills as emissions. This is somehow paradoxical, since the imports of sand which was among other things utilized for the expansion of island area was accounted for as an used internal flow. This compromise was mainly based on two arguments: a) since the sand for island expansion was largely imported and paid for as an article of trade it was clearly a direct flow. b) Since the gained land was often sold and has the character of a commodity, it is clearly a product of a socioeconomic process, and therefore needs to be accounted for. Furthermore there will be future labor and resources invested to maintain those reclaimed land areas. Therefore they should be classified as part of the infrastructure. As documented in the appendix the data availability of substrate origin used for island area expansion is very weak. The possible volume of solid waste used for fill appears comparatively small, whereas probably larger volumes of sand used for island expansion have been extracted domestically and have also been imported without documentation. Future research in that area would be necessary to clarify those uncertainties.

3) While the 4 material categories biomass, fossil fuels, construction and industrial minerals refer mainly to raw materials or semi-processed goods, the category ‘products’ refers to complex commodities of heterogeneous composition, in advanced stages of their life cycle. Cities are typical locations of industrial and manufacturing activities, which are converting the former 4 material categories into the category ‘products’. In two cases (study Buenz Valley and Amsterdam) this category ‘Products’ reported a net export of goods (2 and 18 tons per capita respectively), while in the other cases including Singapore the net trade balance of the category products was negative (the weight of semi-manufactured and final products imported exceeded that of imports). The degree of data resolution into distinct material flow categories strongly affects in how far those effects of lateral flows over the life cycle of a commodity can be observed and this information was not documented for the two studies cited from literature.

3.2.2. Comparison with national MFA data

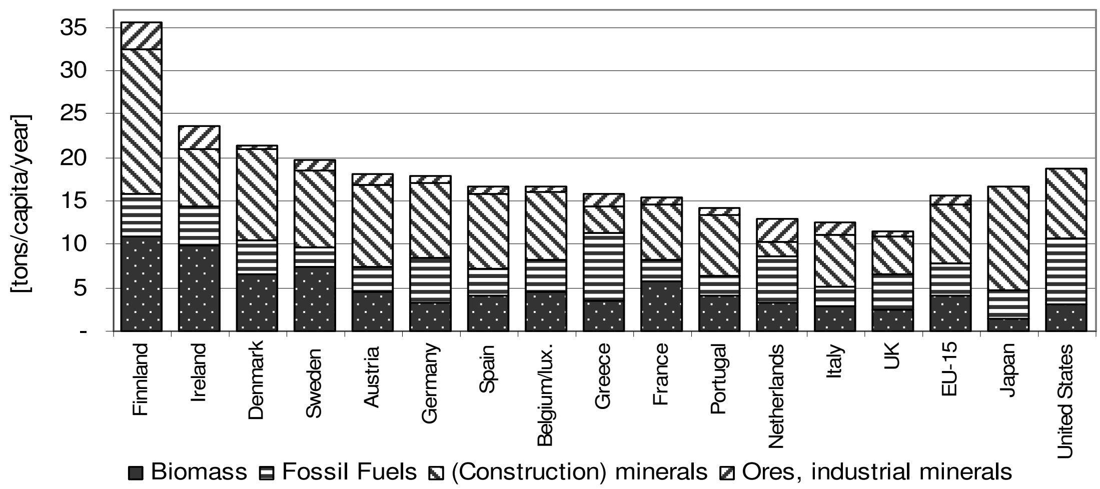
The volume and composition of Singapore’s material flows was compared with published data on material consumption of larger economies on a national level such as the EU15, the United States and Japan to identify relative functional differences in the metabolism of cities and possible effects of scale.

Figure 16 Domestic Extraction, Trade and Consumption, EU15.



Source: Eurostat 2002

Figure 17 Domestic Material Consumption European Union 15, 2000, Japan and US (1991) (Eurostat 2002), (Adriaanse et. al 1997).



Regarding the overall flows in- and out- of the EU15, it is interesting to note that despite a fair monetary trade balance the total weight of imports into the EU 15 equivalents 4 times the weight of all exports. This hints to a systematic pattern of the import of heavy raw materials, and export of refined products with relative lower weight and high value.

When comparing the pattern of domestic extraction, trade and consumption of Singapore (**Figure 11**) with the EU15 (**Figure 17**) the relative openness of the economy of Singapore stands out. The exceptionally low contribution of domestic extraction to direct material input (DMI) can be described as a typical urban feature. But also in the dataset on the EU 15 there are two countries were trade dominates material use: the Netherlands and Belgium. These patterns have been interpreted as effects of the harbor of Rotterdam (the largest port in Europe) and to a lesser extent the harbor of Antwerp. Both countries do also have high population densities and levels of urbanization.

Regarding the absolute values of per capita domestic material consumption, the amplitude of values for Singapore is starting at a lower level than any of the EU15 countries; it also peaks in 2000 at a higher level than recorded for any other country in the EU15 dataset. The dominance of trade flows illustrates the character of cities as physical attractors of material flows (centers of consumption), while in the economic reading they are usually conceptualized as centers of production.

On the other end of the spectrum the high level of DMC in Finland is reflecting the extractive character of Finland's economy (wood and paper production, extraction of iron and other ores) and its low population density. Similar high values have been reported for other 'peripheral' countries with significant primary sectors, such as Chile (Giljum 2004) and Australia (Poldy and Foran 1999).

The metabolic profile of Singapore in contrast is likely much more comparable to other examples of open economies from the EU15 dataset, such as the Netherlands characterized by large differences between DMI and DMC and low levels of per capita DMC, since they are able to externalize parts of the material inputs by imports of refined products. In that case one can expect that the volumes of by-products and waste during earlier phases of the products life cycle are then remaining in the exporting countries (compare the discussion on direct-indirect flows in chapter 2.1.1.)

The current high value of DMC in the case of Singapore is furthermore reflecting the rapid development of its industry and expansion of infrastructure. The long term trend displayed could therefore contain a compressed and rapid but limited growth period that will finally lead to low DMC values, once the expanded infrastructure is in place. The relatively low current levels of domestic material consumption (DMC) for some countries in the EU have likewise been explained by the long history of growth of those systems (Schandl and Schulz 2002). In the context of urban environmental transitions this acceleration and compression of growth effects in recently urbanizing and industrializing systems can be described as an example of ‘time-space telescoping’ (Marcotullio 2004).

3.3. Energy

Energy accounts were provided by the International Energy Agency. They provide an overview of energy use by economic sector. Those balances allow comparisons among different countries as well as comparisons with the world total consumption and have been provided in annual time series since 1971. Their boundary definition of consumption is not completely comparable with the accounting framework for carbon emissions due to fossil fuel use by the IPCC.

3.3.1. Total primary energy supply and total final consumption by sector

As displayed in (**Figure 18**) the character of Singapore’s energy system is to a larger extent defined by the trade and manufacturing of energy carriers then by domestic consumption. The dominating energy carrier is imported petrol and only very recently Singapore started also importing some gas from Indonesia. Furthermore there is a tiny volume of biogas produced from biomass waste and the capture of methane from landfills.

Singapore consumes only 30% of the overall imports and production of fossil fuel as ‘Total Primary Energy Supply’ (TPES). Around 50% are re-exported and another 20% is sold as bunker fuel for international shipping.

Total final energy consumption (=TFC, which excludes the conversion losses in the energy sector, e.g. due to electricity generation) was 11 million tons of oil equivalents (toe) in the study period; this equals about 40% of TPES. Roughly one quarter of this amount is attributed to international aviation, more (3 million tons) by the chemical and petrochemical sector, and about 2 million tons are used for car transport. Only a minute fraction (24,000 toe of TFC) was used for rail (mass rapid transport). Also residential consumption is low at 500,000 toe, about 5% of TFC.

The volume reported as final consumption in the IEA energy balances still overstates Singapore's consumption of fuel as defined in IPCC definitions of fuel use since it includes international aviation as one category of national energy end-use (as displayed in the graph on total final consumption, see **Figure 17**). In IPCC records of carbon emissions in contrast, the end-use international aviation is not accounted as domestic consumption within the national responsibility. Together with fuel for marine international transport they are merely included as bunker fuel, items of memorandum.

Another detail of the accounting logic of energy flow is somehow inflating the reported level of energy use on the TPES level as well as Singapore's CO2 emissions according to IPCC accounts:

The imports and exports of fuel from Singapore are actually not of the same quality. While Singapore imports crude oil, it exports largely refined fuels. The intermediate refinery losses are considerable: in the 3 year period 2000-2002 the volume reported as output from refineries comprised only 87% of the inputs (in units of toe). In the energy balances refinery losses are allocated to the level of TPES, although they actually refer to a volume of resources of at an earlier level on the accounting sheet where net trade is balanced: Since the net-export of refinery products (as fuel product or bunker fuel) significantly exceeds the domestic consumption of petroleum products, Singapore's refineries appear very inefficient if those losses are put in relation to the fuel volume consumed on the national level.

So in fact some of the emissions that occur over the life cycle of petroleum use are allocated to Singapore, although the fuel is finally sold and used in other countries, mostly in the Asian-Pacific area or for transport in international territory.

This example illustrates how the processing of oil is a service that Singapore delivers to oil importing countries and global sea-freight providers. On the other hand Singapore profits well from that service and despite a per capita income at the average OECD level and the fact that as non Annex 1 country it would not be obliged to any emission reductions it does not belong to the 163 Signatory countries of the Kyoto protocol or to those 157 countries that ratified it[10].

[10] Singapore did although sign the UNFCCC convention in 1992 and ratified it in 1997.

Figure 18 Imports, primary energy supply and final consumption, 2000

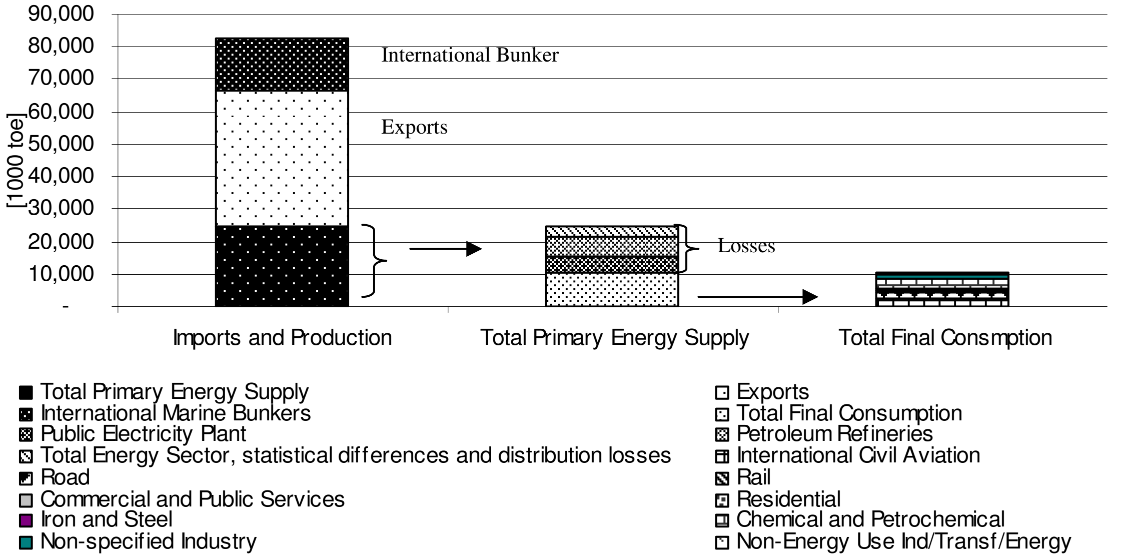


Figure 19 Total final consumption by sector / activity

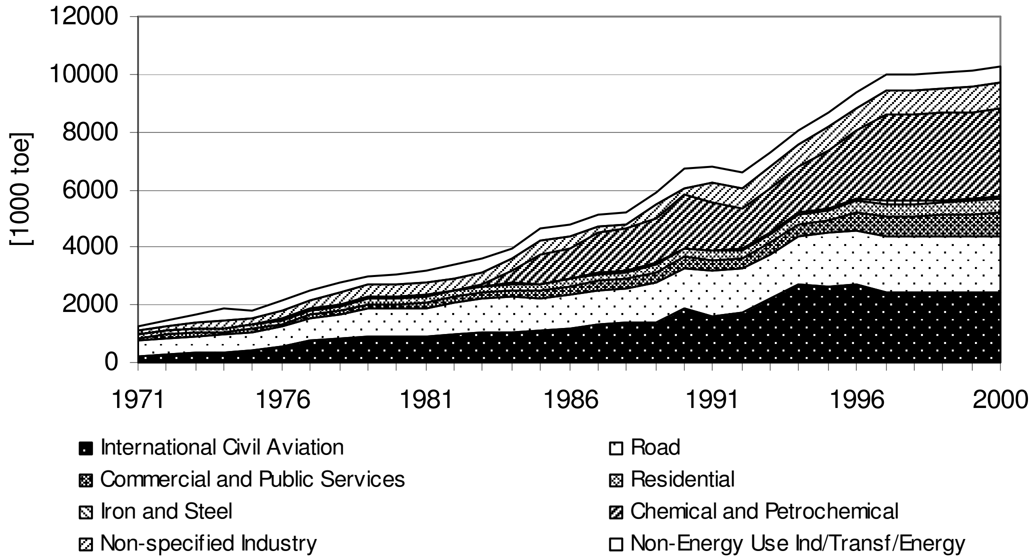


Figure 20 Ratio: Exosomatic (TPES) / Endosomatic Energy conversion

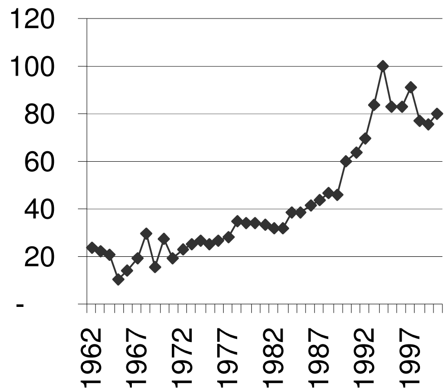


Figure 20 compares the ratio of technical energy conversions (exosomatic energy use, Lotka 1925) with the endosomatic energy consumption of the human population through nutrition (Giampietro 2003). While during the first quarter of the time series this value was around 20 (technical energy consumption was equal to 20 times the direct energetic content of human nutrition, a value similar to the national average of Portugal or Spain), this value rose to figures between 80 and 100 during the 1990s, values comparable to those of Canada and the US (Pastore et al. 2000).

4. Discussion

As (Machlis et al 1997) point out human ecosystems are hierarchically structured and can be described at various scales. For this study it was chosen to analyze Singapore, a fully urbanized system at the national scale for methodological reasons of homogenous data availability at the urban level and significant development over time. Since the urban and industrial growth dynamic of Singapore transformed already neighboring cities and villages like Johore and Riau, which are now forming part of an extended metropolitan region, the reported volumes of resource consumption at constant scale should be interpreted as a conservatively low estimate.

Among the essential elements of human ecosystems Machlis et al. distinguish 3 types of resources: natural-, socioeconomic- and cultural resources. This study only covered elements of the first two categories: natural resources such as biomass, minerals and in the most recent period some estimates for the use of water and air. Regarding socioeconomic resources it covers imports and exports of raw materials and processed goods. This study aimed at a comprehensive biophysical account for material and energy resources used in the socio-economy of Singapore. This perspective is considered more meaningful for environmental management than e.g. narrowly focusing on waste as it lacks a universal definition[11]. A focus solely on the end-products of resource consumption furthermore misses environmental and social pressures associated to the extraction and allocation of resource inputs.

The pattern of material and energy consumption of Singapore differs considerably from that of other nationwide accounts (**Figure 11**, **Figure 12**, **Figure 16**, **Figure 17**).

The per capita material consumption in the initial period before 1980 is much lower; and in the late 1990s it is much higher than in those case studies.

The use of biomass per capita is very low throughout the time series and has been decreasing over time. In the comparison of national case studies, Japan showed the lowest consumption of biomass, around 1.5 tons per capita. The level of Singapore although is even lower between 0.25 and 0.5 tons. The case of Singapore describes a specific urban situation that differs from other nationwide accounts in which biomass intensive processes (such as agriculture, livestock rearing, paper -or fiber production) are externalized.

The per capita use of fossil fuel use is high and still increasing; - this reflects the continuous extension of refinery capacity and the development of chemical industry.

The use of construction minerals has been increasing to a level per capita much higher than in any other national economy we found data for, except the regional scale study of the Buenz valley (Brunner et al 1994). It also fluctuated very much from year to year. This is reflecting the changes of urban morphology. Over the past 40 years there had been considerable restructuring, towards dominance of high rise buildings for residential and business use. Besides large infrastructure projects (airport, and freeways in the late 1970s to early 1980s) the main use for sand and aggregates in the 1990s was the increase in land area and

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[11] Waste might or might not impose hazards. In an economic reading waste is just material that under the current framing conditions does not possess utility value. Those framing conditions (such as prices of raw materials) and legal definitions are subject to change over time as illustrated by the example of CO2 emissions.

expansion of Jurong island, Changi airport and other infrastructure projects as documented in **Appendix 1**.

Outputs are dominated by emissions of used water and the release of CO2 to the atmosphere. Solid waste emissions originated mostly in the category products and biomass, while construction and industrial minerals had high rates of recycling, reflecting advanced systems of waste treatment.

Regarding the balance of input and output flows it is most striking that documented outputs are covering only about 20% of the inputs (excluding water and air). – More than 80% of the inputs that is almost 24 tons of material per capita are either resulting in not documented emissions or are adding to the infrastructure stocks. As explained in Appendix 1 most of this material is imported sand and gravel probably used for the expansion of the island and other infrastructure., although the data base on such activity is generally very week.

As explained earlier this study was restricted to the description of direct flows at the specific scale of Singapore. An inclusion of indirect flows (such as energy embodied in the imported goods or biophysical costs of mobilization and transport of resources form abroad) would have required dynamic factors for the changing technology in various source countries of imports. Since Singapore maintains trading connections with most countries on the world, produces most complex goods such as computers and its hinterland comprises practically of the entire globe such a task would clearly have exceeded the possibilities of this project.

As indicated in **Figure 1** the volume of material flows must not be interpreted as directly proportional to environmental impacts. The hidden flows (such as overburden from mining of imported ores or soil erosion due to the import of wood or other biomass) can be of magnitudes larger than weight of the actual imported products (as in the case of various metals). And even with the indicator 'total material requirement' as underlying the MIPS concept (Schmidt-Bleek 1993) and aiming at accounting for the total volume of mobilized material, one is left with the task to value the environmental harm caused by the different categories of material inputs (A ton of stone is clearly less harmful then for example a ton of mercury, but how much exactly?). The detrimental- or harming effect of mobilized material flows and disrupted natural cycles (Holdren 1990) are clearly dependent on the specific ecosystem that they are occurring in. On way forward in this task might be the application of distance- to target measures that are sensitive to variation in environmental vulnerability. Those measures which are commonly used in LCA on the other hand reduce the comparability of results.

Despite those problems of interpretation it should be argued here that the physical flow accounts are especially powerful in comparative analysis: they allow ranking different socioeconomic systems according to their resource intensity and to show the variability in resource use according to technology, level of consumption and economic measures. Such accounts enable to study historic changes over time of development which is a condition to identify realistic and viable future scenarios. As illustrated they can be applied at various scales allowing a better understanding of rural-urban and national-international disparities in the use of ecosystem services as a condition to address issues of fairness in the inter- and intra-generational distribution of resource use, a central challenge for sustainable development.

5. Conclusion

This paper contributes to the discussion on the environmental consequences of urbanization. While some authors highlight that dense settlement patterns enable to conserve natural ecosystems elsewhere, others underline the dependence of cities on resources from abroad and the effects of emissions and waste beyond the city limits. In fact it is not clear to what extend the potential gains in efficiency in resource use due to urbanization are compensated by changes in lifestyles and consumptive behavior. This paper presented an empiric time series analysis of the urban metabolism (material and energy use) of one of the most dynamic cities in Southeast Asia.

The metabolism of Singapore was characterized by very low levels of biomass use, high levels in the use of petroleum products and exceptional levels in the consumption of construction materials. Together with the strong importance of trade in relation to domestic extraction this pattern differed considerable from other reported accounts on a larger, national level and can be described as typical for an urban system in a phase of rapid reconstruction. Also the dynamic of physical growth with economic development was noteworthy: Singapore started from a very low level of per capita resource consumption that rose fast and still continues to grow to levels higher than in most other documented case studies. A decoupling of economic growth and the input and consumption of aggregate material resources (DMI, DMC) could not be observed. Either the level of development of Singapore was still too low (and the hypothesized threshold has not jet been reached) or the proposed relation does not hold true in such a universal way. In the last five years of the time series however there has been considerable fluctuation in resource intensity and the trend of this relation will need further investigation. The high values of material consumption of Singapore might be explained by two specific aspects:

1) The much more regionalized small scale of analysis (which depicts more dynamics in the flows that would be "buffered" at a coarser scale).

2) The very compressed 'telescoped' (Marcotullio 2004) character of the developing experience that completely transformed the urban morphology within two decades, whereas similar processes historically used to evolve over longer periods.

The past 40 years of successful industrial transformation of Singapore had a considerable impact on ecosystems in its immediate environment (local marine and costal habitats) (Corlett 1992, Turner et al 1994, Brook et al. 2003), neighboring ecosystems (forest resources in adjacent countries, marine habitats) and increasingly more subtle and distant effects (such as caused by high per capita CO2 emissions). This study applied tools to systematically link economic activities to such pressures. It should be noted that the method used here (bulk flow MFA) is a highly aggregated measure of resource consumption. It only provides an overview and can be decomposed for example into substance flow analysis to address toxicological concerns (Tarr & Ayres 1990) or can be disaggregated by product groups (e.g. trade with tropical timber products) to address specific environmental problems. The reliability of the data compiled in this study is still considered preliminary, since some of the flows had to be approximated for lack of documentation by official sources. Most problematic in this context has been the domestic extraction and the import of construction minerals, as described in Appendix 1. It is hoped that the findings of this case study will contribute to our understanding on the environmental effect of urbanization and the role of urban centers as nodes in the fabric of an increasingly integrated world. Further research on the following fields would be needed:

1) Balancing outputs over time, accounting for changes in material stocks (infrastructure, artifacts and durable goods) as they are latent sources of waste that are also triggering biophysical maintenance costs;

2) A quantification of indirect flows, upstream of the production and consumption process;

3) Investigating the links of the abovementioned flows (including trade) to environmental pressures on specific habitats and populations.

4) Relating those pressures to structural patterns in the economy, possibly via extended input-output tables

5) Association of such interactions to other socioeconomic factors like employment, lifestyle and environmental risks to the population.

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Appendix 1

Land Reclamation in Singapore

During this study it became visible that land reclamation had been a major activity, not only during the past ten years, but throughout the time series (**Figure 30**). Centralized or systematic data collections on land reclamation activity and the origin of the used substrate could not be found. Therefore data was compiled from a range of sources and summarized in this appendix and **Figure 31**. Its purpose is to indicate the order of magnitude of the earthworks and point towards the uncertainties in the data.

Background

Despite its relatively small area size Singapore has a diverse topography. While the centre of the island is characterized by round granitic hills, including the highest point at 156 m above sea level, most of the Islands are is less than 15 meters above sea level. The west and southwest of the mainland are composed of sedimentary rocks, carved by northwest to southeast oriented ridges (**Figure 27**). The eastern part of the island is flatter in character and build on older alluvial deposits.

The island is drained by several short streams who are building the interface to the sea. Historically they had been mediated by a diversity of ecosystems, including freshwater swamps forests, mangrove forests, estuaries and lagoons. The original coast has been characterized by interrupting sand beaches, tidal flats and corral reefs (**Figure 26**).

The area of Singapore had been transformed profoundly over the past two centuries, (**Figure 24** and **Figure 25**), a process that accelerated since Singapore's independence in 1965.

Major trends in land use during the past 40 years were reductions in the area used for rubber- and coconut plantations and other agricultural use, the construction of "New-Towns" – compact satellite settlements with integrated functions, connected to the centre via mass rapid transport system (MRT), the construction of Changi International Airport, a ring-road of connecting freeways, and the expansion of area devoted to industrial use like manufacturing, petrochemical industry and several container terminals.

A most striking feature within the development over the past 30 years had been the actual expansion in total land area of Singapore. Between 1967 and 2003 the area had been increased by 20% from 582 to 697 km2 by land reclamation, filling of mangrove swamps and tidal flats and amalgamation of smaller islands to units able to support industrial settlements.

Although there have been some smaller projects of land reclamation carried out before the 1960s (e.g. around Keppel harbor **Figure 28**), the most consequential projects were conducted in the period between 1967 and 2003. For descriptive and analytical purposes those projects can be divided in two phases:

Expansion Phase I 1967-1987

During the first phase between 1967 and 1987 the main development projects were land reclamation along the south-west coast, including the Jurong industrial estate, the expansion of the western tip of the mainland around Tuas, expansion of Jurong island, (which hosts now 3 of the 5 refineries of Singapore), land reclamation around the Marina City and downtown at the Singapore river delta and on the south-east coast of the main island. Also the outlets of several streams were dammed to collect runoff and to build freshwater reservoirs. In 1975 the decision was taken to build Changi International Airport on 1300 ha on the western tip of the mainland. Terminal I opened in 1981, in 1985 construction of terminal II was commenced which opened in 1990. Currently construction of terminal III is under way which is scheduled to open in 2008. The capacity of the terminals each is around 20 million passengers per year. In 2008 it will reach a total of 64 million passengers, about 14 times the population of Singapore.

For the first phase of the Changi project (construction of terminal1) 870 hectares of land were reclaimed from the sea (670 hectares using sea-fill and 200 hectares using landfill). In 29 month about 12 million cubic meter of earth were removed from nearby hills, and about 40 million cubic meter of sand were dredged from the seabed[12].

As indicated in **Figure 30**, **Figure 28** and **Figure 29**, the Changi I project had not been isolated, but one among several. Reports on the total volume of sand or earth material required for land-filling during this first phase between 1970 and 1987 are incomplete and sources are sometimes contradicting. An attempt will nevertheless been made here to broadly estimate the magnitude of earthworks required for the achievement of island expansion by

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[12] source: http://www.changi.airport.com.sg/, retrieved June 05

54.5 km2 (+9% of the 1967 value). Using the data from the Changi I project, we derive at a value of 5.98 m3 of filling material to reclaim one m2 of land. (This can be thought of as an average of 4 meter water depth and two additional meter of altitude above sea level, ignoring settling and compaction of the material and other factors). Applying this ratio to the 54.5 km2 of reclaimed land we derive at a total volume of about 325.7 million m3 of sand- and earth-fill, required to complete the projects, assuming similar framing conditions. From the trade statistics described above it is possible to calculate the net volume of sand and gravel that have been imported and not been used for the production of concrete: In the period 1967 to 1987 this volume amounts to about 20.7 million tons, or roughly 10 million cubic meter. A remaining 310 million cubic meter have probably been domestically extracted or imported without documentation over the period of 20 years (in average this amounts to about 31 million tons per year, or an additional 7.5 tons per capita per year).

There are various reports that during the first phase of land expansion still a considerable volume of filling material had been derived from deposits and excavation works on Singapore Island (**Figure 29**), in case of the Changi project this volume was about 23% of the total reported filling material.

Expansion Phase II 1988-2003

In the following second phase between 1987 and 2003 an even larger area of land had been reclaimed from the sea: An additional 61 km2, or 11% of the 1967 surface area were added. Due to diminishing resources of potential deposits of sand and gravel on the mainland, which by now has already become relatively flat, and due to higher domestic environmental standards during the past 20 years, it is reasonable to conclude that the land reclamations were more dependent on sand extracted from the sea. The shore depth that needed to be filled during the first stage of land expansion has been relatively low, around 6 meters. In the period after 1987 the depth increased to reported values up to 20 meter, requiring approximately 4 times the volume of sand to reclaim one m2 of land.

Major projects during the second phase of land reclamation after 1990 were a further expansion of Jurong Island for the petrochemical industry, the abovementioned expansion of Changi Airport terminal 3 and a significant enlargement of the Tuas Peninsula, forming the inlet of the straits of Johor (Selat Johor).

It is not clear how much volume of sand has been used and will be required for further use as filling material towards completion of the goals outlined in the 2001 strategic plan. The reported volume of sand imported between 1988 and 2003 and not used for concrete was about 370 million tons, or about 185 million cubic meters.

Assuming a shore depth of 6 meter, like in the previous time period leads to demand of about 360 million cubic meter of filling, 185 of which have been reported. Assuming three times that shore depth, one would arrive at a demand of 1.46 billion cubic meters of sand. After subtraction of the reported imports, some 1,275 million tons of undocumented imports would remain. As mentioned earlier, those calculations are order of magnitude estimates, based on scattered and inconsistent media reports[13] and would need further investigation. Newsletters of major dredging operators are referring to the Singapore projects as one of the largest dredging operation in history, that required cooperation of the world leading companies in that technology from Belgium, the Netherlands, Japan and Korea to generate the required capacity.

International Reactions

The land reclamation projects especially in the Strait of Johor, was perceived by Malaysia as an intrusion into their territorial waters and therefore a violation of the law of the sea.

It feared that it impacted their free passage of shipping, and redirected tidal flows with a number of environmentally adverse effects: The shoreline of the Malaysian side was reported to increasingly erode, siltation in the Strait of Johor was reported to have increased by a factor of 4, plumes of silt reduced the oxygen concentration of the water, salinity was reduced since the flow of several rivers on the Malayan side was affected. Irreversible, large scale habitat destruction was reported for mangrove forests, sea grass fields and corral reefs which are known for high levels of biodiversity and large numbers of endemic species.

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[13] As reported in the Straits Times, Asia Times, The Jakarta Post. Other media reports also hint to the need to remove soft marine clay and sediment under the projected reclamation sites for reasons of stability and to avoid later land subsidence. Since those clay layers can measure several meters, and are possibly contaminated from historical industrial activities, they provide a disposal problem, and would further increase the total volume of sand fill required.

Economic impacts included adverse effects on local fisherman and aquaculture undertakings, navigation, moorings and jetty stability with consequences to the economy of costal villages and regional trade.

The conflict had been brought by Malaysia to the International Tribunal for the Law of the Sea, requesting provisional measures, and had been settled in 2005. Singapore had been cleared of the territorial violation, but agreed to compensate local fisherman and to contribute to mitigation projects for the environmentally adverse effects.

The land reclamation also affected the relation between Singapore and Indonesia, the other principle neighboring country of Singapore. Most of the sand used during the second phase of land expansion (according to some media reports 80%) was extracted from Indonesian territory in the Province Riau, across the Singapore Strait. Riau is located in the centre of Sumatra Island.

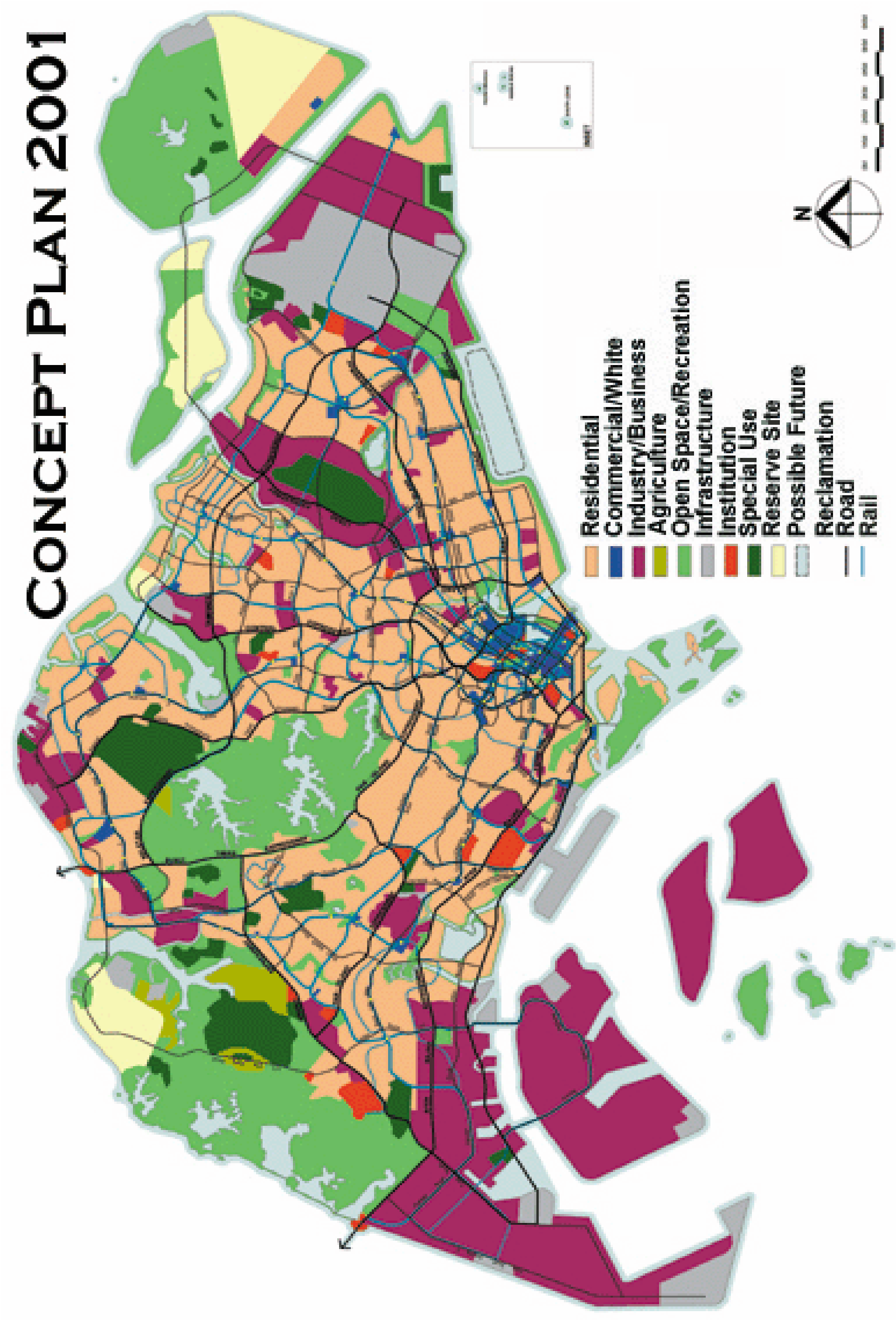
While sand clearly is a ubiquity in that area its extraction and export has a number of environmental, social and economic effects that would need monitoring, regulation and compensation. Media reports and environmental campaigning groups have been repeatedly noticing that sand was illegally extracted from Indonesian territory for reclamation works in Singapore. At some point Indonesian military was capturing vessels transporting sand. One aspect of this practice is the loss of royalties to the Indonesian government, which were estimated in the order of several hundred million US dollars, comparable to illegal timber exports. Another aspect is the often irreversible environmental habitat destruction and resulting consequences for local populations and economies.

In 2003 Indonesia halted all exports of Sand to Singapore. Regarding the achieved extent of land reclamation there are still large discrepancies compared to the goals set out in the project plan of 2001 (compare **Figure 30**).

Figure 21 Recent Satellite Image of Singapore

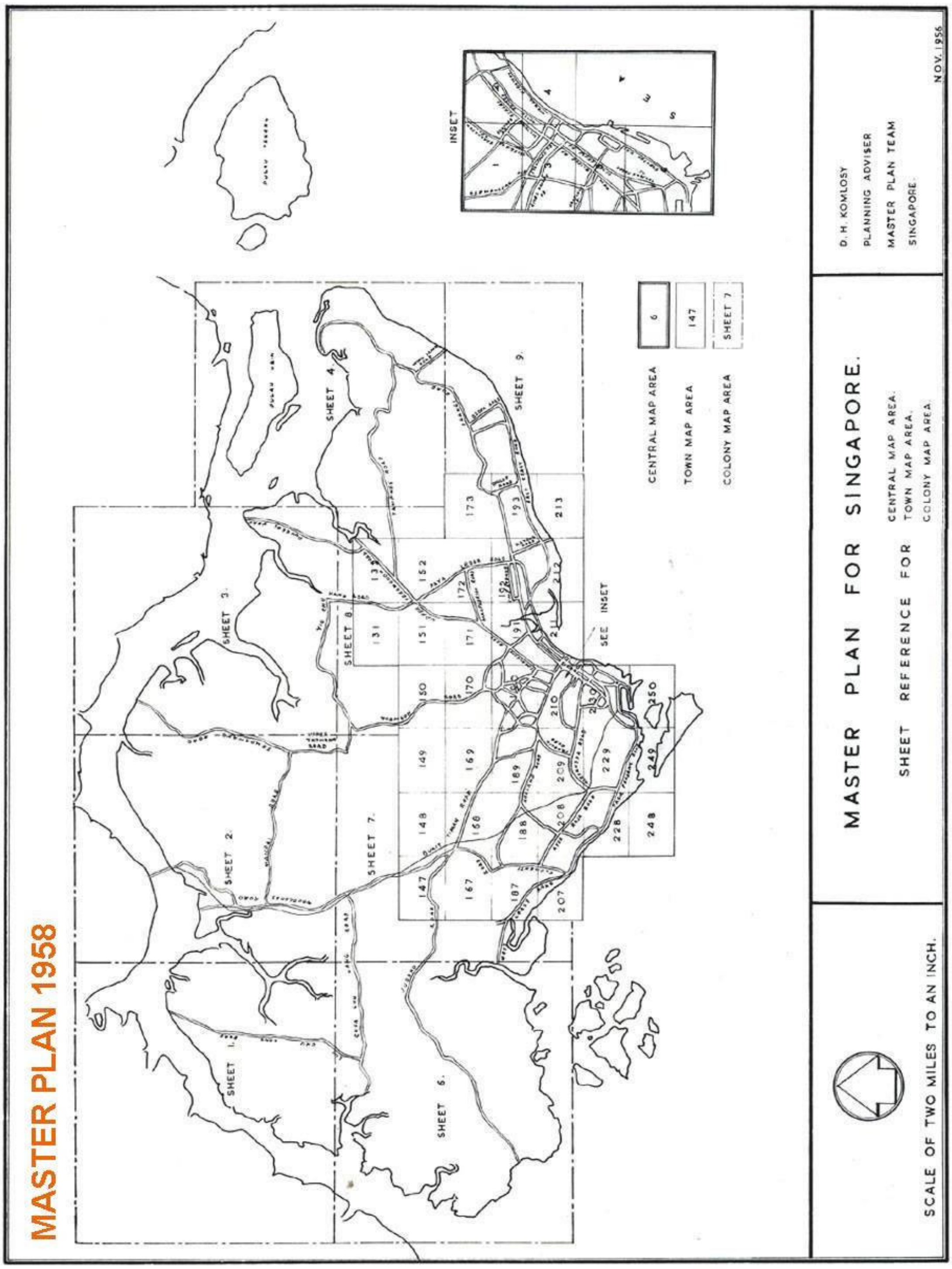
Author: National University Singapore (NUS), Centre for Remote Imaging, Sensing and Processing (CRISP) published through Straits Time's website (April 23. 2001, http://straitstimes.asia1.com.sg/)
Acquired: 18th January 2001, based on SPOT data, from CNES.

Figure 22 Concept Plan 2001



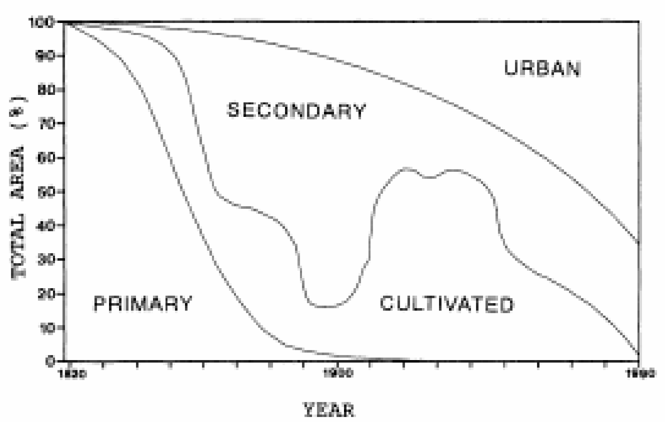
Author: Urban Redevelopment Authority,
Source: Internet, http://www.ura.gov.sg/conceptplan2001/index.html, retrieved: June 05

Figure 23 Master plan 1958



Author: Colonial Singapore Improvement Trust, Singapore City Council, Singapore Rural Board.
Source Internet: http://www.ura.gov.sg/dc/mp58/mp58map_index.htm, retrieved: June 2005
Date: 1958

Figure 24 Land use changes in Singapore, 1819-1990

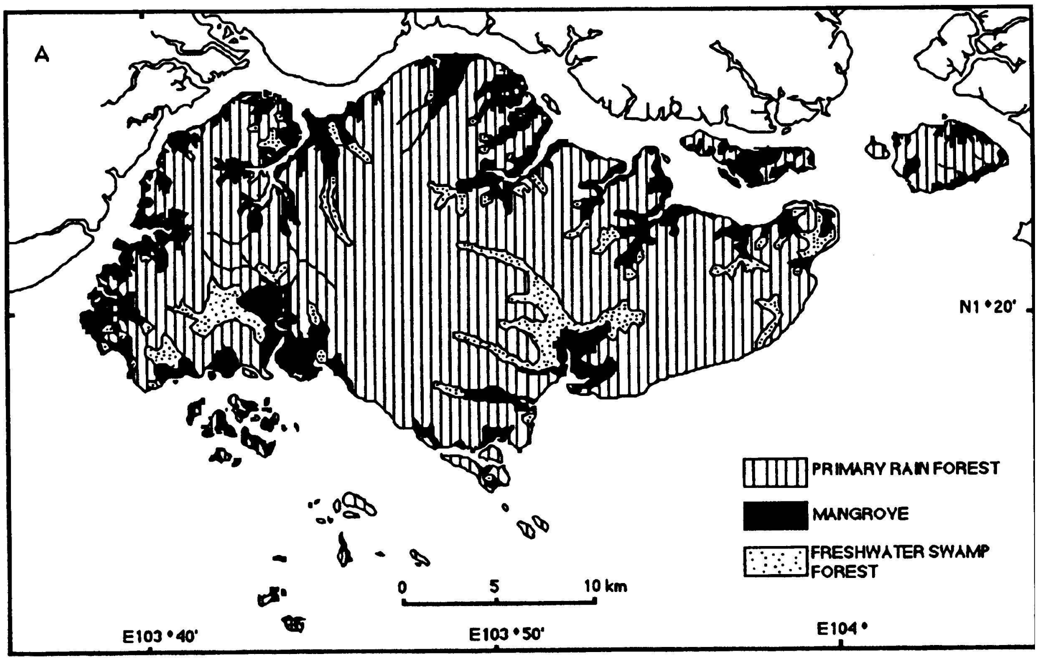


Notes: Excluding offshore islands and reclaimed land. PRIMARY = primary forest, CULTIVATED = cultivated land, including tree crops; SECONDARY = secondary grassland, scrub and forest: URBAN = urban areas, including parks and gardens. Source: Richard D. Corlett, The ecological transformation of Singapore, *Journal of Biogeography*, (1992), 19, 411-420

Figure 25 Settlement-history Singapore Island, (pre 1970).

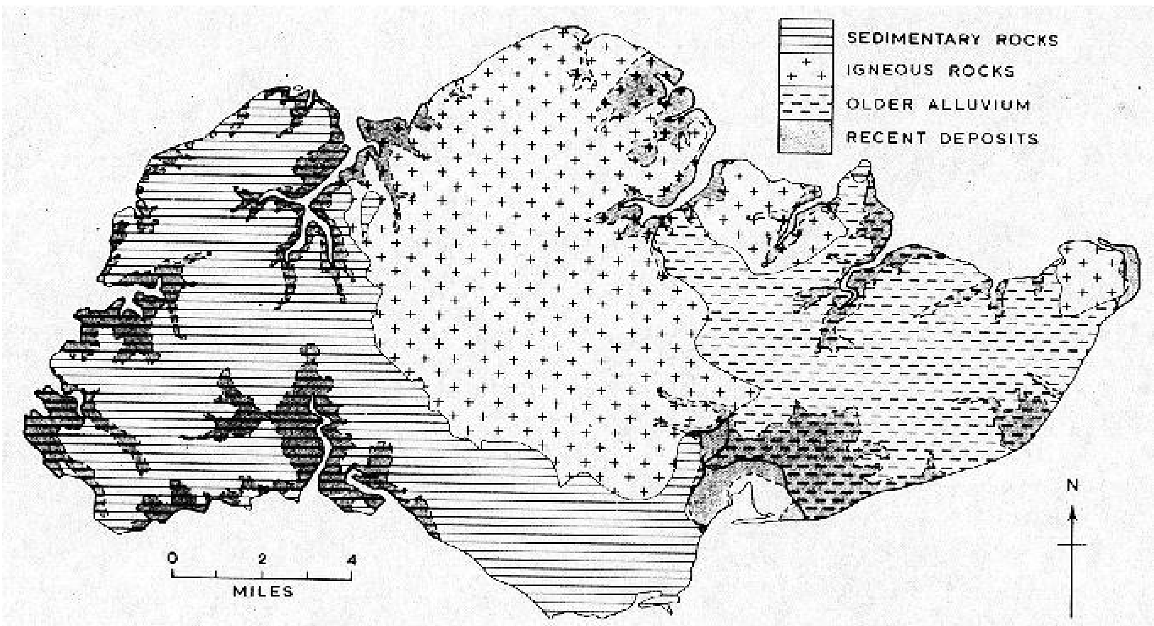
Source: CMPS (1971), *The Urban Renewal and Development Project, Singapore*: For the United Nations Development Program (Special Found), Singapore, Crooks Michell Peacock Steward Graphics and Printing Division (five parts and summary volume)., reprinted in: Howard Dick, Peter J.Rimmer: *Cities, Transport and Communications – The Integration of Southeast Asia since 1850*, Palgrave Macmillan, Houndmills, Basingstroke, Hampshire and New York 2003.

Figure 26 Reconstructed Vegetation of Singapore 1819



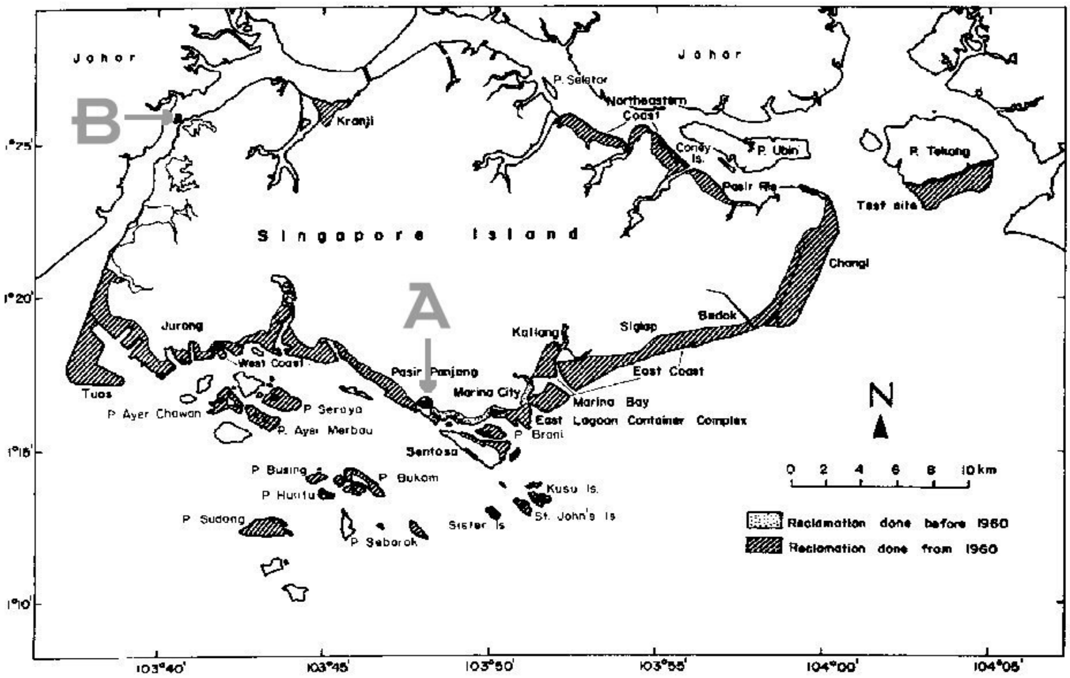
Source: I.M.Turner, H.T.W.Tan, Y.C. Wee, Ali Bin Ibrahim, P.T. Chew, R.T.Corlett, A Study of Pland Species Extinction in Singapore: Lessons for the Conservation of Tropical Biodiversity, *Conservation Biology*, Vol.8, No.3 (Sept.1994), 705-712.

Figure 27 Geology of Singapore



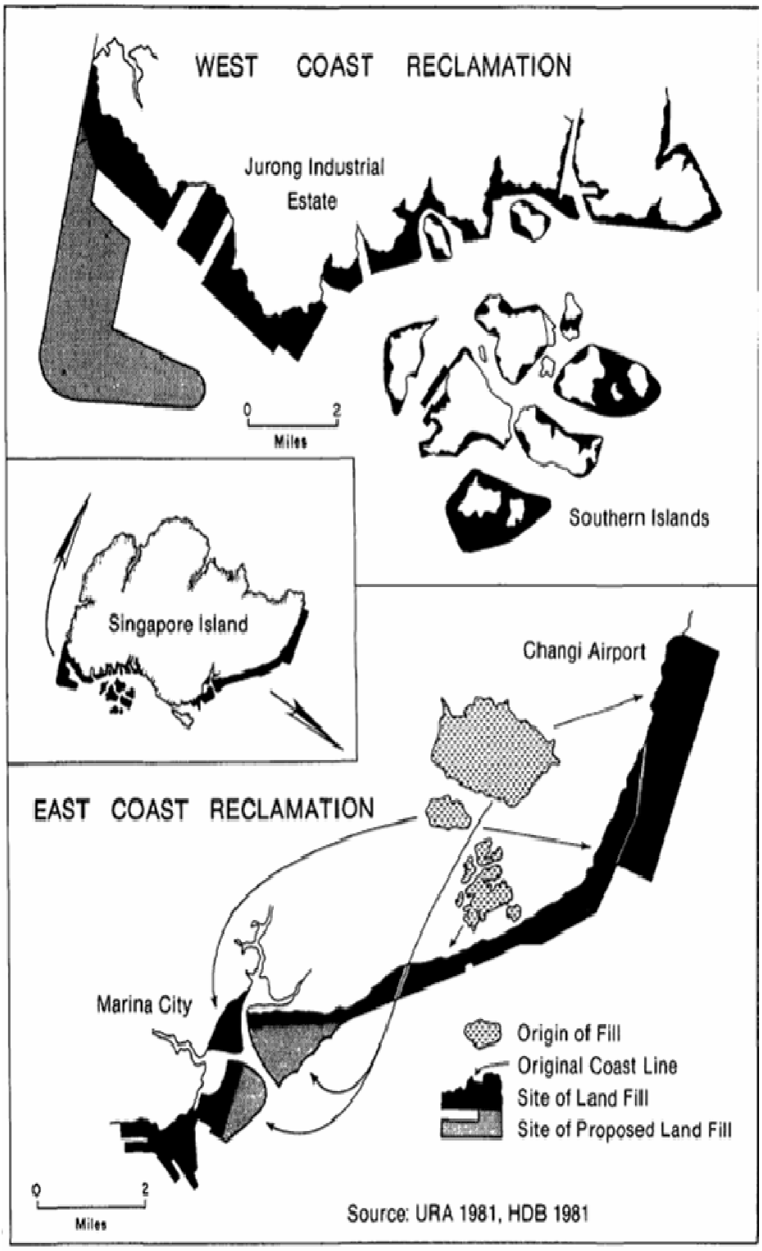
Author: Unknown,
Source: Internet, http://www.fishesnpets.net/explore/map/geology.jpg, retrieved: June 05

Figure 28 Land reclamation, various years (pre 1990)



Author: Unknown,
Source: Internet, http://www.fishesnpets.net/explore/map/reclaim.jpg, retrieved: June 05

Figure 29 Costal reclamation showing the original coast line and new shore areas created through landfill activities (black areas), (pre 1983)



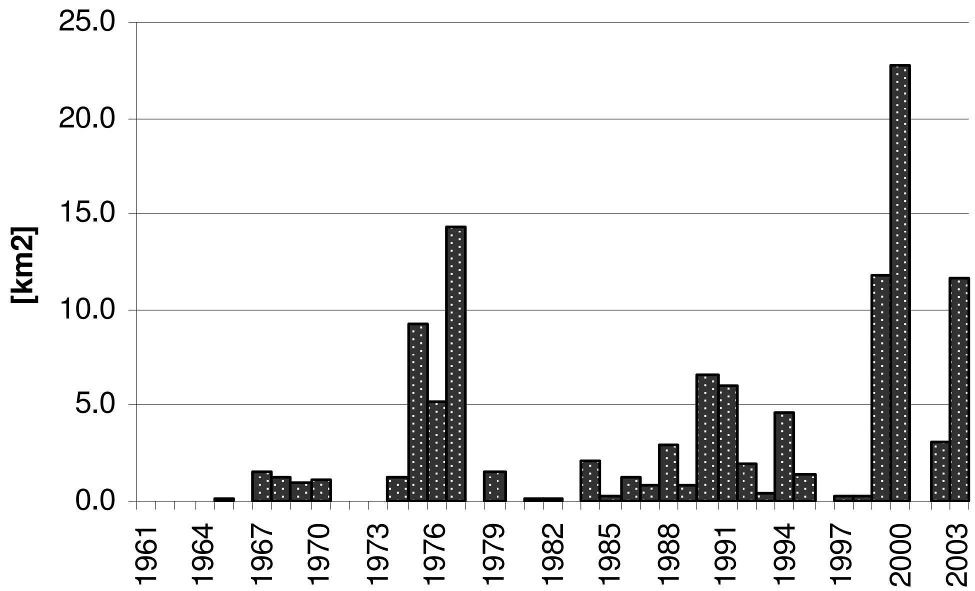
Source: Gerald Krausse, The Urban Coast in Singapore: Uses and Management. *The Asian Journal of Public Administration* Vol 5, No 1, 33-62 (1983)

Figure 30 land area and population

year	Population [million]	Area [km2]	[1000 person/km2]
1960	1.75	581.4	3.01
1965	1.98	581.5	3.40
1970	2.15	586.4	3.67
1975	2.33	596.8	3.90
1980	2.65	617.8	4.28
1985	2.77	620.5	4.47
1990	3.18	633.0	5.02
1995	3.74	647.5	5.78
2000	4.16	682.7	6.10
2045*	5.5*	784.6*	7.01*

Sources: Area- Singstat, Yearbook of statistics, various years, Population: Source: Groningen Growth and Development Centre and the Conference Board, Total Economy Database, retrieved January 2005, http://www.ggdc.net *Projection: Urban Redevelopment Authority Concept Plan 2001

Figure 31 Land reclaimed per year



Sources: Calculated from land area reported in Singstat, yearbook of statistics, various years.