UNIVERSITY OF LEEDS

Lifestyle Change, Structural Transitions and Natural Resources: New Approaches and Applications of Input-output Analysis to China

DABO GUAN

Submitted in accordance with the requirements for the degree of Doctor of Philosophy
The University of Leeds
Sustainability Research Institute
School of Earth & Environment
May 2007

Acknowledgements

I would like to firstly express my gratitude to a dedicated and wonderful supervisor, Dr. Klaus Hubacek, and above all for being a great and inspiring friend. Klaus and his wife, Christina has been extremely patient and kind to help, encourage and comfort me when I faced many difficulties in both academic and daily life. They are always there for me for listening and advising. I will not forget the trips we went together to China, Japan and maybe many more in the future. The only word to say is – many thanks, Klaus and Christina.

I would also like to give my appreciations to Professor Faye Duchin at Rensselaer Polytechnic Institute (RPI), U.S. Faye is my research grandmother, who has been so kind like my really grandma to advise on several journal papers I published as well as job applications. Equally, I am very grateful to Professor Laixiang Sun from the School of Oriental and African Studies University of London. Without your recommendations, I would not have this fantastic job offer from University of Cambridge. Thank you, Faye and Laixiang.

Many thanks to International Institute Applied System Analyses (IIASA) at Laxenburg, Austria provided me the opportunity to join the Young Scientist Summer Programme in 2004. I developed my first journal publication there, and built my confidence in academic development. Furthermore, I had the best summer in my life there and met so many friends, Ning Sun, Wenyan Chen, Xiaozi, Liu, Qiang Li and Rob. I have to give my special thanks to Dr. David Wiberg for your suggestions in improving my first paper. In addition, many thanks to the people helped me in organising the successful Asian Day there, which made me famous there, especially Barbara, Ascott.

There are so many people who have made my life much fuller during the past four years, and contributing in one way or the other to my personal development I would give this special thank to all my PhD mates in Room319, especially to Anamika Barua, Shova Thapa, and Karla Utting. We helped each other, enjoyed so much fun and I will never forget about it.

At last, I feel the most indebted to my mum. She raises me up by her own, takes care of me and has paid me everything along my education. My mum is the most beautiful and generous person in the world, at least to me.

Abstract

This PhD thesis employs and further develops the current input-output techniques from different approaches to explore the opportunities for quantitative research on sustainable development in developing countries, particularly applied to the case of the fastest growing economy – China.

China's economic success can be confirmed by showing a continuous annual Gross Domestic Production growth rate of over 8% since 1980; being the world's fourth strongest economy since 2005 and the second largest exporter in 2006. China's economic structure has been transformed from agricultural to industrial based while the tertiary sectors are gaining increasing importance. Much of China's population has been experiencing a transition from poverty to adequate food and clothes, and a growing part of populations are changing to "western lifestyles". The economic reform also creates unbalanced regional development, which has resulted in significant income gaps between rural and urban areas, coastal and interior China.

All these developments have left deep marks on China's environment. On the other hand, deteriorated eco-systems have the potential to affect the continuity of development and in some regions, as for example North China. This thesis investigates the interrelationships and interactions between the economy and the environment in order to identify the major drivers of environmental degradation for the fast developing economies in the "South".

Chapter 4 designs a hydro-economic accounting framework to demonstrate how water has been involved in production, then discharged to the natural environment with degraded quality and its impacts to the regional hydro-systems. By applying the framework to North China which is characterised as water scarce, the water demand was 96% of its annual available water resources, mostly for the water and emission intensive sectors. Chapter 5 takes a different angel by assessing virtual water flows between North and South China. It uses international trade theory as a starting point to address its inability to treat natural resources properly as a factor of production. Both

Chapters 4 and 5 suggest that it is important 'to design' an economic structure as well as trade patterns at the beginning of industrialisation process, especially for newly industrializing countries in the "south", from the perspective of sustainable development. Chapter 6 conducts an IPAT-IO structural decomposition analysis on China's CO_2 emission to picture a race between consumption growth and technology improvements over the past 20 years. It also points out that it is vital to establish policies to switch westernising consumption trend to more sustainable consumption patterns to reduce CO_2 emissions. This might be the case for many other developing countries as well.

PhD Publications

Peer-Reviewed Journal Papers

- Peter G. and C. Webber, **D. Guan** and K. Hubacek (accepted pending minor revisions) "China's growing CO_2 emissions – A race between lifestyle changes and efficiency gains" **Environmental Science and Technology**.
- Hubacek K., **D. Guan,** J. Barrett and T. Wiedmann (under review) "Environmental implications of urbanisation and lifestyle change in China: Ecological and Water Footprints" **Journal of Cleaner Production**
- **Guan D.** and K. Hubacek (forthcoming 2007) "A New Integrated Hydro-economic Accounting and Analytical Framework for Water Resource Consumption: A Case Study for North China" **Journal of Environmental Management**
- Hubacek K., **D. Guan** and A. Barua (forthcoming 2007) "Changing Lifestyles and Consumption Patterns in Developing Countries: A Scenario Analysis in China and India" **Futures: The Journal of Policy, Planning, and Futures Studies**, Volume 39, Issue 9.
- **Guan D.** and K. Hubacek (2007) "Assessment of Regional Trade and Virtual Water Flows in China" **Ecological Economics**, Volume 61, Issue 1, Page 159-170

Book Chapters

- Hubacek K., **D. Guan** and A. Barua (forthcoming 2007) "90 years lifestyle changes and CO_2 emission in China and India" Scenarios and Indicators for Sustainable Development, edited by ISEE and INSEE, Oxford University Press.
- Hubacek K., **D. Guan** and L. Sun (2005) "An analysis of China's water problems: A long term perspective". Walter, Leal (ed.). Handbook on Sustainability Research. Peter Lang Scientific Publishers: Frankfurt, New York, Bern, Vienna

Conference Proceedings and Presentations

- **Guan D**. and K. Hubacek (2007) "An Integrated Hydro-economic Accounting and Analytical Framework – A case study for North China", The 16th International Input-output Conference, 2nd – 6th, July 2007, Istanbul, Turkey.

- Hubacek K., **D. Guan** and A. Barua (2006) "Changing Lifestyles and Consumption Patterns in Developing Countries: A Scenario Analysis in China and India" The 9th Ecological Economics Conference, 16-18 Dec., 2006, Delhi, India.
- **Guan D**. and K. Hubacek (2006) "A Hydro-economic Accounting and Analytical Framework for Water Resource Consumption in China" The Intermediate International Input-output Conference, 26-28.July 2006, Sendai Japan.
- **Guan D**. and K. Hubacek (2005) "Development and Implications of a Hydro-economic Accounting and Analytical Framework for Water Resource Consumption in China" Conference of Complexity and Ecological Economics, Complexity Science and Society, 11-14 Sept 2005, Liverpool UK.
- **Guan D**. and K. Hubacek (2005) "An Extended Input-output Analysis on Accessing Virtual Water Flows in China" The 15th International Input-output Conference, 27 June – 01 July 2005, Beijing, China.
- **Guan D**., K. Hubacek and A. Barua (2005) "Changing lifestyle and consumption patterns in developing countries: A comparative study of India and China" Proceeding of Sustainable Consumption: the Contribution of Research Workshop, 10-12 February, 2005, Oslo, Norway.
- **Guan D**. and K. Hubacek (2004) "Water consumption and virtual water flows in China" Proceedings of the 6th conference for postgraduate students, young scientists and researchers on Environmental Economics, Policy and International Environmental Relations. 07 – 08 October 2004, Prague, Czech Republic.
- Hubacek K. A. Barua and **D. Guan** (2004) "Outcome of the workshop at Leeds." Proceedings of the Third International Workshop on Sustainable Consumption. October 21-22, 2004 in Tokyo, Japan. Organized by the Society of Non-Traditional Technology, Research Centre for Life Cycle Assessment.
- **Guan D.** and K. Hubacek (2004). "Lifestyle changes and its influences on energy and water consumption in China: a historical analysis." Proceedings for the International Workshop on Driving Forces for and Barriers to Sustainable Consumption. 05 -06, March 2004. Leeds, UK

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Chapter 1: Introduction

1.1 Research motivation

Ever increasing production and consumption is putting a strain on the environment, polluting the earth and damaging ecosystems. Large-scale economic development in the North occurring in the first half of last century has left deep marks on natural resources' availability and quality. These are dangerous side-effect of the development model the North follows and the South emulates. In recent decades, changing lifestyles and consumption patterns has been a common feature of most developing nations. Increasing income provides their citizens with more options; people's lifestyle choices largely determine what impact economic growth has on the environment. As nations develop and their economies grow, so too does the consumption of resources. Nevertheless, over-consumption may not only be the result of too many humans competing over a limited resource base but also economic elites using that resource base excessively and abusively to the detriment of other sectors of society, poorer nations, future generations and other species.

Water and energy are essential inputs used throughout the whole production chain of economic goods and services. Until recently, people almost have felt free to use environmental resources such as water and rarely give the desired economic respect to the resources until it became scarce in many countries and regions. Consumers allocate their incomes to purchase goods and services to maximise their satisfaction; producers or businesses withdraw scarce resource (e.g. labour, capital, water and energy) in a variety of productive activities to maximise their profits; and societies allocate resources and products to consumers in such a manner as to achieve the 'end' – maximise welfare of the societies (Rogers 1997). Traditional macroeconomists rarely took natural resources into consideration and thus water and energy are usually not recognised as factors of production. But in reality both water and energy are primary inputs to all goods and services either directly or indirectly; and its available quantity and quality can affect output of products and thus influences the level of economic activities especially in agricultural societies and as one will see also to some extend in industrialising and modernising economies such as China.

Water quality is selected as an environmental indicator to study the interactions between the economy and the ecosystem, particularly to account the environmental degradations due to pollution discharges. Energy and its related emission (CO_2) are used as environmental indicators to analyse the driving forces of the trends in environmental degradation due to energy consumption over the past two decades.

1.2 An impressive story: China's "economic miracle"

China occupies almost entire East Asian landmass of about 9.6 million square kilometres; habitats 1/5 of world population of 1.3 billion by 7% of world's arable land, and 6% of fresh water resources (Fischer et al. 1998). China is rich in human resources and diversified natural resources, but lacks technology and suffers from low per capita availability of resources.

Nevertheless, the latter half of the 20th century was the period of the 'economic miracle' for East Asia. East Asian countries including Japan and Korea achieved a high annual growth rate of GDP (Gross Domestic Product) averaging about 8% during the 1960s and 1970s. They achieved industrialisation, urbanisation, electrification, and motorisation in a short time period of about 20 – 30 years. However, at the same time China was engaged in 'socialists' movements', especially the ultra leftists of the 'Great Leap Forward' and 'Cultural Revolution', which severely stagnated China's economic development for 30 years. China accelerated its economic development with an annual GDP growth rate of almost 10% after economic reforms were started in 1978. In comparison the world average was 3.3% during the same period (Hubacek et al. 2007). By 2005, China's GDP had reached 1.13 trillion US dollars, which put China among the four largest economies or even the second largest economy if counted in purchasing power parity (PPP). China's economic reform has created very competitive and favourable circumstances for domestic and foreign investors in terms of cheap labour costs, a huge domestic market, low workers safety standards and environmental criterions (Guan and Hubacek 2007). As a result, large amounts of capital have been flowing into China, especially in the southern and eastern parts, which has made China one of the largest manufacturers and exporters in the world (Guan and Hubacek 2007). However, Deng's 'ladder-up' strategy of economic developments has increased regional income inequality, for example, between the more affluent coastal urban areas and mainly rural western

China and also between southern and northern regions, which can be shown by the Gini coefficient of 0.43, and is also reflected in differing development regional policies economic production structures, the scale of foreign direct investment and people's lifestyles pattern (Guan and Hubacek 2004).

The most direct and significant result of China's economic growth is the amazing improvement in quality of life for Chinese people. China's population has experienced a transition from 'poverty' to 'adequate food and clothing'; today growing parts of the population are getting closer to 'well to do' lifestyles. These segments of society are not only satisfied with enough food and clothes, but also are willing to obtain a quality life of high nutrient food, comfortable livings, health care, and other quality services.

At the same time one could also witness a gradual transformation of China's economic structure of a shifting dominance from agriculture to growing shares of industrial and service sectors, along with the availability of a wider range of products the consumption patterns changed. By 2003, the second and tertiary industries contributed approximately 85% of the national GDP (Guan and Hubacek 2004). However many of China's industries are still characterised as labour- and resources-intensive. Those industries, especially heavy industries were spatially allocated in terms of geo-political reasons and less consideration of natural resource availability.

1.3 Behind the story: competing demand for natural resources

The change of production and consumption patterns directly relates to the allocation and consumption of natural resources. Along with the large-scale industrialisation and urbanisation since 1980, domestic, municipal, and industrial sectors started to compete for the resources, which accelerate the exploitation and exhaustion of the natural resources. From the perspective of energy consumption, the per capita consumption grew from 264.3 kgce[1] in 1965 to 614.4 kgce in 1980, and further increased to 1707.9 kgce in 2005 which was 6.5 times more than 1965's level (Guan and Hubacek 2004). The tale of self-sufficient energy supply has been broken in 1993. Until 2005, 40% of China's energy consumption is supplied by foreign importers.

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[1] kgce: kilogram coal equivalent

Furthermore, the categories of residential energy consumption has been transforming from cheap but less efficient biomass fuels to more commercial energy (e.g. coal, oil & gas). In fact, China's rapid industrialisation was built upon high intensive energy consumption. China is trying to escape from that and to move towards more efficient energy production and consumption (Peters et al. 2007).

A similar situation can be found with regards to water resources, it is already considered as the most critical natural resource in the regions of China in terms of the low availability of per capita volume, 2,300 m^3, about 1/3 of the world average value. During the 1990s, in every year, on average 26.6 million hectares of land experienced drought (Wiberg 2003). The water shortage was 30 billion m^3 in irrigation areas and 6 billion m^3 in the cities (Wiberg 2003). Along with the large-scale industrialisation and urbanisation since the early 1980s, domestic, municipal, and industrial water consumption joined the competition for limited water resources, which accelerates the exploitation and exhaustion of water resources (Hubacek and Sun 2001).

A growing part of the population lives in cities and together with large-scale industries infringes on the best agricultural land, which lies on the plains in the eastern part of the country (Wiberg 2002). About half of China's population lives on about one third of the country along the coastal areas and Eastern part of the country. At the same time China's water resources are unevenly distributed as well. Generally speaking, the South is rich in water while the North is short in supply. North China has only about 20% of total water resources in China, which results in the per capita water availability in North China of as little as 225 m^3 (less than 1000 m^3 per capita is considered water scarce), 1/10 of the national level and 1/25 of the world average (Hubacek et al. 2007). Furthermore, there are seasonal variations of water resources and inter-annual disparities with frequent flood and drought disasters.

Furthermore, the quality of the water is degraded due to the large-scale industrialisation and urbanisation, which further burdens the ability of water supply. Water is contaminated by untreated residential and industrial waste, leakages from outdated waste-treatment systems, and due to increasing uses of agricultural fertilizers and pesticides. About 80% of the wastewater is untreated. The concentrations of water pollutants are among the highest in the world, causing damage to human health and lost agricultural productivity (Ministry of Water Resources 1998). The severe pollution and water shortages have become one of the bottlenecks for economic development of some of the regional economies (Guan and Hubacek 2007).

In terms of water consumption patterns, its allocation has been shifting from traditional agricultural irrigation to larger shares for industrial and domestic uses. However, agriculture is still the main consumer in water consumption, although its total consumption fell from 97% to 69% during the last 50 years. Industrial and domestic users raised their shares from 2% to 21% and 1% to 10%, respectively (Hubacek et al. 2007).

1.4 Assessing structural change with input-output analysis

Economists have become increasingly aware of the interactions between economic activities and natural environment in their theorising and model building. Input-output analysis is one of the most effective tools to model flows between the two systems. An input-output table demonstrates a detailed flow of goods and services between producers and consumers and the intermediate linkages (inter-industry analysis) between all producing sectors in a given year. Input-output analysis has been developed and applied in many countries as a policy tool to quantify the mutual interrelationships among their production and consumption sectors of economic systems, which was developed by Wassily Leontief in the late 1930s. He was awarded the Nobel Prize in Economics in 1973 due to his contribution for the development of the input-output model. Since the 1960s, many western countries have started to produce input-output tables on a regular basis to research their economic structural changes. China commenced to create input-output tables at the end of the 1970s. China edited three trial versions for 1976, 1981 and 1985. But the first national table with 117 production sectors for 1987 was published in April 1991. Since then, China officially publishes comprehensive benchmark input-output tables once every five years with more than 110 sectors; and during the five years, China published an extended input-output table in years with last digit being '0' or '5', with less than 40 sectors. The latest table was released in September 2006 for year 2002 with 124 sectors.

Over the past few decades, the input-output model has been extended and applied in many environment studies to quantify the environmental impacts caused by economic growth (Leontief and Ford 1972; Victor 1972; Chen 1973; Forsund 1985; Duchin et al. 1993; Marcotullio et al. 2005; Peters and Hertwich 2006), as well as estimating future environmental challenges (e.g. Duchin and Lange 1994; Hubacek and Sun 2000, 2001, 2005). This research is designed to further develop various approaches of input-output analysis and apply these to the Chinese economy in order to investigate the impacts of economic structural transitions and people lifestyles changes to water and energy resources and their related emissions. This thesis's input-output discussion is based on (comparative) static input-output analysis.

1.5 Research purpose and objectives

This research aims to investigate the driving forces of natural resources exhaustion and environmental degradations using China as a case study. China has been engaging in large-scale economic 'experiments' (e.g. establishing special economic development zones) and structural economic and social transformations at great costs for its environment. By doing so, many other countries in the "south" could learn from the experiences from both past western and current Chinese developments to leapfrog to a more sustainable development. The specific objectives of this research are:

- Providing a historical review starting in 1949 on China's economic development, and describing people's lifestyle changes and its influences on water and energy consumption (Chapter 2).
- Describing the evolvements of input-output analysis and its variations and applications to environmental studies (Chapter 3).
- Developing a hydro-economic accounting framework to investigate the interactions between economic production and the hydro-ecosystem (Chapter 4).
- Introducing and further developing the concept of virtual water flows with critical discussion on international trade theory and its applications to regional trade in China by adopting and further developing a hydro-economic accounting framework (Chapter 5).
- Incorporating the *IPAT* model into structural decomposition analysis to assess the changes in CO_2 emissions triggered by population growth, lifestyle changes, economic structure transitions and technology improvements (Chapter 6).

1.6 Thesis outline

The document has been divided into seven chapters. Chapter 2 provides the background of this research, which gives an overview of the past 50 years of China's economic development influenced by policies, people's lifestyle changes, and shows their influences on water and energy consumption. Chapter 3 is a literature review chapter on input-output analysis, which comprehensively explores the developments of input-output techniques and the applications to water and energy research, especially with regards to China. Furthermore, section 3.3.2 discusses the evolvement of the economic-ecological model which provides the background for development of the hydro-economic water accounting framework in Chapter 4. Section 3.3.6 discusses the applications of input-output techniques in China which partly serves the needs of Chapter 5's research on virtual water flows in China. Section 3.3.7 explains the linkage between *IPAT* and structural decomposition analysis, which paves the roads for the construction of IPAT-IO SDA in Chapter 6.

Chapters 4 – 7 are the results sections. Each chapter discusses a separate topic with specific method section based on various input-output techniques, application of the respective approach, followed by discussion of results and conclusions.

Chapter 4 develops a hydro-economic accounting framework by combing economic-ecological input-output technique with a mass balanced hydrological model to evaluate the impacts of economic production to hydro-ecosystems.

Chapter 5 uses this hydro-economic accounting framework developed in Chapter 4 to assess China's regional "virtual water flows" via trade flows with critical discussion on international trade theories.

Chapter 6 presents a new methodological approach to establish the structural decomposition analysis by incorporating the *IPAT* model into the input-output framework; and further applies the framework to eight consecutive Chinese national input-output tables with 18 sectors, covering the years from 1981 to 2002 represented in constant producers' prices, to investigate the main drivers of energy consumption and related CO_2 emissions. At the end of this chapter, the author sets up a simple experiment to investigate what level of technology China would require by continuing the race with consumption growth.

Chapter 7 summarises the main findings and lessons from the above case studies with policy recommendations on sustainable consumption in a developing country's context.

Chapter 2: A Co-Evolution of Production Possibilities and Consumption Patterns[2]

This chapter gives an overview of changing lifestyles influenced by different policies over more than 5 decades of China's volatile development, then picks a few key areas such as diet, housing, education, water and energy consumption to exemplify these changes and discuss some of their causes. In particular, this chapter is designed to

1. investigate how changing policy foci directed economic development and resource allocation;
2. describe lifestyle changes under different stages of economic development with special consideration of urban – rural disparities.
3. generate historical trends for domestic resource consumption along with lifestyle changes, particularly for energy and water consumption.

This chapter uses general statistics to describe people's lifestyle changes starting at procommunist China of 1949 until today 2005 and environmental implications are exemplified through energy and water consumption statistics.

2.1 A brief review of pre –1949: rich versus poor: lavish lifestyles contrasted by plain survival

Before 1949, most parts of China were experiencing unrest and turbulence due to warfare. Over 80% of the total population lived in rural areas. They were engaged in traditional agricultural production.

In rural China, 91% of villagers (peasants) lived on rented land from rural feudal lords (Yang 1986). More than half of the surplus products produced were used to pay

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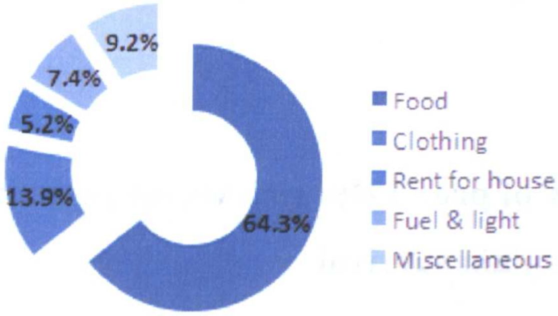
[2] Some results of Chapter 2 have been published in *Futures: The Journal of Policy, Planning, and Futures Studies*, entitled "Changing Lifestyles and Consumption Patterns in Developing Countries: A Scenario Analysis in China and India" (Hubacek et al. 2007). Other parts of Chapter 2 are part of a submission to *Energy Policy* co-authored with Feng, K and K. Hubacek. In addition, the results of this chapter have been presented in *International Workshop on Driving Forces for and Barriers to Sustainable Consumption*. 05 -06, March 2004. Leeds, UK

extremely high rents and loan interests to the landlords (Gabriel 1998). Therefore, there were two completely different lifestyles in rural China. Peasants worked hard for the whole year and produced the agricultural outputs, but they were living under dire poverty and struggling to feed themselves. The daily diet structure for peasants was coarse bran with cheap vegetables, and meat consumption the exception. In contrast, the feudal lords obtained a large income mainly from rents and loan interests. Their lifestyle was much more lavish than the peasants'.

In urban areas, the first industrialisation took place around 1842 after the Opium War when western capitalists encroached the land to build factories and drove the original small economy bankrupt (Lu 2003). As a result, urban workers had to be employed in capitalist enterprises, for which they received little wages but worked over 12 hours per day. Although the some artisans could work independently, the products could only be sold to the large-scale merchants with price setting power (Gabriel 1998). Consequently, they also received unfair payments. For most urban residents, their lifestyles were as plain as for the rural peasants. Figure 2.1 clearly describes the 'starvation' throughout China demonstrating that the majority of income (e.g. 88.2%) was spent on staple food and clothing simply for survival.

Figure 2.1The consumption pattern of Chinese people prior to 1949



Data source: (Yang 1986)

Generally speaking, people's demands on natural resources were very basic. However, the category of resource consumption was much different in terms of the income classes of the populations. The rural landlords and urban capitalists were living in luxury houses with heating supplied by burning coal and firewood; some even had electricity for lighting, however, this was only available for a very small part of the total population (Guan and Hubacek 2004). Most Chinese just acquired free or cheap resources for their livelihoods; water was only for drinking and cooking, stalks were the main source for heating and cooking, and kerosene was the only commercial energy for lighting (Guan and Hubacek 2004).

2.2 Beginning of communism (1949-1957): recovery of the economy and improving lifestyles

The premier task after the New China was established was to recover from the damage done during the war and to generate new economic development. Due to geopolitical reasons, China created a Soviet-style 'Socialist Planning System' giving priority to heavy industry development in cities.

2.2.1 Planning economy and stimulating productivity

Under the socialist planning system, the central government planned the quantities of output command and allocated resources and materials. Public ownership of "Means of Production" is a significant characteristic of this kind of planning economics. The huge income disparities of the feudal era were drastically reduced during this time period.

In rural China, the redistribution of land[3] effectively stimulated China's agricultural aggregate output that increased by 25% in real terms from 1952 to 1957, and with it grew the income and the consumption of peasants (State Statistical Bureau of China 1982).

In cities, the central government redistributed the unequal regional development from coastal to interior areas which were closer in proximity to raw materials and energy resources. This stimulated industrial productivity and worker's motivations to produce increasing outputs. Even though industry made remarkable efforts on urban constructions, the industrial sector only contributed 7% of annual GDP on average as compared to the primary sector, which produced 74% of GDP (Demurger 2001). However, 90% of China's capital was concentrated in the urban industrialisation, which foreshadowed the significant economic developments in cities.

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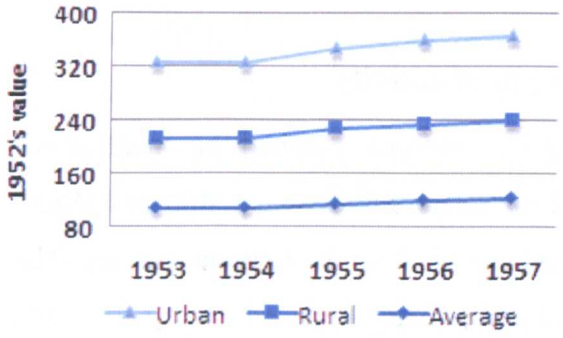
[3] Land Reform of 1950 was implemented throughout China's rural areas, which demolished the old rural landlord system and replaced by a self-exploiting direct production system, which was completed in 1952 (Gabriel 1998)

2.2.2 Steady improvement of people's living situation

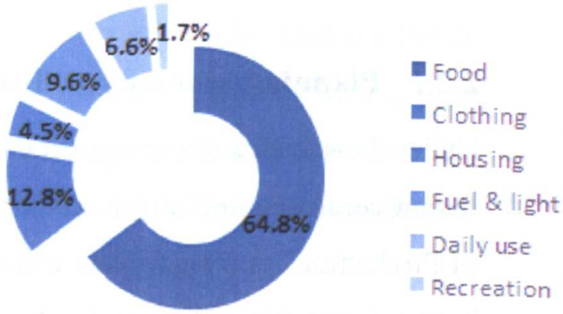
The effective beginning of 'new' China's economic development contributed to the growth of people's net income levels. Figure 2.2 shows people's annual consumption expenditures increased by 2.3% in countryside and 3.2% in cites respectively. Those increases led to some improvements and poverty reduction. The figure of poverty population decreased from 71.9% prior to 1950 to 64.4% by the end of the 1950s (Hu 2003). From the perspective of people's consumption pattern during the first *Five Year Plan (FYP)*, food and cloth still dominated the majority of people's income as shown in Figure 2.3., and one can see that there was no significant difference between urban and rural lifestyles.

Figure 2.2: Residents' consumption levels in 1950s



Data source: (State Statistical Bureau of China 1987)

Figure 2.3: Peasant's consumption pattern in 1957



Data source: (Yang 1986)

In terms of food consumption, people's dietary structure changed from surviving to increasing consumption of higher quality and more diverse food products such as pork, fruits, milk products and eggs; the total calorie intake and material consumption grew rapidly, for example, grain consumption increased by more than three times and cloth consumption more than doubled (Table 2.1).

Table 2.1: Per capita consumption of selected goods

	Grain (kg)	Pork (kg)	Fresh Eggs (kg)	Cloth (piece)
Pro-1949[4]	61.0	2.0	0.2	3.2
1957	203.0	5.1	1.3	6.8

Data Source: (Yang 1986)

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[4] The data of pro-1949 was estimated by Yang (1986)

Housing was another important category establishing significant differences between urban and rural lifestyles. Although the types of houses were similar (bungalows), urban residents enjoyed their houses, as 'welfare benefits'[5] while rural peasants had to pay for the houses by themselves (Taylor 1996).

2.2.3 Biomass for villagers, coal for city dwellers

There was a substantial difference in residential energy consumption pattern between urban and rural households. Urban residential energy was more commercial energy based, while biomass fuels dominated energy consumption in villages, accounting 86% of the total household energy usage (State Statistical Bureau of China 1982). For example, coal and firewood were purchased for cooking and heating in cities, in contrast crop residues and stalks were used in rural cooking and heating because this was free and convenient to acquire. In addition, about 90% of Chinese cities had been provided with electricity for residential lighting by the end of 1950s (Luo 1998), while most rural people still kept the traditional way for lighting by using candles and kerosene[6].

2.2.4 Queuing for wells

China's water withdrawal was mainly used for agricultural irrigation, which accounted for 97.1% of the total water consumption in 1949. The amount of industry water consumption increased four times from 2.4 billion m^3 in 1949 to 9.6 billion m^3 in 1957, as shown in Table 2.2, because of the large-scale industrial developments in urban China during the first Five Year Plan (FYP) (Ministry of Water Resources of China 2000). Meanwhile, per capita residential water usage for urban households slowly increased from 28.5 to 38.4 litres per day[7]. The main reason was that most people still got their water from a source near their home for daily drinking, cooking and washing in rural China. Showering or bathing were rare activities for Chinese people at that time. This was different to urban China as the infrastructure of the water

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[5] Housing commercialization was restricted at that time. The houses were provided by government or State-owned employer and came as a part of their jobs.

[6] The governmental provided 1kg kerosene for each rural household per year for lighting (Zheng 1998).

[7] The figures were calculated based on the data provided by Ministry of Water Resources of China (1999) by the author.

supply system was quickly expanded in order to ensure the industrial output during the first FYP. The urban water supply system only covered 60 cities prior to 1949, and expanded to more than 150 cities by the end of 1950s, which created great gap of residential water usage between urban and rural China.

Table 2.2: Water use in China 1949 – 1957

	1949		**1957**	
	billon m^3	percentage	billon m^3	percentage
Agriculture	100.1	97.1%	193.8	94.6%
Industry	2.4	2.3%	9.6	4.7%
Domestic	0.6	0.6%	14	0.7%
Total	**103.1**	**100%**	**204.8**	**100%**

Data source: (Ministry of Water Resources of China 1999, 2000)

2.3 A tumultuous period: political conflicts and economic stagnation: 1958-1978

Economic recovery stopped in the following years. Instead, the radical left took possession of governmental politics and their ideas quickly spread to all areas of social and economic life.

2.3.1 A crash industrialisation program - 'Great Leap Forward':1958 – 1960

In early 1958, Mao called on China to 'walk on two legs', which further emphasised the importance of heavy industry, especially iron and steel productions (Lu 2003). Thousands of small steel-making furnaces were set up in rural China[8] throughout the country in response to Mao's call of 'steel as the key link'. Ironically, 90% of these types of steel products could not be utilised and had to be remelted which obviously resulted in am extreme low energy efficiency[9]. As a significant number of peasants switched to industrial production, particularly to steel production, natural disasters

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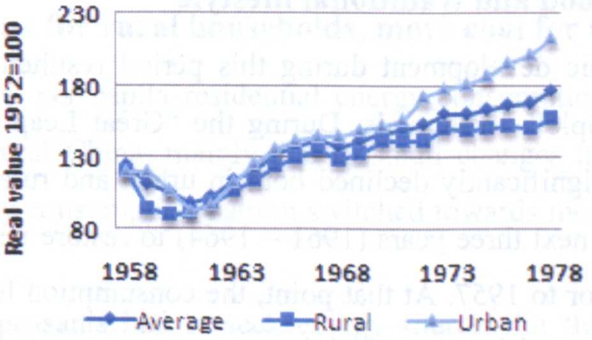
[8] The household registration system was implemented to ensure the control of steel outputs. Households were the basic unit of producer communities.

[9] The annual growth rate of energy consumption was 26.7% during the Great Leap Forward period, but the annual average change of GDP growth was -2.0% (State Statistical Bureau of China 1987).

resulted in the dramatic decreases of agricultural output causing serious starvation for large parts of the population in the early 1960s.

The decline in GDP directly influenced people's livelihoods. As shown in Figure 2.4, the average value of consumption level decreased from 125 Yuan in 1958 to 104 Yuan in 1962, the value reached the lowest point of 99.4 Yuan in 1961, which completely negated the economic efforts during the first FYP (State Statistical Bureau of China 1987).

Figure 2.4: People's consumption level 1958-1978



Data source: (State Statistical Bureau of China 1982, 1987)

2.3.2 Economic disaster – "Cultural Revolution": 1966 – 1976

Although the failure of the Great Leap Forward was disastrous, Mao still believed leftist politics could be used to achieve a circumstance of equalitarianism in China's society. By contrast, Liu Shaoqi and Deng Xiaoping believed that the socialist society had to be built based on a sound economic base. They believed that some income inequality is a product of an effective economic development, which should be reduced to acceptable levels but not minimised or annihilated. Due to the inconsistency in political opinions, Mao launched the 'Cultural Revolution' against any kind of Western or capitalist ideology. The government concentrated all their energy in large-scale political movements; China's economy reached the brink of collapse at the end of the 1960s. The annual growth rate of GDP per capita declined for two years by -5.7% in 1967 and -4.1% in 1968 respectively (State Statistical Bureau of China 1987).

The radical movement almost ended in 1972. Chinese government returned to normal and started to re-construct the national economy under the national work plan of 'increasing equipment imports and enlarging economic exchange' (Lu 2003), which resulted in a 2.7% annual growth rate of GDP per capita from 1970 – 1978.

During these 20 years, China's population grew by 50% from 660 million in 1958 to 963 million in 1978 putting further strain on the already limited resources (State Statistical Bureau of China 2000). The average annual growth rate of GDP per capita was 3.2% over the two decades while other Asian countries (i.e. Japan) were developing fast with economic growth rates of about 8% (Guan and Hubacek 2004).

2.3.3 Basic livelihood and traditional lifestyle

The devious economic development during this period resulted in a stagnation of improvements in people's livelihoods. During the "Great Leap Forward", people's consumption levels significantly declined both in urban and rural China. Therefore, China had to use the next three years (1961 – 1964) to restore people's consumption standard to levels prior to 1957. At that point, the consumption level started to grow again; the 20 year period following 1966 the average consumption growth rates were 2.9% in cities and only 1.37% in rural areas. Table 2.3 illustrates the consumption pattern of Chinese peasants; food and cloth still dominated the majority of people's consumption expenditures without any notable changes in other consumption categories, which at least demonstrated that peasant's lifestyles were the same as usual. Meanwhile, many urban residents escaped from poverty and shifted to fairly 'adequate levels of food and clothing' (Lu 2003).

During these 20 years, the policies were designed to fight against everything that could be related to Western- or 'capitalist' links. The government prohibited Western influences from flowing into China. Therefore, people had no opportunity to realise how huge the differences were between themselves and Western people. Many Chinese thought their lifestyles had been dramatically improved compared to the standard prior to 1949. Moreover, they were not motivated to further change because all the other people had the same.

Table 2.3: Peasants' expenditure categories (1957 – 1978)

Years	Food	Clothing	Fuel	Daily use	Recreation	Housing	Total expenses
1957	67.8%	13.4%	10.0%	6.9%	1.7%	2.1%	100
1963	63.3%	11.2%	9.3%	8.8%	2.7%	4.7%	100
1965	68.5%	10.5%	8.3%	7.2%	2.7%	2.8%	100
1978	67.8%	12.7%	7.1%	6.6%	2.7%	3.2%	100

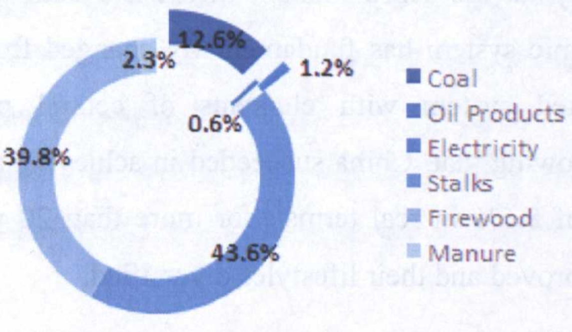
Data Source: (State Statistical Bureau of China 1987), (Yang 1986)

2.3.4 Less biomass for rural households, more coal for urban residents,

During the 20 years, per capita residential energy consumption barely increased in neither urban nor rural China, mainly due to small changes in people's life styles. However, the energy consumption pattern switched towards more commercial energy sources.

Before the 1970s, peasants had to seek energy sources for their residential use by themselves because rural energy infrastructure constructions were excluded from the national plan. Until 1975, the government allowed small local coalmines to be developed to meet peasants' increasing residential energy demands, which resulted in rapid increase of coal consumption in rural areas, from 9.73 in 1965 to 95 million tons in 1978 (Zheng 1998). However, many peasants were still struggling against poverty, and preferred to save for better food and clothes rather than buy fuels (e.g. coal). Therefore, biomass fuels still occupied 85% of total rural energy consumption, but some commercial energy started to be consumed as shown in Figure 2.5.

Figure 2.5: Rural residential energy consumption pattern prior to 1978



***Data source**: China's Rural Statistics Yearbook, 2000*

Cities were granted favourable policies in construction of energy infrastructure. Prioritising all resources to cities provided sufficient energy to industries and also to cities dwellers. Each urban resident consumed 774 kgce[10] commercial energy per year (70% was coal for heating and cooking), which was about 6 times more than rural people (Pan 2002). By 1978, electricity became a popular energy source for lighting in 90% of urban households while peasants generally were still using kerosene lights.

2.3.5 Wells in rural China but tap water in urban China

Similarly, the development of water infrastructure did not happen in rural China. People had to acquire their living water from wells, which did not allow for significant increases in rural household's water consumption.

By contrast, per capita residential water consumption in cities grew at an outstanding rate of 4.7% annually during those 20 years due to the tap water system being established for almost 90% of the cities. By 1980, the per capita residential water usage for urban households was 97.3 litres per day (Ministry of Water Resources of China 1999). The figure includes the daily usage (e.g. cooking, drinking and washing), and other regular activities, such as horticultures and showering and bathing in public bathing places.

2.4 A stirring period: new policies, booming economy and diversifying lifestyles since 1980

In December 1978, Deng Xiaoping launched the economic reforms and established the 'open-door policy' at the Third Plenum of the Eleventh Party Congress. Since then, China's economic system has fundamentally changed from a central planning economy to a mixed system with elements of central planning and market mechanisms. By following that, China succeeded in achieving an annual growth rate of GDP per capita of 8.6% in real terms[11] for more than 20 years. People's living standards rapidly improved and their lifestyles diversified.

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[10] kgce: kilogram coal equivalent.

[11] The GDP per capita is calculated at 1995 constant prices. Tibet and Hainan was not included due to missing data for GDP components. The data source is (State Statistical Bureau of China 2002).

2.4.1 Deng's "open-door" policy

In rural China, the government decided to change rural agricultural policies in 1978 to guarantee higher levels of agricultural output. The '*Household Responsibility System*' was therefore established throughout the country. Under this system, peasants could independently arrange, produce and sell their products, which effectively stimulated peasants' motivations and responsibility and was enthusiastically accepted. As a result, agricultural outputs grew to almost four times the pre-reform level by 1997 while productivity increased 1.5 times during the same period (Fan 2002).

Another important government activity in rural China was the opening up of the rural economy. The rural enterprises have therefore been dramatically developed during the past two decades. In the early 1980s, employment in the agricultural sector accounted for 97% of total rural labour, but this figure declined to 60% in 2005 (State Statistical Bureau of China 2006), which is still a considerable share. The new rural economic structure led to a growth in peasants' net income from 133 Yuan in 1978 to 521 Yuan in 2005 in 1978's price; the annual growth rate was 5.2% in real terms (State Statistical Bureau of China 2006).

In cities, the real reform did not actually start until the end of 1984 (Hu 2003). The central government granted more autonomy to local authorities, which formed the basis for domestic competition between provinces (Hu 2003). The direct consequence from this competitive mechanism was an increase in industrial productivity resulting in rapid GDP growth. In addition, China started to intensively attract foreign direct investments and an increasing share of international trade relationships since the early 1990s, which not only made a significant contribution to China's economic growth but also brought advanced technology and management systems to Chinese enterprises (Fan 2002). Consequently, city dwellers' net income increased as an annual growth rate of 6.2%. By 2005, the average income for each urban resident was 10,493 Yuan in absolute price and 1727 Yuan in 1978's price, three times more than peasant's level. People did not only settle for sufficient food any more; and started to purchase high-quality goods and adopted more diverse lifestyles.

2.4.2 Rapid consumption growth

Figure 2.6 and 2.7 illustrate the changes of consumption pattern from 1980 to 2005 for the average rural and urban residents respectively. All the numbers in both figures are in 1978 prices. The proportion of expenditures on food and cloth steadily decreased while the proportion of other items' increased. The figures for food, housing, education expenditures, and water and energy expenditures significantly changed; therefore those indicators are selected to reveal people's lifestyle changes since the early 1980s.

Figure 2.6: Rural consumption expenditure patterns

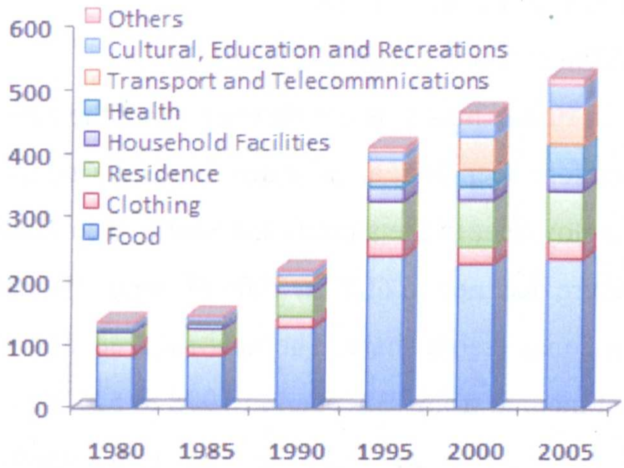
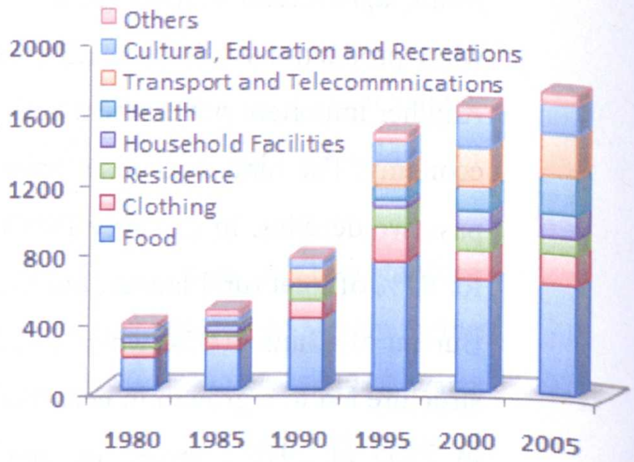


Figure 2.7: Urban consumption expenditure patterns



Data source: (State Statistical Bureau of China 1986, 1994, 2002, 2006)

2.4.2.1 Diet change:

Although food and cloth still dominated people's expenditure both in urban and rural areas, the share has been progressively decreasing since 1978 (see Figure 2.6&2.7). From the perspective of food structure, people's diet contained more meat and nutritious food (e.g. eggs and aquatic products), but less cereal products. Figure 2.8 illustrates the decline of grain consumption in both rural but mainly in urban China in recent 10 years. The decline of grain consumption does not mean the total calorie intake decreased, but rather that one can observe a switch to more diverse diets with higher share of meat, fish, fruits, etc.

In fact, there is a substantial gap in the consumption patterns of urban and rural consumers due to the inequality of income levels. For example, per capita grain consumption in 2005 by rural households (209 kg) was almost treble that by urban households (77 kg). Meanwhile, urban per capita consumption of pork, red meat, poultry, eggs and aquatic products were much greater than rural consumption, as showed in Figure 2.10 and 2.11. But the saturation of the pork market in urban China is narrowing this gap between urban and rural pork consumption (Wu 2003).

The significant increase of availability of meat and other dairy products boosted the development of livestock production, and other agricultural products (Hubacek and Sun 2001). As a result, diversified agriculture emerged in rural China, as many peasants shifted from the traditional agriculture of crop cultivation to more commercial agriculture. As Figure 2.9 shows, the share of livestock output almost doubled from 16% to 30% in 1970 – 2000. The fishery production even grew at a higher rate. One of the outstanding features in the changes of agricultural structure is that the share of grain drastically declined from 78% to 50% (Gale 2002). Along with the emergence of diversified food and changing demand, the industry of food processing and manufacturing has been flourishing since the reform.

Figure 2.8: Grain consumption 1978-2005

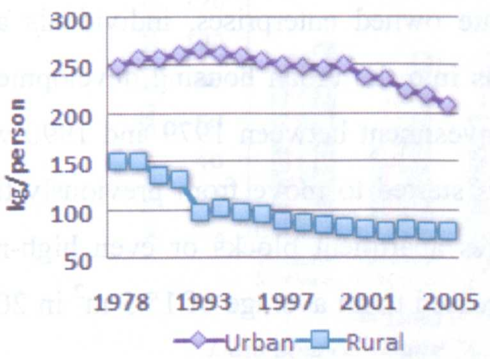
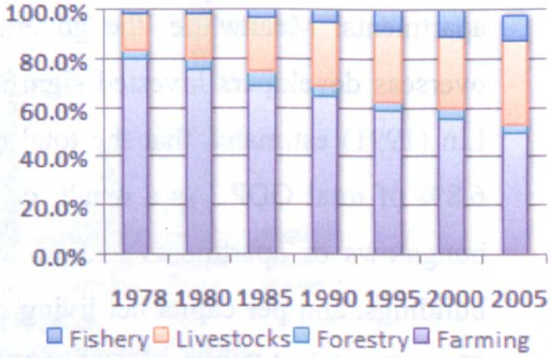


Figure 2.9: Share in agricultural output



Data source: (State Statistical Bureau of China 1997, 2001, 2006)

Figure 2.10: Rural non-cereal consumption

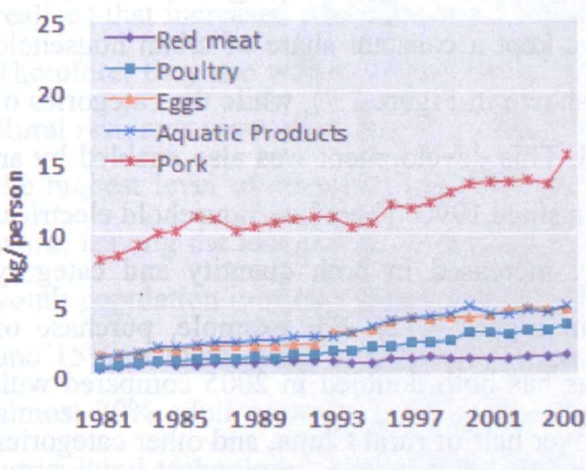
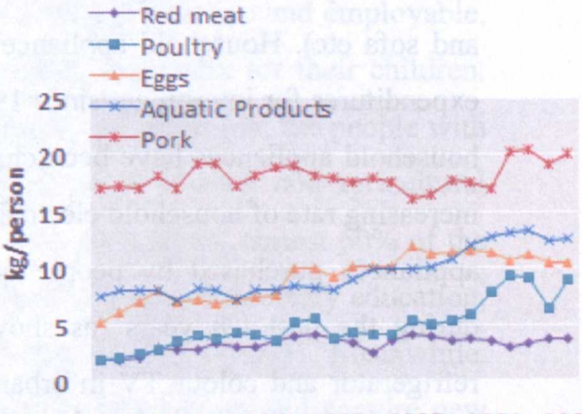


Figure 2.11: Urban non-cereal consumption



Data source: (State Statistical Bureau of China 1997, 2001, 2006)

2.4.2.2 Housing and household appliances

The outstanding increase of expenditure on housing during the time period from 1978 to 1990 both for rural and urban households (as shown in Figure 2.6 & 2.7) could reveal people's *willingness* to improve their living conditions. Many rural households rebuilt and extended their bungalows by using building materials of concrete bricks and tiles instead of marl and wood. At the same time, per capita living space expanded from 8.1 m^2 to 24.2 m^2, and the lifespan of houses extended by more than 20 years (State Statistical Bureau of China 2002).

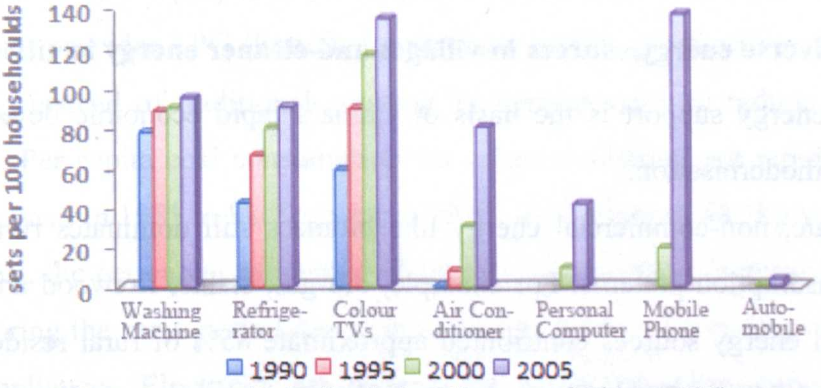
In urban China, the problem of housing shortage was much more serious than in rural areas. The per capita net living space for urban residents was only 3.6 m^2 prior to 1978, mainly because of restrictions on private house ownership. Cities dwellers urged the development of housing. Since 1981, the Housing Reform Policy was introduced to solve the problems of urban housing shortages and poor housing conditions. This policy encouraged private ownership and people buying their own apartments. Meanwhile, the government, state owned enterprises, individuals and overseas developers invested significant funds into the urban housing development. Lin (1991) estimated that the total housing investment between 1979 and 1990 was 6.8% of total GDP. As a result, city dwellers started to move from previously tiny bungalows or apartments to new Multi-stories apartment blocks or even high-rise buildings, and per capita net living space increased to an average of 15.5 m^2 in 2001 (State Statistical Bureau of China 2002).

People settled in more spacious living places that allowed them to shift their attention to household appliances and other durable goods. For example, since the 1980s, urban residents spent increasing amounts on large durable furniture (e.g. wardrobes, beds and sofa etc). Household appliances have kept a constant share of urban household expenditures for investment since 1985 (shown in Figure 2.7), while the categories of household appliances have been changed. This development was also enabled by an increasing rate of household electrification since 1990. Therefore, household electrical appliances purchased by people quickly increased in both quantity and category during the past ten years (as showed in Figure 2.12). For example, purchase of refrigerator and colour TV in urban areas has both doubled in 2005 compared with 1990. Colour TVs have already covered over half of rural China, and other categories of electric appliances have also rapidly spread through China.

Similarly, the latest consumer items such as air conditioners, personal computer, mobile phones and automobile, were previously the sign of the wealthy, increased significantly as well. Air-conditioners and personal computers have become essential household items for many families. Mobile phones are popularised in urban China; every household had on average 1.37 sets in 2005 (State Statistical Bureau of China 2006). The dream of owning a car is a reality for only a few households but it is still a far away goal to the mid/low income households.

The changes in consumption structure find also reflection in the production structure. For example, the popularisation of household electrification dramatically boosted household appliances industries. The electronic industry has become the largest industry in China, which contributed about 8-10% of GDP, and 30% of export profits (State Statistical Bureau of China 2006).

Figure 2.12: Urban Household Appliances



Data source: (State Statistical Bureau of China 2006)

2.4.2.3 Education

With the unfolding of the reforms and liberalisation, more and more peasants have realised that increased education would make them more productive and employable. Therefore, they are willing to pay more for education, especially for their children. Rural residents view schooling as a means to migrate to an urban job; the people with the highest level of education and skill are the most likely to enter non-agricultural work, leaving the less skilled in farming (Gale 2002). As a result, almost 60% of the youth population in rural China could complete the nine years compulsory education, and 15% of them could be sent to colleges for further studies by 2001. Meanwhile, almost 20% adult peasants joined part-time courses to learn about and acquire new agricultural technology. Although the above figures are not outstanding, it is pleasing to see the transformation of turning peasants into modern peasants, which speeds up the commercialisation and modernisation in rural China.

In cities, people's ideology is progressively opening up to the West as they admit to and try to reduce the disparity between themselves and Western lifestyles. It not only shows in spending on general living conditions, but also in the gradually increasing investment in education and medical care. 'Go abroad to study or work' for the youth generation (age: 19-36)[12] has become a popular topic in urban China today. The total number of overseas people dramatically increased in the past couple of years. For example in 1978, only 860 people, most of which were sponsored by government went abroad to study or work, the figure leaped to 84.0 thousand in 2000, and doubled again in 2001. By 2005, the total amount reached 118.5 thousand, 93% of them financed by themselves (State Statistical Bureau of China 2006). Although 'Go abroad' could not happen to everyone, it accelerates the process of people's realisation of the West, and stimulates urban households to further aspire "Western" lifestyles.

2.4.2.4 Diverse energy sources in villages and cleaner energy in cities

Adequate energy support is the basis of China's rapid economic development and household modernisation.

Even to date, non-commercial energy like biomass still dominates rural residential energy consumption patterns. For example, bio-gas, stalks, firewood and other non-commercial energy sources contributed approximate 85% of rural residential energy in 1980, and 74% in 2004. The overuse of biomass energy caused problems such as land degradation of cultivated land and forest resources. Since the policy of biomass energy conservation and forestation were established in the middle of the 1990s, the absolute amount of biomass energy consumption has fallen from 250 Mtce[13] in 1995 to around 200 Mtce in 2000. However, the total amount of residential energy is continuously growing, with major increases from commercial sources. The total amount of commercial energy consumption grew remarkably by 3.6 times, from 41 Mtce in 1980 to 198 Mtce in 2005. Therefore, it is interesting to note that commercial energy for rural residential uses seems to gradually replace biomass energy and become the major energy source in the future. Coal consumption shows a descending tendency after 1988, which demonstrates that coal is no longer the favourite source for rural household daily use. In addition, the government encouraged people to use fuel-saving stoves to replace the traditional ones since 1986. The fuel-saving stoves could increase the thermal efficiency by 25% - 30% (Zheng 1998), as contributes to a

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[12] These are either self-supported or supported by their parents/relatives.

[13] Mtce: Million tons coal equivalent

reduction of coal consumption. By the end of 1997, the fuel-saving stoves had been installed in 180 million rural households, which accounted for 89% of rural households (Wang 1998).

The improvement of urban people's living conditions significantly changed urban residential energy consumption pattern. In terms of heating, most urban areas still keep the traditional way of heating by burning coal[14]. The increase of per capita net living space is likely to result in more coal being consumed. However, the previous type of individual heating has been switched to large-scale central heating as people moved from bungalows to apartment blocks, which effectively enhanced energy efficiency. Furthermore, many rich cites (e.g. Beijing) have introduced the 'home heat control system' of heat supply to allow individual regulation of the heat. Furthermore, the government provides LPG (liquefied petroleum gas) or gas pipelines for people's daily cooking instead of traditional cooking by burning coal, to reduce urban coal consumption. Per capita coal consumption for urban residential use rapidly declined from 348.5kg/year in 1985 to 88.2kg/year in 1999, and further to 48.1kg/year by 2004. But in contrast, the per capita residential electricity consumption increased more than four times during the same period due to increased purchase of a variety of electronic household appliances. Electricity has become the dominant energy consumed in all Chinese cities, accounting for 59% of the whole household energy consumption (State Statistical Bureau of China 2001).

2.4.2.5 Water reform in villages, potential scarcity in cities

Reflecting changes in lifestyles, also residential demand for water has significantly grown since 1978, although it remains a relatively small share of total water consumption, which is 3.8% in cities and 6.8% in the countryside (Ministry of Water Resources 1997)

The per capita water consumption in rural area was 89 litres per day and 244 litres in urban area in 2000. The reason of this noticeable gap is due to the lack of water infrastructure in rural China (especially tap-water supply). Many rural residents still need to extract water from wells. However, this indicates that rural residents would have great potential demand once the infrastructure is constructed. According to the 1997 census of agriculture, only 17% of rural households had access to tap water (USDA 2000). With the increase of peasant's net income level an increasing demand

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[14] Household heating mainly happens to the northern China.

for water related household appliances such as kitchen sinks, washing machines, and shower heads (standard urban amenities) is evident but hard to achieve due to the poor water supply situation. Therefore, the demand for improving rural water infrastructure has progressively increased in recent years. The Chinese government invested 4 billion Yuan in 2000 in order to construct water tap supply systems in rural China, which has already covered 41% of the whole countryside by the end of 2002.

More and more efforts have been made in improving housing conditions in cities. If one compares the present housing design standard with previous ones, now, over 70% of the new apartments have flush toilets, kitchen sinks, showers and other basic facilities, but only 34% of households had flush toilets prior to 1980 (Zhang 2003). Many household appliances such as washing machines, dishwashers, refrigerators and water heaters which were novelties in the early 1980's are now popular among urban households. For each 100 families, 92 had washing machines, 52 had water heaters by 2001 (State Statistical Bureau of China 2002). All those housing improvements contributed to the increase of per capita daily household water consumption from less than 100 litres in 1980 to 244 litres in 2000, with the expectation to be further increased to 280 litres per day by 2010. However, compared with American daily use with some 400 litres per capita, one can see enormous potential for further increases of residential water demand as lifestyles change.

2.5 Conclusion

China's case is an interesting example of how consumption patterns have been changing in a relatively short period of time. A large share of the population (almost 70%) is still living in rural China following rural lifestyles. Often there is no adequate infrastructure to provide for electricity and water and people have to gather their own energy sources and collect their water from wells. The changing of their lifestyles depends on the opportunities provided by income and availability of products and infrastructure. The story of changes in lifestyles in China is still mainly a story of economic development and of catching up with the rest of the world. People mainly in urban areas are closer to a "Western Ideal" in terms of consumption of products and services. Sustainability in consumption is not quite an issue yet. The first goal is to achieve a certain standard before thinking about the environmental side effects.

Environmental destruction in China has reached enormous scales already increasing awareness and pressure on policy makers and production facilities. China has proven to quickly develop from a developing country to an important economic player. Maybe in terms of sustainability one can hope for a similar quick development. Given the size of the economy and China's population one would hope so.

This chapter selected energy and water as environmental indicators to assess change of people's consumption patterns and their direct impacts on natural resources over the past five decades. The following chapters adopt input-output analysis to evaluate the indirect impacts to energy and water resources and their related emissions.

Chapter 3: Input-output Method and Tables

This chapter provides selective literature review on input-output analysis using key articles and examples from the origin of the input-output concept, to the later developments by Wassily Leontief, and more recent applications to environmental studies.

Firstly section 3.1 traces the concept of *production of circular flows* back as early as the 17th century by William Petty and Richard Cantillon, which can be regarded as early conceptualisations of input-output systems designed to portray the relationships of production in the economy. Then the author briefly discusses the *Tableau Économique* developed by François Quesnay in 1750s and Wassily Leontief's later contributions to the input-output method. Secondly section 3.2 describes the structure of basic Leontief's input-output tables and its related mathematical meanings for quantitative analysis. Thirdly section 3.3 introduces several more recent developments based on Leontief's input-output techniques for environmental research, which consists of "environmental extended input-output analysis", "economic-ecological model", Leontief's pollution-abatement model", "hybrid input-output model", "physical input-output model", input-output analysis to water research and finally "structural decomposition analysis on energy issues".

3.1 Origin of input-output analysis

3.1.1 Early contributions

An input-output analysis is an analytical quantitative framework to investigate the complex interdependences within an economy, which was developed by Wassily Leontief in the late 1930s. However during the development, input-output analysis borrowed some economic concepts from the earlier classical political economy such as, *productive interdependences within an economy* (William Petty), *social surplus* (William Petty) and *general equilibrium analysis* (Léon Walras). For example, Leontief (1928) in his PhD dissertation stated that "*Economic analysis should rather* *focus on the concept of circular flow which expresses one of the fundamental 'objective' features of economic life*" (quoted after Kurz et al. 1998). In fact, the other concepts can also be found in much earlier research. William Petty (1662) coined the famous dictum "*Labour is the Father and active principle of Wealth, as Lands are the Mother*" indicated the productive interdependence between different producers in a system characterised by the division of labour and that of normal cost of production. Petty believed the production, distribution and disposal of the wealth of a country are well intertwined, and the problem of value as reflecting the interrelationship among these aspects. Furthermore, Petty (1662) put forward a concept of *social surplus*. He expressed the agricultural surplus as corn output minus necessary corn input, including the subsistence of labourers measured in terms of corn, and identified it with the *rent* of land (quoted after Kurz et al. 1998).

More than a century later, Richard Cantillon was greatly influenced by Petty's work. He put forward a tripartite distribution of products between the proprietors of land, farmers or undertakers, and assistants or mechanics (Cantillon 1755). Moreover, Cantillon (1755) emphasised that all members in the society relied on the basis of the production of land; and he also had a very clear concept of reproduction for the first time (quoted after Kurz et al. 1998).

However, it can hardly conclude that these early researches in the seventeenth and eighteenth century are the origins of systematic economic analysis or input-output analysis.

3.1.2 François Quesnay's tableau économique

François Quesnay, a French economist illustrated a two-sector expression, proposing that the production of commodities relies on commodities, in his publication of "*Tableau Économique*" in 1758. Containing a detailed example, his following publication, named "*Analyse de la formule arithmétique du Tableau Économique de la distribution des dépenses annuelles d'une Nation agricole*", was published in 1766, in the *Journal de l'agriculture, du commerce et des finances*. Marx appraised the *Tableau* "*... an extremely brilliant conception ...*"; (Marx 1956, p.344), quoted after Kurz and Salvadori (2000). The *Tableau* was the foil against which Marx developed his own *schemes of reproduction* (Kurz and Salvadori 2000). Leontief also praised Quesnay's work in his 1936 paper that "*The statistical study presented ... may be best* *defined as an attempt to construct, on the basis of available statistical materials, a Tableau Économique of the United States for 1919 and 1929*" (Leontief 1936, p.105) quoted after Kurz and Salvadori (2000).

The *Tableau Économique* portrays a circulated process of commodities and money between the economic categories of production, distributions and expenditure which is regarded as a reproduction process. The fundamental aim for Quesnay to design the *Tableau* was to trace the origin of national revenue and the other factors which can affect its size – factors which can be manipulated by economic policy aimed at fostering national wealth and power (Kurz et al. 1998).

Quesnay identified two goods (grains and crafts) flows between three distinct classes according to people's different economic role in the reproduction process:

(1) the productive class (farmers and agricultural labourers)

(2) the proprietary class (landlords or other natural resources owners)

(3) the sterile class (artisans and merchants)

The productive class, for example farmers who work in agriculture, usually produces value in commodities that exceeds the cost of production. The difference between total proceeds and total costs by productive class is then distributed to the proprietary class (e.g. landlords) as rent. The sterile class represents the employees who are working in industrial and manufacturing sectors, for example the artisans; however they do not generate a revenue or surplus[15]. The prices of manufactures cover just costs of production, including the means of subsistence of artisans. One of Quesnay's important contributions is that he pointed out the intersectoral flows between economic sectors (Kurz and Salvadori 2000). For example, farmers produce agricultural goods but buy industrial products as means of production, artisans purchase food and raw materials, and the landlords receive money as rent but need to pay for agricultural and industrial goods and so on (Miller and Blair 1985). Both agricultural and industrial commodities enter either directly or indirectly into the production of both commodities. Quesnay emphasised that agriculture could generate surplus, therefore farmers are the productive class, and manufacturing and commerce, on the other hand, were considered unproductive, hence the expressions of Quesnay's 'classe sterile'are non-productive class. However, industry or manufacturing was regarded as productive sectors later by Torrens (1821) and Marx ((1894) 1967).

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[15] Quesnay is a physiocrat who believed that only agriculture can generate a surplus, a *produit net* (Kurz et al. 1998)

However services were always considered with suspicion and referred to as 'luxuries': stated that "*this surplus, or profit of ten per cent, they (i.e. the cultivators and manufacturers) might employ either in setting additional labourers to work, or in purchasing luxuries for immediate enjoyment*" (Torrens 1821).The *Tableau* was very inspirational for many economists especially also in today's discussion of the circular economy and the environmental discussion. On the other hand Quesnay's work had many shortcomings. The *Tableau Économique* did not separate producers and consumers, and the physical flows and monetary flows were mixed in one table, which cannot be operated as a mathematical model to clearly demonstrate the economic flows in the economy (Miller and Blair 1985).

Another important theorist of the time was Karl Marx. He discovered that Quesnay's *Tableau* was not restricted to the problem of quantities and growth: it also provided a much needed *general* framework to determine the general rate of profit consistently (Kurz and Salvadori 2000). This rate of profit was important for his political economic vision. Marx clarified that a "*determination of the rate of profit and relative prices presupposes taking into account the total social capital and its distribution in the different spheres of production*" (Marx (1894) 1967 p.158 and 163), quoted after Kurz and Salvadori (2000). Marx proposed a two-step procedure to determine the rate of profit. Firstly, he specified the general rate of profit as the ratio between the value (e.g. labour) of the economy's surplus product and the value (e.g. labour) of capital, consisting of a constant capital (means of production) and a variable capital (wages). In a second step this (value) rate of profit was then used to calculate prices (Kurz and Salvadori 2000). Karl Marx based his theoretical observations on the value theory of labour. According to his theory of value, labour is the only source of exchange value: Commodities, therefore, in which equal quantities of labour are embodied, or which can be produced in the same time, have equal value.

In addition and often forgotten, he was a serious student of agriculture. He realised that production requires both labour and nature. The labour process for Marx is the transformation of natural resources into objects of utility for humans (Perelman 1979). Both Marx and Quesnay developed important ideas in their theories that reverberated within the economics profession during their time and even until today. Many classical economists in the 19th century believed only labour and/or capital are *the* factor of production but neglected the inputs from the environment (for a discussion see Hubacek and van den Bergh 2006); but other classical theorists such as Marx and

Quesnay were very aware of the role of the environment and elements of their theories can be found in modern ecological economics approaches.

3.1.3 Walrasian general equilibrium theory and input-output analysis

More than a century after Quesnay, another French economist, Léon Walras (1874) developed a theory of general equilibrium in economics. In his model, the economy consists of consumers (residents) who intend to achieve the maximum utilisation and the producers (firms) who maximise the profits. Labours and fixed capitals are provided by residents for firms to produce goods which will be purchased by residents. All the activities can be achieved in markets. Walras utilised a set of productions coefficients that related the quantities of factors required to produce a unit of a particular product to levels of total production of that product (Miller and Blair 1985), which is very similar to the technology coefficients in Leontief's input-output model. In the literature, on input-output analysis, one frequently encounters the view whether Leontief's input-output model is an offspring of Walrasian general equilibrium model. In terms of Kurz and Salvadori (2000), Leontief also stressed at times that the general equilibrium is the theoretical background of input-output analysis, his analysis and that of Walras' are compatible with one another (e.g. Leontief 1941, 1966; Leontief 1986). However, there existing some differences between the two approaches.

Both approaches concerned the mutual interdependence between national income and product [16] (Davar 2005). In Walras' approach this interdependence is directly expressed, i.e., the prices of factors and commodities are adjusted by the change in quantities. This is based on the supply curves of the factors and the demand curves of commodities, assuming that prices are uniform and are measured in monetary terms. The equilibrium equality required two types of price for commodities: the supply (cost of production) and demand (consumption). However Leontief adopted a naturalistic or material point of view to investigate the economy. He focused on "*directly observable basic structural relationships*" (Leontief 1987, p860) and not, like Walras's general equilibrium theory, on utility, demand functions etc., which cannot be directly observed in the economy. In Leontief's input-output approach, this

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[16] The national income is determined as the value of used primary factors (quantities multiplied by their prices) and the national product is determined as the value of demanded commodities (quantities multiplied by their prices).

interdependence is relatively implicitly expressed. Input and output is described in money terms where prices and physical quantities are amalgamated in one magnitude (Davar 2000). In other words, Leontief's input-output model has one uniform measurement, which is in monetary terms. It has to be pointed out that Walras's price distinction between production factors and commodities can reflect better today's economics.

Furthermore Leontief also enriched Walrasian general equilibrium model by adding public sector and exports on in consumption (final demand) side, and taxation and imports on the supply (primary input) side (Davar 2005). From that moment forward, Leontief applied input-output analysis to various economic topics: dynamic aspect of the economy, the choice of technology, world trade, environmental pollution and so forth.

3.2 Leontief's basic input-output table

3.2.1 Structure of the input-output table

The significant step of a systematic input-output analysis was achieved by Wassily Leontief in 1930, which was initially applied to determination of direct and indirect input requirements for U.S. industrial sectors. After the Second World War, the techniques of input-output analysis have been significantly enhanced while the approach was spreading out to many fields (e.g. energy, materials flows and environmental pollution) and applied in many other countries, regional or even village or company level. And many multi-regional input-output models have been constructed in recent years.

An input-output model or table demonstrates a detailed flow of goods and services between producers and consumers. In other words, all economic activities could be assigned to production and consumption sectors. As shown in Table 3.1, the basic structure of an input-output table is divided into four quadrants, which are intermediate transactions, final demand, and the primary inputs for production and primary requirements to final demand. The quadrant of intermediate transactions illustrates the intermediate deliveries between production sectors in an economy. The final demand quadrant describes the sales to the final consumers such as households, governments and exports. Furthermore, an input-output table contains information of primary inputs, which describes not only those necessary inputs for production such as the fixed capitals, compensation of employees and taxes etc (the third quadrant). It also describes the primary inputs to the final consumption (the fourth quadrant).

The core perspective of input-output analysis is that the technology of production of goods and services are determined by final demand generated by users of those products (Duchin and Lange 1994). The structure of an economy would be coordinated or transformed in terms of the changes of people's consumption patterns as people's lifestyle improves.

Table 3.1: Structure of Leontief's input-output table

Monetary unit e.g.: Yuan

	Activities Intermediate Demand	**Final Demand**			**Total Output**
		Households	**Governments**	**Exports**	
Activities Intermediate Inputs	(Quadrant I)	(Quadrant II)			
Primary Inputs	(Quadrant III)	(Quadrant IV)			
Imports					
Total Inputs					

Modified from Bouhia (2001)

3.2.2 Mathematical representation of input-output analysis

The following section and the later chapters will concerns many mathematical symbols, formulas and equations. Hereby, for clarity, matrices are indicated by bold, upright capital letters (e.g. **X**); vectors by bold, upright lower case letters (e.g. **x**), and scalars by italicised lower case letters (e.g. x). Vectors are columns by definition, so that row vectors are obtained by transposition, indicated by a prime (e.g. $\mathbf{x}'$). A diagonal matrix with the elements of vector **x** on its main diagonal and all other entries equal to zero are indicated by a circumflex (e.g. $\hat{\mathbf{x}}$).

The mathematical structure of an input-output system consists of n linear equations in n unknowns, as shown in Equation 3.1. The equation depicts that the value of total production is equal to the intermediate deliveries plus final demand for each sector.

$$x_i = z_{i1} + z_{i2} + \ldots + z_{in} + y_i, \quad i = 1, 2, \ldots n \qquad \textbf{(3.1)}$$

n: the number of economic sectors of an economy;

x_i: the total output of sector i;

y_i the total final demand for sector i's product;

z_{in}: the intermediate delivery from i^{th} sector to the n^{th} sector.

A fundamental assumption in input-output analysis is that the inter-industry flows from i to j (Miller and Blair 1985), represented as z_{ij}. By dividing z_{ij} by x_j (the total output of j^{th} sector) one can obtain the ratio of input to output z_{ij}/x_j, denoted as a_{ij}, which reflects the production efficiency with present technology. It so-called technical coefficient or direct requirement coefficient that depicts that the requirement from economic sector i to produce one monetary unit of product in economic sector j.

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{3.2}$$

A a_{ij} is a fixed relationship between a sectors outputs to its inputs. Thus, there is an explicit definition of a linear relationship between input and output and there are no economies of scale, rather the Leontief model represents constant returns to scale. Thus, doubling inputs will double outputs; reducing inputs by half will reduce outputs by half. In essence, the coefficients represent the trade from economic sector i to economic sector j. By accepting the notion of technical coefficients, Equations (3.1) can be rewritten, replacing each z_{ij} by $a_{ij}x_j$, as showed in Equation (3.3)

$$\begin{aligned}
x_1 &= a_{11}x_1 + a_{12}x_2 + \cdots + a_{1j}x_j + \cdots + a_{1n}x_n + y_1 \\
x_2 &= a_{21}x_1 + a_{22}x_2 + \cdots + a_{2j}x_j + \cdots + a_{2n}x_n + y_2 \\
&\;\;\vdots \\
x_i &= a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n + y_i \\
&\;\;\vdots \\
x_n &= a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nj}x_j + \cdots + a_{nn}x_n + y_n
\end{aligned} \tag{3.3}$$

In matrix notion (Equation 3.4), **A** represents the nxn matrix of technical coefficients (a_{ij}) and **x** and **y** is the corresponding $n\times 1$ vector:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \tag{3.4}$$

By re-arranging above Equation 3.4 to get Equation 3.5:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y} \tag{3.5}$$

where the term of $(\mathbf{I} - \mathbf{A})^{-1}$ is usually written as $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ which is the so-called Leontief inverse matrix. Matrix **L** accounts for the total accumulative effects including both direct and indirect effects on sectoral output by the changes in final demand. In other words, in order that every sector delivers one unit of final demand, every sector has to produce not only its own final demand, but also the direct and indirect requirements needed for its own and the other final demand. The direct requirements in monetary term means the gross revenues received by producers for final purchases of goods and services by consumers, government, and exports; and the indirect requirements are the expenditures on factors of production to input supply sectors triggered by the direct requirements.

Matrix **L** also reflects technical change in the economy, which are changes in the input-output relations of economic sectors.

3.2.3 Leontief's price model

The early version of Leontief's input-output model was a "physical model" represented in monetary units. Leontief was the first to study the interdependence of prices within an inter-industry framework for the US economy, which he labelled as the "cost-price structure" formulation or Leontief price model (Bazzazan and Batey (2003).

$$\mathbf{p} = \mathbf{A}'\mathbf{p} + \mathbf{v}$$

where **p** is a column vector representing the price of products, **A'** is the transpose matrix of the technical coefficients matrix – **A**; **v** is the row vector of value added. However, Leontief's price model has some problems when modelling the price change in the real world. Firstly, the model assumed that all entrepreneurs always expect prices to remain constant (Bazzazan and Batey 2003), which cannot be always true in real world. Secondly, one may get different price equations if one evaluates the factor of price changes over time without technological improvements by assuming that the entrepreneur always maximises the profits and minimises the losses (Morishima 1958; Solow 1959), quoted after Bazzazan and Batey (2003). Thirdly, most of the developed price models are based on assumption that wages are a part of value added, but in the case of Leontief's price model, value added is fixed even if the price of goods has been changed (Bazzazan and Batey 2003).

Nevertheless, Leontief's price model has been applied to interesting research such as modeling long term economic structural changes (Johansen 1978; Duchin and Lange 1992 etc.).. This model had also been applied by Leontief himself in addressing the environmental costs due to the economic activities already in the 1970s (Leontief's pollution-abatement model). Both the model and its weaknesses are discussed in section 3.3.3.

3.3 Input-output model applications for environmental analysis

Input-output analysis has been applied not only in economic and financial accounting, but has also been extended to account for environmental pollution and abatement associated with inter-industry activities. These studies have been conducted since the second half of 1960s. Since then, many scholars have been devoted to extending input-output analysis to the research of environmental problems. Now, the input-output analyses have been diversified to many aspects and applied to various economic-environmental related studies. The following texts discuss several extended environmental input-output models, including both historical approaches and contemporary developments. Following sections 3.3.1 and 3.3.2.2, and part of contents in 3.3.2.1 are summarised based on Gloria (2000).

3.3.1 Cumberland's monetary environmental input-output model

The input-output analysis was applied for the first time to environmental issues by Cumberland (1966). Cumberland's approach was to add rows and columns to an input-output table in order to identify environmental benefits and costs resulted of economic development and to distribute these to each economic sector. His model is shown in Table 3.2. Row vector **q** and **c** measures the monetary estimates of any environmental benefits or costs by sector correspondingly. Then, row vector $\mathbf{r} = \mathbf{q}\text{-}\mathbf{c}$ which is the overall effects of any economic activity or development to the environment. Column **b** represents the costs which would be required by the public and private sectors to eliminate the environmental emissions and restore the environment to its base period quality levels (Gloria 2000). Cumberland's model adopts monetary values on environmental effects rather than measuring the emission in physical terms. For many cases, the environmental impacts are hardly estimated in monetary terms, and difficult to implement based on the qualitative nature of environmental impacts (Richardson 1972), quoted after Gloria (2000). One of the key limitations of this model is that it does not incorporate the flows from the environment into the economy and vice versa (Richardson 1972). .Cumberland's model is much closer to a "cost-benefit" analysis of environmental effects than to an analysis of studying the interdependences and interactions between the economy and the environment (Richardson 1972).

Table 3.2: Cumberland's environmental input-output table

A	y	X	Cost of Environmental Restoration **b**
V			
x'			
Environmental Benefit **q (+)**			
Environmental Cost **c (-)**			
Environmental Balance **r =(q-c)**			

Source: Modified from (Richardson 1972)

where, **A** is the Leontief technique matrix; **V** is the value added matrix; **x** is the column vector of total output; **x'** is the row vector of total inputs; and **y** is the column vector of final demand.

3.3.2 Economic-ecological model

3.3.2.1 Daly's and Isard's approaches and related discussions

Both Daly (1968) and Isard (1972) developed similar approaches to integrate economic activities and environmental processes into Leontief's input-output framework, so-called as "economic-ecological model". The model can picture interactions both within the economic and the environmental system, as well as between them.

As shown in Table 3.3, Daly's model (1968) employed a highly aggregated industry-by-industry characterisation of the economic sub-matrix (agriculture, industry, and households) and a classification of ecosystem processes, including life processes such as plants and animals and non-life processes such as chemical reactions in the atmosphere, which could be captured in the sub-matrix of "flows within the ecosystem" (Daly 1968; Miller and Blair 1985), quoted after Gloria (2000). In order to calculate technical coefficients Daly summed up across the rows adding up economic and ecological commodities. His model, however, had been criticised for using non-comparable units by incorporating ecological commodities, with no market prices, and economic commodities, which do have such prices.

Table 3.3: Daly's model

	Industry	**Ecological processes**
Industry	Flows between industries	Flows from industry to the ecosystem
Ecological processes	Flows from the ecosystem to industry	Flows within the ecosystem

Table 3.4: Isard's model

		Industry	Ecological processes
Commodities	Economic	A_{xx}	A_{xe}
	Ecological	A_{ex}	A_{ee}

Source: Modified from (Miller and Blair 1985)

At the same time, Walter Isard (Isard 1972) developed a similar model as Daly did for the economic-ecologic model, as showed in Table 3.4. The essential difference is that Isard uses the coefficients of production directly from technical data (Miller and Blair 1985). Furthermore, Isard uses a rectangular matrix for his ecological system, which allows for several ecological commodities per sector. He also included in his "ecological sectors" biotic and abiotic substances, such as amounts of water, nutrients or light, and amounts of organisms. Isard defined regions, land, water bodies, and air, which are characterised by definite ecological processes and physical flows that are mutually dependent. In both Daly and Isards' models, a wide variety of elements such as land, water, chemical reactions in the air had been included and fully implemented. Their models are the most comprehensive ones even in present days. However, the data shortages concerning the environmental subsystem and the interaction between the subsystems appear to be the most ambitious point (Richardson, 1972, Victor 1972, Isard et al., 1971).

Besides the data problem, there are two additional issues regarding the above two tables. Firstly, both models assumed linear relationships within the ecological system. However, ecological processes are often non-linear and exponential in nature (Gloria 2000). Based on similar ideas, Steenge (1977) identified the feasibility of *mathematically formulating a viable ecosystem* by *using a classical activity analysis approach* – von Neumann's model. He agreed that *extreme complexity is an essential characteristic of most natural systems* (Steenge 1977 p.98). However, there would be a remarkable state of equilibrium: "*it is generally agreed that the same species are found in the same habitat during the same seasons for many years in succession and that they occur in numbers which are of the same order of magnitude*" (Pimentel 1966), quoted after Steenge (1977 p.99). A von Neumann's approach allows one to identify the stable, balanced development over time of a certain interrelated system. However Steenge's approach performs well without interruption by human- or economic-activities, such as pollution. Steenge stated "... if their compositions would be altered, or if they would disappear altogether, the system under study will easily be changed or break down..."(Steenge 1977 p.104).

Secondly both Daly and Isard assumed that 'free' environmental resources remain stable over time. Both Daly's and Isard's model could not capture the issue of resource degradation, which may cause the change of the production functions (Kapp 1970; Richardson 1972; Guan and Hubacek 2007).

Since the Agenda 21 (United Nations 1992), a reflection of the overall environmental quality has gradually become one of the vital indicators for evaluating a country's competitiveness. The conventional indicator of the "gross national income" (GNI) is not able to accurately assess a country's welfare of the general public taking the natural resources depletions and degradations into account. Therefore, a reliable "*Green Accounting*" has risen to become a vital instrument that can correctly reflect the state of the environment and economy (Jao 2000). Keuning and Steenge (1999 p.6) stated that "*a correct estimation of Green National Income thus requires a re-calculation of National Income, simulating what would have been its size if the economy had been sustainable*". In recent years many developed countries, including the United States, Germany, Canada, Japan, and the Netherlands have compiled the green GNP account while some developing countries like Philippines, Mexico, Indonesia, India, Thailand, South Korea and China have undertaken pilot runs under the System of Integrated Environmental and Economic Accounting (SEEA) led by the United Nations and the World Bank (Jao 2000). However, the "green GNP accounting" lacks a "*fully developed*" methodology to conduct such accounts (Denes 2002). The commonly adopted way to implement green accounting by imputing artificial cost to environmental assets and adjusting GNP would be inappropriate (Denes 2002). For example, Keuning and Steenge (1999) drew a parallel: "*nobody seriously proposes to value the 'cost' of unemployment and to 'subtract' this from GDP*". Furthermore, they also pointed out that it would be fundamentally wrong to *deduct the environmental costs from GDP, because the units are not the same as claimed, thus such an algebraic operation is not justified, quoted after Denes (2002).* GDP is in "*real money*" that actually entered *transactions – real dollars*, whereas imputed environmental costs are in a "*hypothetical money unit*" – *imputed dollars* (Denes 2002). Chapter 4 designs a hydro-economic accounting model, which indicates that it may make more sense to account the environmental resource and its degradation from the perspective of physical availability in future green GNI accounting developments.

3.3.2.2 Victor's approach

Daly's and Isard's models were too comprehensive to be practical enough to model. Victor (1972) presented an approach that limited the scope of their models to accounts only for flows of ecological commodities (free goods in Victor's model) from the environment into the economy and of the waste products from the economy into the environment (Gloria 2000). Victor believed that the information of $\mathbf{A}_{ee}$ matrix in Isard's model (e.g. Table 3.4) was too difficult to obtain. Instead, he adopted the commodity-by-industry implementation approach which allows for multiple outputs, the ability to express economic data in monetary units and ecological data in physical units (Victor 1972; Miller and Blair 1985), quoted after Gloria (2000).

Victor's work was the first study in which comprehensive estimates of material flows were used to extend input-output analysis in order to quantify some of the more obvious links between the economy and the environment of a country. Thus, the model was represented by commodities, industries and their associated activities (Victor 1972), as shown in Table 3.5.

Table 3.5: Victor's model

	Commodities	Industries	Household Consumption	Total Output	Ecological Commodities
Commodities		**U**	**e**	**q**	**R**
Industries	**V**			**x**	**S**
Value added		**W**			
Total Inputs	**q'**	**x'**			
Ecological Commodities	**P**	**M**			

Source: Modified from (Miller and Blair 1985)

In terms of Gloria (2000), the definition of the elements in Table 3.5 is below:

Economic sectors:

U = inputs of economic commodities by industries, and is referred to as the 'use' matrix;

V = outputs of economic commodities by industries, and is referred to as the 'make' matrix;

e = the vector of final demand;

q = The vector of economic commodity gross outputs,

x = the vector of industry total outputs;

q' = the sums of columns of matrix V showing total output by economic commodities,

x' = the sums of columns of matrices U and W showing total economic inputs of industries.

Ecological Sectors:

R = outputs of ecological commodities discharged as a result of final demand for economic commodities,

S = discharges of ecological commodities by industries,

P = inputs of ecological commodities used in conjunction with the final demand for economic commodities,

M = inputs of ecological commodities used by industries.

Victor pointed out that all economic activity requires inputs of raw materials (Gloria 2000). These inputs might be provided by privately owned parts of the environment, such as coal from mines, or rival but non exclusive environmental goods without specific property rights, such as the atmosphere and the oceans. A material flowed into the economy to support either production or consumption is referred to as an ecological commodity. However, once a material is processed for further use or is satisfying for people's consumptions, it is then referred to as an economic commodity. When it is discarded by either producer or consumer and leaves the economy, it becomes once again an ecological commodity with degraded quality (e.g. emissions) (Victor 1972), quoted after Gloria (2000). However, Victor did not solve the issue of resources quality degradations.

The Victor model is a commodity-by-industry table with additional rows of ecological commodities inputs **P** and **M**, and columns of ecological commodities outputs **R** and **S**, as shown in Table 3.5. Here the ecological outputs are equal to the ecological inputs consistent with the materials balance assumption (Gloria 2000). This assumes that the model is a closed economy and there is no accumulation of mass in the economy itself (Victor 1972), quoted after (Gloria 2000).

3.3.2.3 Later developments on the economic-ecological model

Since the early attempts by Isard and Daly, the economic-ecological has been extended to incorporate the full range of sectors in linked ecosystems (see e.g.Clark 1976; Bockstael et al. 1995; Lange 1998). Very recently, Jin et al. (2003) developed an economic-ecological model by merging an input-output model of a coastal economy with a model of a marine food web, and applied it to the marine ecosystem in New England. Their modelling approach links the workings of an economy, with a so-called matrix of economic exchanges, with those of a related ecosystem, known as matrix of ecological exchanges. In order to make this model feasible, they paid careful attention to characterise and study the linkages between the two types of systems. They linked the economic and ecological systems by using two matrices of coefficients. The first one is a matrix of ecological to economic exchanges, which suggests that trophic levels in the marine ecosystem can be treated as analogies of the industrial sectors of an economy (Jin et al. 2003). The second one is called matrix of economic to ecological exchanges, which can make the external effects of industrial activities on the ecosystem more apparent. They also developed natural measures of the ecosystem impacts of changes on final economic demand (so called ''resource multipliers'') that incorporate these linkages explicitly.

3.3.3 Leontief's pollution-abatement model and extension

Leontief (1970) developed the pollution-abatement model to account the environmental emissions. The model is shown in Table 3.6. The row vector of pollution represents the amount of emission each sector generated for its production. Its delivery to final demand is the amount of pollutants households are willing to accept. In order to balance the table, the 'anti-pollution' column was introduced to account for the total eliminated emissions by pollution abatement industries. With this model he was able to estimate the direct cost of abatement, the amount of pollution abated, and the indirect impact on gross output (Rose and Miernyk 1989). This extended model has been extensively discussed by Leontief and Ford (1972), Chen (1973), Leontief (1973), Steenge (1978), Lowe (1979), Qayum (1991), Arrous (1994) and Luptacik and Böhm (1999). But it was also criticised for its sole focus on the emission side and for ignoring the material balance principle (Victor 1972).

Another key weakness of Leontief's pollution abatement model is related to the price aspect of the model (Steenge 1978, 1999). The emitted pollution in Leontief's pollution abatement model is endogenised (Steenge 1978). According to Steenge (1999), there is a duality between price effects and the real world. The equilibrium price can be calculated by identifying appropriate information. However if there are any externality effects in the system, the simple duality would break down. Instead, one needs to seek other options to allocate the costs of the abatement of pollution such as the "*polluter pays principle*" (Steenge 1978, 1999). The polluter pays principle has been debated for over four decades, the main reason is that it hardly identifies who is the "polluter" as the economic system is interdependent from the perspective of the input-output approach. The polluter pays principle is basically based on "*direct pollution*" (Steenge 1999). But recently, the concept of "shared responsibility has been advocated (see Lenzen et al. 2007). Furthermore, Steenge (2004) created a link between the concept of shared responsibility, and the Coase Theorem (Coase 1960). By adopting the Leontief's pollution abatement model, Steenge (2004) confirms Coase's original idea that *overall* allocation of resources will be efficient independent of allocation of property rights by using a numerical example, given no income effects and zero transaction cost (Lenzen et al. (2007).

Ayres and Kneese (1969) presented a similar extension to Leontief's pollution abatement model, one that incorporates residual flows and pollution abatement. The major difference in the Ayres-Kneese model is that it includes a further elaboration to deal explicitly with raw materials extracted from the environment as well as waste materials returned to the environment (Ayres 1978). The fundamental idea of the model is that of materials balance.

Table 3.6: Leontief's pollution abatement model

Monetary unit e.g.: dollars

	Manufacturing	Services	Pollution Abatement	Final Demand	Total Output
Manufacturing					
Services					
Pollution Generation					

Source: Modified from (Miller and Blair 1985)

3.3.4 Hybrid input-output models

Environmental goods such as energy or water in traditional input-output analysis will be attributed to the final demand sectors via intermediate deliveries. The prices are the key element to handle the allocation. However, one of the basic assumptions of input-output analysis is price uniformity of products sales (Bullard and Herendeen 1975). For example, in an energy input-output analysis different production or final demand sectors would pay the same price but in reality different prices per unit of energy. Thus the deliveries from the energy sectors, in monetary terms does not correspond to real physical deliveries (Bullard and Herendeen 1975; Wilting 1996; Hubacek and Giljum 2004). The problem was first recognised by Bullard and Herendeen (1975), who developed the 'physical units' method (or so-called hybrid or hybrid-unit model) as a solution for energy deliveries, which represents the deliveries of the energy sectors in the input-output table in physical units. The hybrid input-output table extended the Leontief's input-output table by adding energy sector(s) in physical units such as British thermal units, barrels of oil, or kilowatt. Therefore, the whole hybrid input-output table and its related technology coefficients can be mixed with monetary and physical units (not necessarily in the same physical units). For example, in the two-sector case, where the first sector is an energy sector and the second is a non-energy sector, the calculation of the matrix A* (where * refers to mixed units) gives the following hybrid units (Bullard and Herendeen 1975):

$$A^* = \begin{bmatrix} \frac{Btu}{Btu} & \frac{Btu}{\$} \\ \frac{\$}{Btu} & \frac{\$}{\$} \end{bmatrix}$$

The invention of the hybrid input-output table was for accounting energy requirements for the commodities. From a lifecycle analysis point of view energy is consumed not only in the production process, but also in transport and waste disposal. Therefore, the hybrid IO framework was used to compute total energy consumption, including both directly and indirect energy requirements (Bullard and Herendeen 1975). The hybrid method complies with two key principles, mass balance (e.g. the weight of a product should equal the total weight of the materials of which the product is composed of plus the waste) and the financial balance principles for the monetary sections of the table. The applications of the hybrid method have been spread to a variety of environmental accounting, including land and water pollutants (Johnson and Bennet 1981; Duchin et al. 1993), indicators of air pollution, CO_2, SO_2, NO_X etc. (Duchin and Lange 1994), and specific materials such as plastics (Duchin and Lange 1998). Nakamura and Kondo (2002) developed a hybrid input-output model to deal with waste treatment and management from the perspective of lifecycle assessment. The core of their waste input-output model is to deal with the dynamic nature of waste treatments by incorporating an engineering process model of waste management. For engineering models of waste management, the level and composition of waste feedstock entering into the system are "exogenously" given. Integrated into their waste input-output model, these variables become "endogenous" and can be determined by the interaction between goods production and waste treatment for a given level and composition of the final demand.

Since the price of energy differs across the sectors and household consumption, the hybrid input-output approach is usually better than the monetary approach when one needs to study or project sectoral energy consumptions. However when one conducts structural decomposition analysis[17], the hybrid model would induce arbitrary results (Dietzenbacher and Stage 2006). Structural decomposition analysis usually distinguishes the changes of final demand between structure ($\mathbf{y}_s$) and total volume (y_v). It would be problematic if one evaluates the changes of the total final demand volume (y_v) by using a mixed-units hybrid model, because an economically meaningless sum of monetary and energy units would occur for the factor of y_v, which Dietzenbacher and Stage (2006) referred as *mixing oil and water*. Therefore, the stability of monetary input-output model may be better than the hybrid one in implementing structural decomposition analysis. This thesis, Chapter 6 conducts an IPAT-IO structural decomposition analysis by using monetary unit input-output tables and only an extended row representing CO_2 emissions in physical units.

3.3.5 Physical input-output models

PIOTs have been discussed on a theoretical level for quite a while (e.g. Georgescu-Roegen 1979; Strassert 2001) and have been empirically used in biology (e.g. Hannon and Ruth 1997) and applied to ecosystems studies. Only in recent years one has witnessed the publications of physical input-output tables representing material flows

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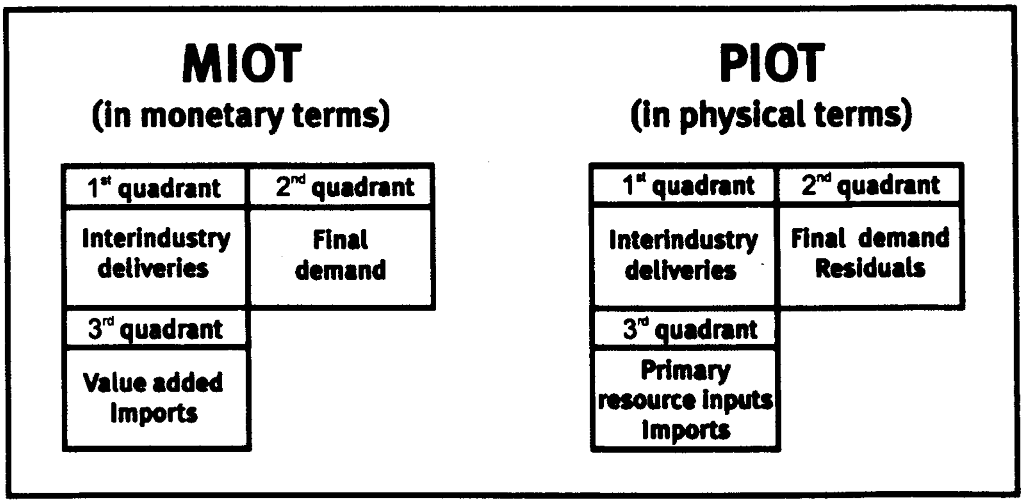
[17] Please refer to section 3.3.7 and Chapter 6 for details of literatures and mathematical principle of structural decomposition analysis (SDA).

in economies (Kratterl and Kratena 1990; Kratena et al. 1992; Stahmer et al. 1997; Pedersen 1999; Stahmer 2000). The physical input-output tables record all the flows and transactions of goods and services in physical units (e.g. kilowatts) (Dietzenbacher 2005). PIOTs seem to be a powerful tool in current input-output analysis, especially in the fields of material flow accounting, energy accounting, land use and their implications to pollution diversion and resources management.

The basic theory of PIOTs is the material/energy balance principle which is expressed in such way that net material accumulation is equal to the excess of total inputs over total outputs. Therefore in terms of this principle, in a PIOT, the sum of all physical inputs and outputs has to be equal for each economic sector as well as for consumption activities of private households (Hubacek and Giljum 2004).

Generally speaking, a PIOT comprises not only the production flows as the traditional input-output table does, but also material flows between the natural environment and the economy. In addition, a PIOT opens the black box that remains in Material Flow Accounting (MFA) and illustrates the flows between the different sectors and to various types of final consumption within an economic system (Hubacek and Giljum 2004). The following figure makes the comparison between monetary input-output table and physical input-output table. According to the information in the 1st quadrant of the intermediate activities with the economy, the PIOT is directly comparable to the MIOT, but with physical units instead of monetary units (Hubacek and Giljum 2004). The major difference between the two tables is that the environmental sector in the PIOT can be seen as a source of raw materials on the input side (3rd quadrant) and as a sink for residuals (solid waste and emissions to air and water) on the output side of the economy (2nd quadrant) (Stahmer et al. 1997). In other words, in a PIOT the environmental products enter the economic system as primary inputs from the nature whereas in a MIOT environmental products are generated and used for production within the economy (Hubacek and Giljum 2004).



Source: from (Hubacek and Giljum 2003)

Although there are many similarities between a MIOT and PIOTs, they are two different systems of input-output analysis. Furthermore, it cannot be converted between these two tables even if with the detailed information of prices provided (Stahmer et al. 1997; Hubacek and Giljum 2003; Giljum et al. 2004; Dietzenbacher et al. 2007). In statistical publications each product has a corresponding uniform price. However, in published input-output tables, this price is even further from reality since economic sectors in the IO table are comprised of many sub-sectors (depending on the level of aggregation). For example, a factory may produce several products, but it will be classified in a certain economic sector in terms of its major/primary product. Furthermore, even the same product can be sold at different prices, e.g. cheaper prices (discounts) for consumers of large quantities (Dietzenbacher et al. 2007).

PIOT has the same problem as MIOT as it uses one unit to aggregate very different qualities. MIOT uses $ and PIOT uses tons. The discussion in Hubacek and Giljum (2003) versus Suh (2004) and Giljum, Hubacek and Sun (2004), Giljum and Hubacek (2004) and (2007), Dietzenbacher et al. (2007) was that the structure of a PIOT despite the aggregation problem is closer to biophysical realities (and thus environmental problems) than the MIOT.

3.3.6 Input-output analysis and water consumption and pollution

The applications of input-output analysis to water issues were relatively rare in the last few decades. One of the earliest water input-output model was conducted by Carter and Ireri (1970) who developed an interregional IO model extended by water use coefficients to calculate water embodied in product flows between California and Arizona. Harris and Rea (1984) studied how to effectively allocate water resources among the economic sectors in order to maximise value added, and determined the marginal value of water for different users. Duchin and Lange used water use coefficients for Indonesia (1993) and on a global level (Duchin and Lange 1994). Lange (1997) in her work on Namibia shows how natural resource accounts (NRA) comprising six categories of water supply and its uses can be applied to economic analysis. Lange (1998) in her study on Indonesia shows how NRAs together with input-output modelling can be used to evaluate different policies such as food self-sufficiency given changes in economy and society and given a certain resource endowment. Since the late 1990s, a number of studies evaluated the internal and induced effects to water resources resulting from economic production and domestic demand, especially in water scarce regions and countries (e.g. Yoo and Yang 1999; Lenzen and Foran 2001; Duarte et al. 2002; Leistritz et al. 2002; Wang et al. 2005). Bouhia (2001) developed a hydro-economic model by combining a water resource allocation model based on a linear programming model with a static input-output model. Water is represented in monetary and physical terms balanced in material balance accounts. Bouhia developed a set of water multipliers allowing her to assess the effects of different development scenarios of water demand. She also added a column of 'change in the Natural Stock of Water' in final demand quadrant of the input-output table to deal with wastewater. In her assumption,. wastewater is deposited after the first production process and withdrawal by other sectors afterwards. By doing this the wastewater flows back to the whole economy again.

Only a handful of input-output studies were conducted with regards to water issues in China. For example, Xie Mei et al. (1991) applied input-output modelling to the Beijing urban water systems. Chen (2000) inserted three water sectors (fresh, recycle and waste water) into the intermediate demand section of input-output model to estimate the economic value of water in Shanxi province. Hubacek and Sun (2005) adopted input-output techniques to conduct a scenario analysis forecasting the water consumption for China's economy in 2025. There innovation was to match watershed boundaries with regional input-output boundaries with the help of a hydrological model that allowed them to reallocate water flows.

Despite of all of these advances, water resources need to be assessed in terms of both water quantity and water quality. Existing studies have rarely taken water quality aspects into consideration. There are only very few exceptions including water degradation into input-output frameworks. For example, Thoss and Wiik (1974) developed a generalised IO model for residuals management, which was applied for water pollution in the Ruhr. Førsund and Strøm (1985) developed a macro-economic model accounting for water pollution at a national level for Norway.

For the case of China, Ni et al. (2001) conducted a regional study on one of the fast-growing economic zones, Shenzhen, South China; they added a pollution sector into the input-output tables, aimed to adjust the economic structure for minimising the COD (Chemical Oxygen Demand) level in industrial wastewater by giving a predicted maximised GDP. Okadera et al. (2006) accounted for water demand and pollution discharge (carbon, nitrogen and phosphorus) based on input-output analysis for the city of Chongqing, China. Most of these studies add consumption coefficients and/or a set of pollution coefficients for the respective economic sector (and in some cases for households as well) but the linkages between consumption of water dependent on the available water quality on the input side and the pollution on the output side has not been explored. This necessitates an approach similar to the ones developed in integrated ecological economic input-output models, following the definitions in Miller and Blair (1985, pp.236)[18], which allow accounting of water flows throughout economic and hydrological systems. Chapter 4 will follow up the discussion and develop an integrated hydro-economic framework to account for both flows of water quantities and qualities between the economy and the environment.

3.3.7 Linking *IPAT* with structural decomposition analysis

The *Impact* = *Population* × *Affluence* × *Technology* or *IPAT* equation was developed to a further a debate between Paul Ehrlich and John Holdren, on one side, and Barry Commoner, on the other side, on which driver is the most important in contributing to environmental degradation. Ehrlich and Holdren (1971) initialised the construction of the framework by emphasising that population was a major driver to the environmental crisis, showing as: $I = P \times F$, where I is total environment impact, P is population size, and F is the impact per capita. Commoner and his colleague (1971) at

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[18] "Economic-Ecological models result from extending the interindustry framework to include ecosystem sectors, where flows will be recorded between economic and ecosystem sectors along the lines of an interregional input-output model" (Miller and Blair 1985, pp.236)

the first time used the *IPAT* notion to quantify the pollution triggered by economic development in the United States since the post-war. In the following year, Commoner (1972) designed a model of *I = Population* × *Economic good/Population* × *Pollutant/Economic good, population* represents the U.S. population quantity in a given year or the alteration in population over a defined period. *Economic good* refers to the quantity of a specific good produced or used during a given year also referred to as "affluence". *Pollutant* refers to the quantity of a particular pollutant discharged and therefore estimates "*the environmental impact generated per unit of production (or consumption), which reflects the nature of the productive technology*" (Commoner 1972), quoted after Chertow (2001). Commoner criticised Ehrlich's and Holdren's opinion that population growth is the dominant driver in environmental degradation. He argued that neither the growth of population nor affluence could explain the pace of environmental degradation in the U.S. since the Second World War. He concluded that technology is a key driver in environmental degradation.

Thereafter, the *IPAT* identity is regarded as an easily understandable, frequently and widely utilised framework for analysing the driving forces of environmental changes (e.g. Harrison 1993; Dietz and Rosa 1994; Raskin 1995; Dietz and Rosa 1997; Chertow 2001; York et al. 2002; Hubacek et al. 2007). In recent years, much research was done to further develop the *IPAT* framework by incorporating more factors into the equation. For example, Waggoner and Ausubel (2002) using a modified *IPAT* equation to assess the potential actions and policy levers to alter CO_2 emissions; they further disaggregated the technology ("*T*") in the *IPAT* equation into energy consumption per unit GDP (*C*) and CO_2 emissions per unit of energy consumption (*T*) to form a modified identity of *I=PACT*. Similarly, Schulze (2002) pointed out that personal behavioural choices significantly affect environmental impacts, therefore the equation should be extended to *I=PBAT*. However, the driving force of "behaviour" (*B*) was not mathematically defined in Schulze's letter to editor, it can make its applications problematic (Diesendorf 2002; Roca 2002; York et al. 2003). Furthermore, Rosa and Dietz (1998) reformulated the *IPAT* equation into a stochastic model, calling it *STIRPAT* for Stochastic Impacts by Regression on Population, Affluence and Technology; and this model has been further improved by York et al. (2003). The major contribution of STIRPAT model is to allow accounting for non-monotonic or non-proportional effects from each driving forces (York et al. 2003). The main strengths of *IPAT* and other varieties are that it identifies precisely the relationship between the driving forces and environmental impacts by a neat specification; further, it accounts an integrated impact by all of the driving forces as changes in one factor are multiplied by the other factors. In the other word, the *IPAT* identity implies that no one factor can be held singularly responsible for environmental impacts (York et al. 2003).

One of the key limitations of *IPAT* and its varieties is that it can only account for the direct impacts to the environment by the driving forces. Furthermore, it is too aggregated to clearly distinguish or allocate the sources of emissions are actually from which particular industry in the economy. Input-output modelling is a much more suitable tool to evaluate both direct and indirect environmental impacts by examining the flow of goods and services and all intermediate transaction among the producing and purchasing sectors of a country or a region (Leontief 1986). The *IPAT* approach can also be referred to as a decomposition tool as it decomposed impact into a number of contributing factors.

Decomposition analysis based on input-output techniques is usually referred to as structural decomposition analysis (SDA) (Hoekstra 2005). Rose and Casler (1996, pp34) define SDA as an "*analysis of economic change by means of a set of comparative static changes in key parameters in an input-output table.*" SDA has been applied to analyse people's demand, technology improvements and other driving forces to contribute the environmental changes. An important feature of the IO SDA is its capability to distinguish the direct and indirect components of the observed sectoral changes or driving forces (e.g. changes in final demand, productivity changes etc) (Hoekstra and van der Bergh 2002). SDA is a particularly powerful method to account for the indirect effects on one production sector of structural and productivity changes that take place in the other production sectors and are transmitted through the intermediate transactions. For example, Hulten (1978) has emphasised the distinction between "productivity change originating in a sector and the impact of productivity change on the sector through intermediate inputs coming from other sectors" (see Hulten 1978, p511). Casler and Rose (1998) claimed that SDA has become a popular methodology for several reasons. First, it overcomes many of the static features of I-O models and enables the evaluation of changes over time in technical coefficients and sectoral mix. Secondly, SDA enables the analyst to examine responses to price changes, which are only implicit even in value-based I-O tables. Thirdly, SDA is a pragmatic alternative to econometric estimation, which requires a long time series of data; in contrast, SDA requires only at least two I-O tables, one for the initial year and one for the terminal year of the analysis.

The first application of SDA to environmental issues can be traced back to the beginning of the 1970s. Leontief and Ford (1972) studied ordinary air pollutants (e.g. Particulates, SO_x, CO, hydrocarbons and NO_x) produced by the US economic growth since the end of 1950s. They utilised a set of emission coefficients appended to Leontief's augmented environmental IO model in order to generate the preliminary findings that the growth effect was more prominent than structural shifts or aggregate technological change (quoted after Casler and Rose 1998). Most of earlier SDA studies have been focused on energy consumption in the developed countries or regions (see e.g. Ploger 1984; Gould and Kulshreshtha 1986; Gowdy and Miller 1987; Chen and Rose 1990; Rose and Chen 1991; Chen and Wu 1994; Han and Lakshmanan 1994; Jacobson 2000)[19].

Since the early of the 1990s, some researches have been extended to examine the major drivers of changes in green houses gases (GHGs) emissions such as CO_2, SO_2 or NO_x. For example, Common and Salma (1992) adopted the Leontief monetary IO model to derive the changes of CO_2 emission in Australia over four time periods. They decomposed the changes of CO_2 emission into three driving forces, changes in households' final demand, fuel-mix changes and technological improvements. A similar type of analysis was implemented by Proops et al. (1993) for Germany with comparison of the U.K. Casler and Rose (1998) used hybrid IO model to analyse the impact of various influences on CO_2 emissions for the U.S. economy over 1972-1982. Some SDA studies on China have also been performed previously, but have used different methods and addressed different issues. An earlier study by Lin and Polenske (1995) analysed the changes in Chinese energy consumption between 1981 and 1987. They found that consumption growth outweighed efficiency improvements and that structural changes were relatively small. Increased expenditure on capital products was the main factor increasing emissions, followed by households, with the emissions avoided by imports growing faster than the emissions embodied in exports. Garbaccio et al. (1999) analysed the changes in the energy-output ratio from 1987 and 1992 and Andresosso-O'Callaghan and Yue (2002) analysed the changes in economic

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[19] This summary is based on Hoekstra's summary table of environmental SDA studies (Hoekstra 2005).

output from 1987 to 1997. Both studies found efficiency improvements were most important with only minor structural changes.

One can see that there are significant overlaps between the decomposition analyses by *IPAT* and SDA. For example, the drivers in *IPAT* equation, *affluence* could be represented by final demand; *technology* can be better described by the Leontief inverse matrix. Chapter 6 illustrates the combination between *IPAT* and SDA, then describes theoretical backgrounds and mathematical principles of IPAT-IO structural decomposition analysis. Then the author applies eight time-series input-output tables and relative data to the IPAT-IO SDA model to assess the drivers of CO_2 emission since the economic reform.

Chapter 4: Development and Implications of a Hydro-Economic Accounting and Analytical Framework for Water Resources: a case study for North China[20]

Water problems in China have been investigated in depth in a number of studies, especially with regards to the disparities of regional water availability (Wang and Davis 2000; Wiberg 2002; Wiberg 2003) and direct consumptions (see the literature review in section 3.3.6). However most of previous studies have emphasised the amount of water withdrawn but rarely take water quality into consideration. In other words, the water output side (return flows) has mainly been ignored. The quality of the return flows usually changes; the water quality being lower than when it entered the production process initially. It is especially important to measure the impacts of wastewater to the hydro-ecosystem after it is discharged. Thus, water consumption should not only account for the amount of water inputs but also the amount of water contaminated in the hydro-ecosystem by the discharged wastewater.

This chapter firstly introduces China's water situation. Then an integrated economic-ecologic model is proposed by merging the regional input-output tables of China with a mass balanced hydrological model. This method creates the links and interactions between the economy and the hydro-ecosystem. Furthermore this chapter further track water consumption on the input side including rainfall, surface and ground water; assign qualities for wastewater leaving the economy to different hydrological sectors (e.g. surface and ground water bodies); and measure the amount of contaminated water within the hydro-ecosystems. Finally the author applies the model to the case of North China where has been considered as one of the most water scarce regions in the world in order to evaluate the amount of water consumed and contaminated by economic activities.

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[20] The majority of this chapter has been published in *Journal of Environmental Management*, entitled "A New Integrated Hydro-economic Accounting and Analytical Framework for Water Resource Consumption: A Case Study for North China" (Guan and Hubacek 2007). In addition, this chapter has been presented in the *Intermediate International Input-output Conference*, 26-28.July 2006, Sendai Japan.

4.1 A synopsis of China's water situation

China is geographically large yet relatively poor in terms of water resources per capita, 1/3 of the world average. At the same time China's water resources are unevenly distributed. Due to considerable regional differences in water supply and demand and for the purposes of this chapter, it is necessary to model water consumption on a regional level. Therefore China is divided into eight hydro-economic regions[21] to establish water accounts (shown in Figure 4.1) based on watersheds and provincial level administrative boundaries (see Hubacek and Sun 2001, 2005).

Figure 4.1: Hydrological – Economic Regions in China

Source: Land Use Change Group at IIASA

For example, North China has only about 20% of total water resources in China. Generally speaking, in those areas with more water resources, the total water consumption is also high. However, in China, due to the diverse climate types, production structure, total water consumption styles and uneven distribution of population, the water utilisation situation does not coincide with the distribution of

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[21] The eight hydro-economic regions were distinguished in the "Land Use Change (LUC)" model, conducted by the LUC Group, International Institute for Applied Systems Analysis (IIASA). The eight regions are as follows: *North*, including Beijing, Tianjin, Hebei, Henan, Shangdong, and Shanxi; *Northeast*, including Liaoning, Jilin, and Heilongjiang; *East*, including Shanghai, Jiangsu, Zhejiang, and Anhui; *Central* including Jiangxi, Hubei, and Hunan; *South*, including Fujian, Guangdong, Guangxi, and Hainan; *Southwest* including, Sichuang, Guizhou, and Yunnan; *Northwest*, including Nei Mongol, Shananxi, Gansu, Ningxia, and XinJiang; and *Plateau*, representing Tibet and Qinghai.

water resources. However, the main water consumers and polluters, such as irrigated agricultural production, paper making and chemistry are mainly located in the northern part, which causes the tremendous demand for total water consumption in the northern basins and enormous impacts on local hydro-ecosystem, especially in the Haihe River, Huanghe River and Huaihe River Basins. Table 4.1 lists and compares the per capita water availability for each of the economic regions. The total fresh water resource in North China is 84, 350 million m^3, surface water accounts 65% of total, 55,151 million m^3; and groundwater takes the rest 35%, 45,252 million m^3. In addition, the quality of the water is degraded due to the large-scale industrialisation and urbanisation, which further burdens the ability of water supply. Ministry of Hydrology (1997) reports that about 65%-80% of rivers in North China no longer support any economic activities.

Table 4.1: Availability of Water Resource Distribution

Region	Total fresh water resource (10^8m^3)	Population in 2000 (in 1000s)	Per capita water (in m^3)
North	843.5	311,100	271.1
Northeast	1,529	106,334	1,437.9
East	1,926.2	198,149	972.1
Central	2,761.2	167,256	1,650.9
South	5,190.8	129,942	3,994.7
Southwest	6,389.8	243,414	2,625.1
Northwest	2,115.6	111,128	1,903.8
		China Average	**2,271.0**
		World Average	**6,981.0**

Source: (State Statistical Bureau of China 2001; Wiberg 2002)

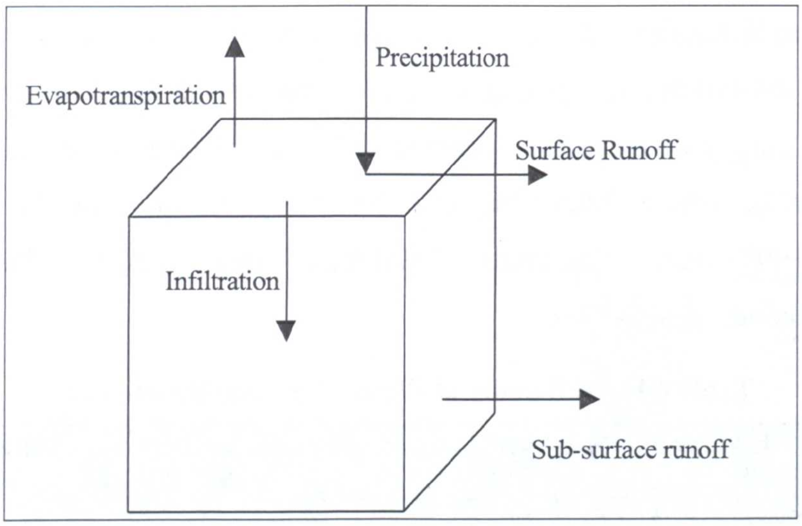
4.2 Construction of a hydro-economic accounting framework

The core of the structure of this model is the combination of a water quality model with an ecological-economic input-output model. In order to set up the framework of a water accounting model, it is important to firstly understand how water flows in nature.

4.2.1 Hydrological cycle and water demand

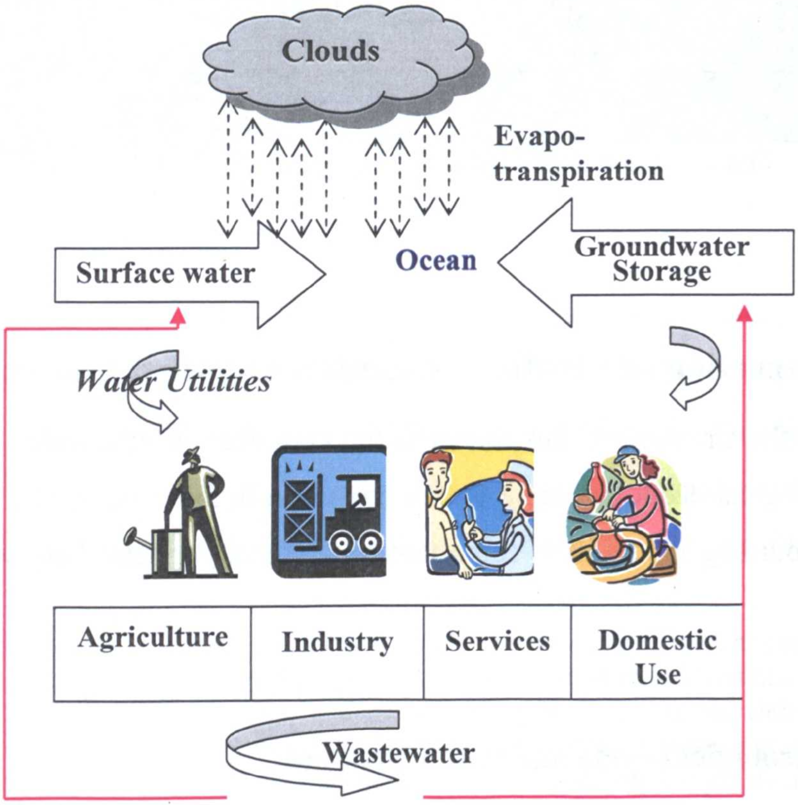
Water exists in the sea, in the air, on the surface or under the ground and in different forms, liquid, solid or gas. Water movement can be perceived as a closed system of water circulation, called hydrological cycle, as shown in Figure 4.2. Water is mainly extracted from two sources: surface water from rivers, lakes, steams and reservoirs, recharged from precipitation and snow melting; and groundwater from porous layers of underground soil or rock, which serve as aquifers; it is renewed through rain and snow melt that infiltrates the soil.

Figure 4.2: Hydrological Cycle



Source: Wiberg (2002)

Figure 4.3: Water Demand for the Economy



Source: own elaboration

As mentioned previously, water is one of the primary inputs and involved the whole economic productions chain. Figure 5.2 shows the water allocation to different users and the return flows discharges back to the original supply sources after the consumption activities. Agriculture is the major water consumer, particularly for irrigation, 74% of the total amount of water consumption is used for irrigations in China. Water is also consumed by industrial and domestic usage, of which wastewater is either recycled or reused for other sectors, or return back to the surface water.

Traditionally, the term of 'water demand' for the economy only consists of the amount of net water consumed for economic production and domestic usage; however the polluted water resources resulting from the return flows after economic activities back into the ecosystem are usually not accounted for. The quality of the return flows usually changes; the water quality being lower than when it entered the production process initially. The entered pollutants would mix and spread in the water bodies to develop a dynamic process causing indirect pollution in the same and sometimes other economic regions. For example, the pollutants in the discharged wastewater will infiltrate into groundwater or mix with surface water and flow downstream where it contaminates other freshwater resources thus being unavailable for other users and next round(s) of economic production and consumption. Furthermore, the sources of polluting substances can be from precipitation (e.g. acid rain), which may also result in the degradation of the water quality in both surface and ground water. The hydro-ecosystem has the ability to self-purify the waste, but this ability is determined by the hydro- or geographic conditions and biological, physical or chemical characters of the pollutants. For example the pollutant discharged from heavy industries (e.g. paper making) usually contains large amounts of toxic chemicals which are hardly purified by nature in any economically relevant time span. Therefore, it is necessary to extend the definition of 'water demand' for the economy by integrating notions of water quality into the water accounting framework and quantifying the impacts of discharged wastewater to regional hydrological environments, as shown in Equation 4.1. The author assign the name of 'hydro-ecosystem water' to account for both natural water losses (e.g. evaporation or infiltration into the soil) and the amount of water that exists in the hydro-ecosystem but is ineligible for any economic purposes as its quality is degraded by discharged pollution.

Water demand = Net water consumption –
Discharged wastewater + **(4.1)**
Unavailable water

Generally speaking, a hydrological cycle is accounted for a fixed time period (Bouhia 2001), in this chapter the year of 1997 is selected to account China's regional water budget, to match the availability of economic and hydrological data.

4.2.2 Structure of the hydrological-economic accounting model

The traditional IO table is an $n \times n$ matrix describing the flows of goods between economic sectors in monetary units. The matrix to $(n + m) \times (n + m)$ is extended by adding water sectors in physical units. The hydro-economic water accounting framework is further developed based on the economic- ecological model so as to represent the interrelationship between economic activities and hydrological processes (shown in Table 4.2).

Table 4.2: Extended Hydro-economy Input-output Table

		Activities Intermediate Demand	Final Demand		Total Output	**Hydrological system**		
			Household	Exports		Surface water	Ground water	Natural losses
Economic Activities		x_{ij} Matrix **A**	y_{ij}	n_{ij}	x_i		r_{il} Matrix **R**	
Primary Inputs		v_{ij}						
Imports								
Total Inputs		x_j						
Water inputs	Surface water	f_{ij} Matrix **F**					b_{kl} Matrix **B**	
	Ground water							
	Rainfall							

Matrix **A** $(n \times n)$ represents the economic flows among economic sectors. Matrix **F** $(m \times n)$ represents the primary water inputs (e.g. from surface, ground water or rainfall) to production sectors. Matrix **R** $(n \times m)$ quantifies the outputs of each economic sector to natural water resources (e.g. pollution). Matrix **B** $(m \times m)$ captures the hydrological changes after the production wastewater that is discharged in the ecosystem. The following sections 3.3 – 3.6 give detailed explanations for the linkage within and between the four matrices.

4.2.3 The economic system

As discussed in section 3.2.2, from the input-output approach, an economic structure can be described by Equation 3.5: $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$.

4.2.4 Water inputs to economic sectors

As mentioned previously, water is a primary input involved in production of goods and services. This connection can be captured in the $m \times n$ **F** matrix. The water input for production consists of three sources, surface water, groundwater and rainfall. The direct water consumption coefficient, f_{kj} (unit: m^3/Yuan) is defined in Equation (4.5),

$$f_{kj} = \frac{g_{kj}}{x_j} \tag{4.2}$$

where g_{kj} (unit: m^3/year) is the amount of water supplied from the k hydro-ecological sectors consumed in economic sector j; x_j (unit: Yuan/year) is the total economic output of the j^{th} sector. This coefficient represents the direct or the first round effects of the sectoral interaction in the economy (Bouhia 2001; Hubacek and Sun 2005). However, water is not only consumed directly but also indirectly. For instance, to produce paper necessary inputs are wood, chemicals, electricity and water (direct consumption). But also the production processes of each of these inputs need water (indirect consumption). Therefore, in order to combine both direct and indirect water consumption, the total water consumption multipliers matrix (**S**) needs to be calculated by multiplying the diagonalised matrix of direct water consumption coefficients $\hat{f}$[22] with Leontief multiplier matrix $(\mathbf{I}-\mathbf{A})^{-1}$, which represents an indicator

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[22] This study attempts to assess the fresh water input to the economy from three hydro-sectors. During the modelling manipulation, the author deals with the water input from different hydro-sector separately. In other words, three individual direct water consumption coefficients matrix: $\hat{f}_{\text{surface-water}}$, $\hat{f}_{\text{ground-water}}$, $\hat{f}_{\text{rain-water}}$ have been employed for accounting the water inputs from each hydro-sector, correspondingly. For example, the author firstly assigns the direct water consumption for each production sector with the distinction among surface, ground and rain water. Then, the author calculates three direct water coefficients matrices ($1 \times n$) for different hydro sectors respectively. Finally, the author diagnolises every direct water coefficients matrix for the purpose of multiplication with other factors in

of the total amount of water used up throughout the production chain for each sector. By pre-multiplying Equation (4.2) with the water consumption matrix S one receives Equation (4.3) describing the direct and indirect effects of water inputs by increasing a unit of final consumption, named as 'Net water consumption'.

$$\textbf{Net Water Consumption} = \hat{f}\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y} \qquad (4.3)$$

4.2.5 Flows from the economic to the hydrological system

The wastewater after the production and domestic discharge will leave the economy and flow back to original water resources (e.g. rivers, lakes or groundwater). Generally speaking, its quality gets degraded. Often the discharged wastewater carries large amount of noxious pollutants infused to surface or ground water. The output (wastewater) of each production sector to the water supply sources shall be captured in the **R** matrix with dimensions $n \times m$. Similarly to the process of determining fresh water consumption coefficients, the direct final wastewater coefficient r_{il} – the amount of wastewater to the l^{th} water supply sources in order to produce a unit of economic output in the i^{th} production sector. The calculation is shown in Equation (4.4).

$$r_{il} = \frac{h_{il}}{x_i} \qquad (4.4)$$

By multiplying the diagonalised matrix of direct wastewater coefficient $\hat{r}'$ with the Leontief multiplier matrix $\mathbf{(I\text{-}A)^{-1}}$, one will obtain the total wastewater coefficient matrix (**T**) which identifies the total contribution of each production sector to the environment by discharging sewage into natural water resources. Multiplying matrix **R** with Equation (4.4), one gets Equation (4.5) representing the total amount of wastewater generated in an economy by final consumption, referred to as 'Discharged wastewater'.

$$\textbf{Discharged Wastewater} = \hat{r}'\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y} \qquad (4.5)$$

Equation 4.3. The similar calculation process has been applied in calculating the amount of wastewater flows out from the economy after the economic activities.

4.2.6 Water flows within the hydro-ecosystem

When the polluting substances carried by rainfall or wastewater are discharged back to the original surface water sources or infiltrates into the groundwater, a series of complex physical and biochemical processes will occur. However these can be summarised as two major counteracting processes: one is the degradation process of water from a given to a lesser quality; the other is the self-purification process leading to improvement of the water quality. The two processes run simultaneously and are interacting with each other. The outcomes of these processes depend on the composition of the wastewater and the receiving water body. Many pollutants such as heavy metals cannot be easily purified by nature and will result in the degradation of the entire hydrological region. Once the pollution disperses, the availability of eligible water for certain consumers (e.g. downstream users) would be reduced. The **B** matrix identifies the water flows within the hydrological ecosystem and the impacts of discharged wastewater to the freshwater resources. In the other words, it measures the natural water consumption in the hydrology (e.g. evaporation loss), and also quantifies the amount of freshwater sources necessary to dilute the pollutants in the discharged wastewater to a respective standard rate (that is e.g. stated in the regulation of water quality and management). This chapter adopts COD[23] (Chemical Oxygen Demand) as water quality indicator measured in *gram/m³*. The following linear formulation is developed to capture the impacts to the hydro-ecosystem when contaminated wastewater enters to the water bodies as well as the natural evaporation process.

$$h_k = \sum_l v_{kl} + e_k, \qquad k = 1, \ldots \mathrm{m}; \qquad l = 1, \ldots \mathrm{m} \tag{4.6}$$

where h_k is the total freshwater required by the ecosystem in the k^{th} hydrological sector, including both natural water loss (e_k) and the amount of water needed for diluting pollution (v_{kl}). To better capture the interactions between the pollution and freshwater resources within the hydro-ecosystem, the author further decompose the freshwater needed for diluting pollution (v_{kl})

$$v_{kl} = b_{kl} h_l \qquad \text{alternatively,} \qquad b_{kl} = \frac{v_{kl}}{h_l} \tag{4.7}$$

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[23] This chapter selects COD as the pollutant indicator as its data is the most available one, actually the pollutant can also be any other water pollutant indicator, such as BOD (Biological Oxygen Demand) or several of ones.

where b_{kl} (unit: m^3/m^3) is the hydro-ecosystem exchanges coefficient[24], which refers to the amount of freshwater inputs required in the k^{th} hydrological sector to dilute the discharged pollution (e.g. COD level) from the l^{th} hydrological sector to a standard level; h_l (unit: m^3) is the amount of pollution discharged to the l^{th} hydrological sector. Therefore one can obtain the Equation (4.11) by combing the Equation (4.9) and (4.10),

$$h_k = \sum_l b_{kl} h_l + e_k, \qquad k = 1\ldots, \mathrm{m} \tag{4.8}$$

The Equation (4.11) can be also re-written as

$$\mathbf{(I - B)h = e} \tag{4.9}$$

where **h** is a m vector denoting the total freshwater required by the hydro-ecosystem, including both natural water loss and the amount of water needed for diluting pollution; **e** is a $m \times l$ vector denoting the natural losses in the ecosystem; **B** is a $m \times m$ matrix referred to as the hydro-ecosystem exchange matrix. The above Equation (4.12) can also be re-arranged as followed,

$$\mathbf{h = (I - B)^{-1}e} \tag{4.10}$$[25]

If one combines the Equation (4.6), (4.8) and (4.13) to formulate the relationship as shown in Equation (4.1), the integrated water demand can be described as,

$$\textbf{Extended Water Demand} = (\hat{f}_k - \hat{r}_l)\mathbf{(I - A)^{-1}\,y + (I - B)^{-1}e} \tag{4.11}$$

where $\hat{f}_k$ is the diagonalised matrix of direct freshwater coefficient; $\hat{r}_l$ is the diagonalised matrix of direct wastewater coefficient; $\mathbf{(I–A)^{-1}}$ is the Leontief multiplier matrix; y is the $n \times l$ vector denoting final demand; $\mathbf{(I–B)^{-1}}$ is the hydro-ecosystem exchange multiplier matrix; **e** is the $m \times l$ vector denoting the natural water loss within the ecosystem.

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[24] The term of "exchanges coefficient" is similar to Hannon (1973)'s study on the structure of ecosystem. He used "ecological coefficient" to describe the energy flows between trophic levels.

[25] To do matrix inverse, the figures on the diagonal of the matrix, for example in this case **(I-B)**, have to be positive. In other words, b_{kl} needs to be less than '1'. However in this study, by employing the mass balanced water quality model (Equation 4.13), the value of b_{kj} is always larger than '1', which means $\mathbf{(I\text{-}B)^{-1}}$ as the hydro-ecosystem exchange multiplier matrix is ineligible in this case. However it would not affect the evaluation of ecosystem degradation, but the coefficient, b_{kl} will not be standardised until a better solution is discovered. Jin et al. (2003) faced similar problem when they assessed the marine ecosystem degradations due to human activities. They claimed that there is no methodological solution to solve the problem unless a different ecological model is applied, such as Hannon (1973).

Equation (4.14) consists of two major parts: the first term, the traditional water demand, accounts for the amount of water withdrawal for economy and emission discharge after the production and consumption; the second term quantifies the amount of degraded water and losses caused by wastewater and hydro-ecosystem effects.

The process of defining the element of **B**, b_{kl} concerns physical water flows in nature. In the following, section 4.3 describes a simple model capturing the process of mixing between wastewater and freshwater in both surface and ground water. In other words, the following water quality model (e.g. Equation 4.16) provides the simply method of quantifying b_{kl}. The natural processes of infiltration and natural runoff exchange between surface and ground water can be also captured in the **B** matrix.

4.3 Mixing pollution in water bodies

In order to identify the element b_{kj} in matrix **B** in Equation 4.11, we employ the following water quality model (Equation 4.12) which is constructed based on a mass balance approach (*concentration* = *mass* / *volume*, or $c = m / q$)[26]. It calculates the concentration of pollutants in the water body after the mixing processes of the discharged wastewater from economic sectors into the original water resources. Equation 4.12 is a simply water quality model, however for a large watershed, the effectiveness is similar to the sophisticated model in estimating water pollution dispersion (Xie 1996).

$$c_{mixed} = \frac{1}{1 + k_1 \frac{v}{q}} \left(k_2 \frac{q_0}{q} c_0 + \frac{q_p}{q} c_p \right) \qquad \textbf{(4.12)}$$

$$q = q_0 + q_p$$

Parameters:

c_{mixed} – pollutant concentration after mixture processes

c_0 – initial pollutant concentration in the water body

c_p – pollutant concentration in wastewater

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[26] In terms of mass balance principle, the primary formulation of Equation 4.12 is: $c_{mixed}\,(q + v) = q_0 \cdot c_0 + q_p \cdot c_p$. Hereby v is the additional freshwater is used to dilute the concentration of discharged emission; v can be '0' if there is no additional freshwater resources available in the environment.

q – runoff rate after completion of the mixing process[27]
q_0 – initial runoff rate (e.g. the amount of water in a river per year)
q_p – wastewater discharge rate (e.g. the amount of wastewater discharged per year to a river)
v – the amount of freshwater flows in to a water body
k_1 – total reaction rate of pollutants after entering the water bodies (e.g. natural self-cleaning ability)
k_2 – pollution purification rate before entering to the water bodies (e.g. filler effect of soils)

Most countries, including China, have implemented water quality regulations using standards for the quality of wastewater and for the receiving water bodies. In order to avoid water pollution, the pollutant concentration in the water body after the mixing processes needs to be less than the standard rate of the respective standard (i.e. $C_{standard} \geq C_{mixed}$). If one replaces the C_{mixed} by $C_{standard}$, the Equation 4.12 can be re-written as follows:

$$\begin{gathered} v \geq \frac{1}{k_1 c_{\text{standard}}}(q_0 c_0 + k_2 q_p c_p - q c_{\text{standard}}) \\ q = q_0 + q_p \end{gathered} \tag{4.13}$$

Hereby, the scalar v is the amount of freshwater in the hydro-ecosystem needed to dilute pollutants in the discharged wastewater in order to reduce the pollution concentration level to the standard rate. In other words, v can be also regarded as the amount of surface or ground water being contaminated by wastewater pollution dispersion and assimilation.

The pollutants in the air (e.g. acid rain) can intervene with other water pollutants. However, their impacts are usually difficult to quantify. This could be done by tracing the air pollutants to specific economic units; measuring the ascertained pollution carried by acid rains and dissolved in water bodies. On the other hand, its impacts on water quality are usually less significant than the impacts from discharged wastewater. Therefore this study ignores air borne emission to water bodies; their treatment would be beyond the scope of this study.

Xie (1996) monitored the water quality of surface run-offs in North China Plain since 1980, and calculated the parameter of natural surface run-offs self-purification for COD in North China in his three-dimensional surface run-off water quality model. He

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[27] Runoff is categorized as surface runoff and sub-surface runoff for surface and ground water respectively. The unit of runoff is usually described m^3/second; in this case, it is million m^3 per year.

also estimated the parameter (k_1) for above simplified one dimension water quality model. When the author conducts the calculation for the impact of surface water due to wastewater discharges, Xie's estimation of 'k_1=3.64' is employed for Equation 4.13. Similarly, another group of hydrologists, Zhang et al. (2003) measured the groundwater self-purification parameter for COD is 1.7 on average. They also developed a series of experiments to measure the filtering effects of soil layers when the pollutants enter the groundwater body by using different soil types[28]. This study employs '$k_1=2.80$' and 'k_2=0.82' in Equation 4.13 when the author calculates the pollution discharged into groundwater bodies.

The advantage of this simple water quality model is that it requires much less hydrological data which is always difficult to obtain so that the feasibility of many macro-level water researches can be significantly enhanced. On the other hand, this model can only represent an individual pollutant or pollution indicator (e.g. COD/BOD[29]) each time so that it cannot catch the interactions between the pollutants. However, a more sophisticated water quality model can be easily incorporated into the accounting framework to replace then current one-dimension mass balance model.

4.4 Hydro-economic regions and datasets

The dataset for this chapter consists of two categories: detailed economic data (input-output tables) – to investigate the flow of goods and services between producers and consumers and the linkages between all production sectors; and hydrological data – comprising four sub-categories: water availability; fresh water consumption coefficients for each of the economic sectors; wastewater discharge coefficients for each of the economic sectors; and the hydraulics parameters in the water quality model (e.g. k_1 and k_2 in the Equation 4.13).

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[28] This chapter employs the result of loess soils as k_2 in Equation 4.13 as there are over 75% of area are covered by loess soils in North China Plain.

[29] BOD: Biological Oxygen Demand

4.4.1 Economic data

The author generated the regional input-output table for North China by merging the six provincial input-output tables for 1997 in terms of the classification of hydrological-economic regions (shown above, Figure 4.2). North China includes Beijing, Tianjin, Hebei, Henan, Shangdong, and Shanxi provinces. The provincial input-output tables, each representing 40 economic sectors, were compiled by the State Statistical Bureau of China and published in 2000. The details of classification of economic sectors are illustrated in Appendix A-1. The "value-added" categories in the table include: capital depreciation, labour compensation, taxes, and profits. "Final use" at the national level comprises six categories: rural households, urban households, government consumption, fixed investment, inventory changes, and net exports.

4.4.2 Hydrological data

The dataset for water availability is extracted from *"China's Regional Water Bulletins*[30] *" in 1997.* The ministry of hydrology in China provides detailed water availability data annually for both surface and ground water for all provinces.

The calculation of freshwater consumption coefficients concerns the usage of two datasets: the total volume of net water consumption for each economic sector; and the total output in monetary term for each sector correspondingly. The dataset of net water consumption for each sector was taken from *"China's Regional Water Bulletins" in 1997, Regional Water Statistics Yearbook in 1999*[31] and annual reports on hydrology from various provincial hydrology-ministries. The data of total outputs for each economic sector is given in the input-output tables.

The calculation of final wastewater discharge coefficients also concerns two datasets: the total volume of wastewater discharge from each economic sector with level of COD concentrations; and the total output in monetary term for each sector. The dataset of wastewater discharge is extracted from the *"Third National Industrial Survey" in 1995, "Regional Water Statistics Yearbook in 1999" and* various authoritative sources (Dong 2000; Zhang 2000; Weng 2002; Li 2003). The average level of pollution in this case, COD (gram/m^3), was not available for all economic

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[30] Published annually by the Ministry of Hydrology in China

[31] State Statistical Bureau (1999), State Statistical Publishing House, Beijing, China

sectors. However, the regional hydrological offices annually implement the surveys of discharged COD in physical unit (e.g. tons) for industry and domestic sectors. The dataset can be found in *"China's Environment Yearbook"*; *"China's Environmental Statistical Bulletins" in 2000*; *"Regional Water Statistics Yearbook" in 1999.* In terms of amount of discharged COD and wastewater, one is able to calculate the average concentration of COD level in discharged wastewater for each economic sector. The values and sources of the parameters in Equation 4.13 are list below:

$c_{standard}$ = 40gram/m^3 (State Environmental Protection Administration of China 2002);
c_0 = 30 gram/m^3 (Ministry of Hydrology 1997)

c_p = 442 gram/m^3 for discharged wastewater to surface water body, and 341gram/m^3 to groundwater body (Ministry of Hydrology 1997);

q_0 = 76,396 million m^3 for surface water body and 62,684 million m^3 for groundwater body (Ministry of Hydrology 1997).

q_p = 12,301 million m^3 discharged to surface water body and 3,487 million m^3 discharged to groundwater body (Ministry of Hydrology 1997).

$k_1=3.64$ for surface water self-purification (Xie 1996) and k_1=2.8 for groundwater (Zhang et al. 2003);

$k_2=0.82$ (Zhang et al. 2003).

4.5 An application to water demand in North China

This section uses North China as a case study and employs the above method to perform the water accounting.

4.5.1 Matrix of economic flows

By employing the Equation 4.3, one can calculate the technical coefficients for the China's economy in 1997. The dimension of the technical coefficients matrix (**A**) is 40×40. It allows to generate the Leontief multiplier matrix - $\mathbf{(I-A)^{-1}}$.

4.5.2 Matrix of Water Inputs to the Economy

By employing Equation 4.6 – **Net Water Consumption** = $\hat{f}\,\mathbf{(I - A)^{-1}\,Y}$, one is able to quantify the total amount of water that has been consumed up in the production chain is thus not available for water consumption for other purposes within that region, including both direct and indirect consumption. As shown in Appendix A-1, the dimension of the "net water consumption" matrix is 40 production sectors with 2 final demand sectors by 3 hydro-sectors (surface, ground and rainfall water), which accounts the total water consumption by each economic production and households sectors, including both direct and indirect water consumption. The rows represent economic sectors, and the columns of water consumption represent the amount of standard quality freshwater withdrawn from hydrological sectors (e.g. surface, ground and rain water). The added column explains the quality of consumed freshwater (COD concentration) in each economic sector[32]. Moreover in this study, agriculture is distinguished in rainfed and irrigated agriculture. Rainfall is regarded as the water input for rainfed agriculture only.

Figure 4.4 shows the net water consumption in North China for 6 aggregated sectors, agriculture, manufacturing, energy generation, construction, transport and posting and services; and two final demand sectors, urban and rural households. In 1997, North China's net water consumption among all production sectors was 49,165 million m^3. The total households' net water consumption is 6,469 million m^3, 35% from urban households and 65% from rural households (Ministry of Hydrology 1997). Hence overall net water consumption is 55,634 million m^3 (excluding precipitations for rainfed agricultures) in comparison to the total freshwater availability of 84,350 million m^3. In other words, about 66% of available fresh water resources are used up. As shown in Figure 4.4, irrigated agriculture is the largest water consumer, which accounts for almost 74% of net water consumption. Households are ranked as the second largest water consumer with 12%. Manufacturing sectors (including food processing, textiles and chemicals etc) accounts for about 10% of net water

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[32] This chapter assumes that the quality of consumed water is same for the consumers within the same economic sector. The water input quality is taken from China's "Environment Quality Standard for Surface/Ground Water Resources" (State Environmental Protection Administration of China 2002), and assumed to be 40gram/m^3 of COD level for irrigated agriculture; 30gram/m^3 for industries; and 20gram/m^3 for services and domestic usages.

consumption, and construction, energy generation and all services sectors shared the remaining 4% of net water consumption.

Figure 4.5 distinguishes the net water consumption by water supply sources. Groundwater supply plays an important role in North China's economy, especially in service sectors and for rural households' consumption. The increasing reliance on groundwater has accelerated its exhaustion in North China. During 1997, an estimated 99,900 wells were abandoned as they ran dry, and 221, 900 wells were drilled (Brown 2001). The deep wells drilled around Beijing now have to reach up to 1,000 m to tap fresh water (Brown 2001), which has seriously damage the underground hydro-ecosystem through depletion and salt water intervention in the costal areas.

Figure 4.4: Net water consumption in 1997 in North China

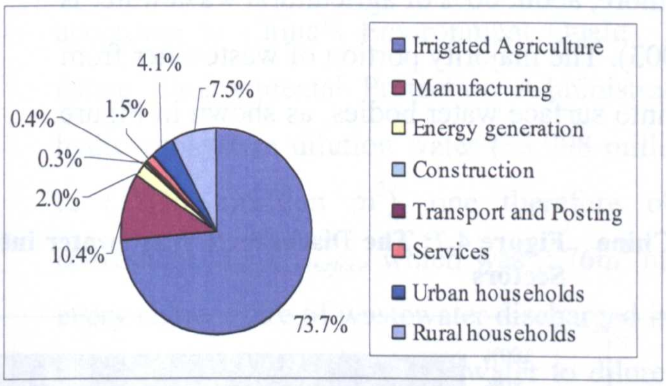
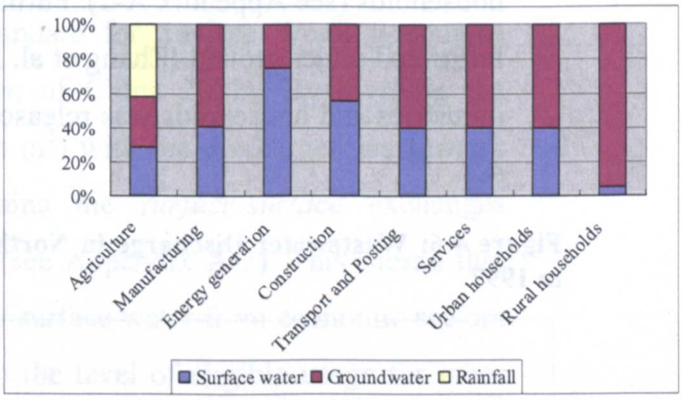


Figure 4.5: The Pattern of Net Water Consumption by Hydro Sectors



Note: aggregation is based on 40 production sectors and 2 final demand sectors as shown in – Appendix A- 1.
Source: Own calculation

4.5.3 Matrix of discharged wastewater from the economy

The Equation 4.8 – **Discharged Wastewater =** $\hat{r}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y}$, allows ones to quantify wastewater flows triggered by final demand in North China. The dimensions of the "discharged wastewater" matrix are 3 hydro-sectors (e.g. surface, ground and natural loss water) by 40 production sectors with 2 households sector[33], as shown in Appendix A-2. Columns stand for economic sectors; the rows of wastewater flow stands for the amount of wastewater discharged from the corresponding economic

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[33] The statistics of households wastewater discharge only consists of urban areas. Therefore this chapter assumes that per rural person wastewater discharge is 1/3 of urban residents' level as rural person consumed 87 litres of freshwater per day with comparison of 220 litres per day for every urban resident. The COD concentration of discharged wastewater from rural households is assumed to be same as urban households' level.

sectors; and the column of wastewater quality stands for the concentration of COD levels in the discharged wastewater, measured in gram/m^3.

Pollution can further contribute to water scarcity and is a major source for diseases, particularly for the poor. Figure 4.6 shows the wastewater discharge pattern in North China in 1997. Due to its low COD levels the wastewater calculations exclude the amount of discharged cooling water from electricity generation plants. The total wastewater discharge was 15,739 million m^3. Agriculture, manufacturing and households were the major polluters, which contributed about 39.1%, 24% and 31.9% respectively, and services, constructions and transport and posting share the rest of 5% of pollution discharge. Although agriculture was the largest discharger, its concentration of COD level was much lower than the pollution level in many industrial and domestic sectors, such as paper making, chemical production and households (see Appendix A-2). Furthermore, about 60% of agricultural wastewater is infiltrated under ground (Zhang et al. 2003). The majority portion of wastewater from industries and households was released into surface water bodies, as shown in Figure 4.7.

Figure 4.6: Wastewater Discharge in North China in 1997

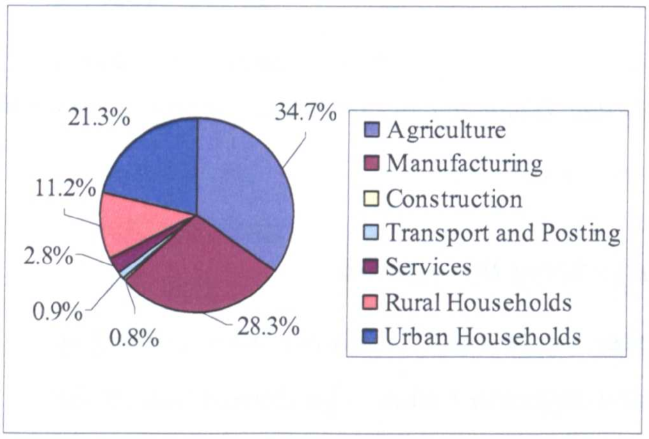
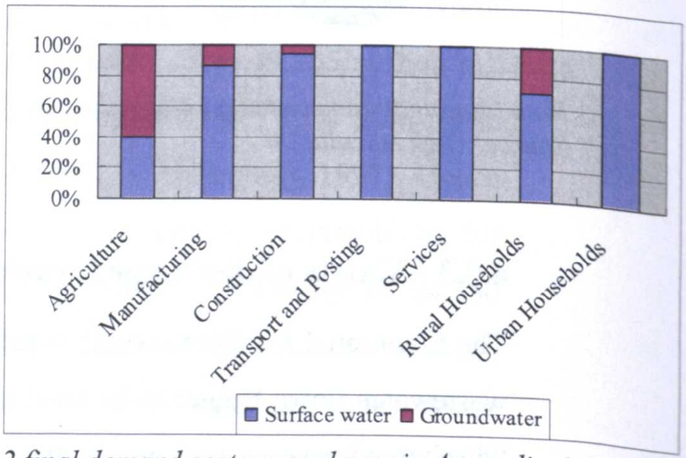


Figure 4.7: The Discharged Wastewater into Hydro-Sectors



Note: aggregation is based on 40 production sectors and 2 final demand sectors as shown in Appendix.A-2.
Source: Own calculation

4.5.4 Matrix of water exchange within hydrological ecosystem

By employing Equation (4.10), one can form the **B** matrix and define its elements – the hydrological exchange coefficient, b_{kl}, which refers to the amount of freshwater in the k^{th} hydrological sector required to dilute the COD concentration of the wastewater discharged into the l^{th} hydrological sector to a standard level. It flows within the 3 hydrological sectors. Due to lack of data, this study is not able to quantify the mutual pollution exchanges between the surface and ground water bodies. This study assumes that only discharged wastewater from the economy would impact on the hydro-ecosystem.

In 1997, the economic sectors have released 12,747 million m^3 of wastewater to surface water bodies. During the process of discharging, there was water loss of about 3.5% due to evaporation (data is estimated based on Xie 1996); the rest of 12,301 million m^3 of wastewater with the COD concentration of 426gram/m^3 had been mixed with surface water bodies. By applying the water quality model of Equation (4.13): one calculates that the surface water body would provide 33,998 million m^3 of freshwater to dilute the COD level in the wastewater to the lowest standard rate of 40gram/m^3, which would be eligible for the purpose of agricultural irrigation according to China's Environment Quality Standard for Surface Water Resources (State Environmental Protection Administration of China 2002). By dividing the hydro-ecosystem dilution water (33,998 million m^3) with the discharged wastewater to (12,301 million m^3), one therefore obtains the *surface-surface* exchanges coefficient, $b_{surface\text{-}surface}$ which was 2.76m^3/m^3 (see Appendix A-3). This means that every cubic metre of wastewater discharged into surface water from economic sectors would require 2.76m^3 of freshwater to dilute to the level of eligible usage for other consumers or next round economic production.

The amount of wastewater discharged from the economy into groundwater was 4,384 million m^3 with an average COD concentration of 341gram/m^3 (see Appendix A-2). However, about 30% of wastewater was retained in the soil layers during the infiltration process or "lost" in other natural hydrological exchanges (Zhang et al. 2003). Hence, about 3,486 million m^3 of wastewater would have infiltrated and mixed with ground water bodies, of which 74% wastewater is from agriculture and 12% is from rural households. Furthermore during the infiltration, the soil layers would also purify the wastewater before it reaches the groundwater bodies. Similarly to the process of defining *surface-surface* exchange coefficient, considering soil-purification, $k_2=0.82$ (Zhang et al. 2003), as well as the groundwater self-purification, $k_1=2.80$ (Zhang et al. 2003), one is able to calculate that there was 7,462 million m^3 of groundwater required, i.e. 16% of groundwater resources in North China, to dilute the pollutants in the wastewater discharged underground. Similar to the above calculation process of $b_{surface\text{-}surface}$, one can get the *ground-ground* exchange coefficient, $b_{ground\text{-}ground}$ which was calculated to be 2.14 m^3/m^3.

Applying all elements into Equation 4.14, one can calculate the extended water demand comprising both net water consumption and polluted water for North China in 1997 with 81,307 million m^3. In comparing this with the total availability of 84,350 million m^3, the water demand was almost 96% of total annual available water resources.

The extended water demand from surface water was 47,043 million m^3, 58% of the total. The availability of surface water in North China was only 55,151 million m^3, which means about 85% of surface water bodies had been either consumed up by the economy or extremely polluted so as to be ineligible for any purpose of usage. The results can be matched with the official report from the Ministry of Hydrology (1997) stating that "about 65%-80% of rivers in North China (e.g. Huaihe, Haihe, Huanghe River) have no longer support any economic activities".

4.6 Conclusion

This chapter has advocated re-defining the term of "water demand" to "extended water demand" which should not only account for the amount of water inputs to the economy but also measure the impacts of wastewater on the regional hydro-ecosystem. Therefore, a hydro-economic accounting framework has been developed following in the tradition of economic-ecological modelling. This framework is designed to evaluate the *linkages* or *interactions* between the economy and the hydro-ecosystem, which is achieved by integrating regional input-output model with a mass-balanced water quantity and quality model. The accuracy of this accounting framework could be further improved by incorporating a more complex water quality model with parameters of biophysical or hydro-conditions. However mathematical water quality models usually require large amount of detailed hydrological data which would not be available from statistical agencies. This framework, is designed for hydro-economic accounting on regional basis, which is able to track the sources of water inputs to every economic sector; to account for the amount of return flows of different qualities to the respective hydro-sectors; and to quantify the amount of freshwater been contaminated in the regional hydro-ecosystem.

The hydro-economic accounting framework has been applied to the region of North China which has been characterised as water scarce. The result shows that North China consumed up to 55,634 million m^3 of freshwater and discharged 15,787 million m^3 of wastewater (after evaporations) that contaminated 41,461 million m^3 of freshwater in the hydrological environment. In 1997, the extended water demand for North China was 81,308 million m^3, which occupies 96% of its total annual water availability. Agriculture, energy generation and households were the most water-intensive consumers, but paper makings and chemical production took the prime responsibility for the degradation of the hydro-ecosystem. From the point of views of water conservation and sustainability, a water scarce region like North China may develop less water-intensive industries (e.g. services), and strictly control and monitor the development of polluted industries (e.g. paper production).

Chapter 5: Assessing Regional Trade and Virtual Water Flows in China[34]

Previous chapters described China as poor of water resources in terms of per capita value. Furthermore, due to the unevenly distributions, North China is poor in water resources availability, but South China is relatively rich in water. Flourishing trade activities on both domestic and international levels has resulted in significant amounts of 'virtual water', i.e. water embedded in products and used in the whole production chain, are traded between regions or exported to other countries. Hence the overall aim of this chapter is to evaluate the current inter-regional trade structure between North and South China and its effects on water consumption and pollution via 'virtual water flows' by referring to the international trade theory, particularly the Leontief's paradox.

Firstly, this chapter introduces the origin of the concept of virtual water flows and distinguishes the concepts between fresh and waste virtual water flows. Secondly, it illustrates that the virtual water needs to be seen as a factor of production by reviewing the previous studies on international trade theory, Leontief's paradox and the relevant discussion on environmental issues. Thirdly, using the hydro-economic account framework developed in Chapter 4, the author generates both virtual fresh and waste water flows for North and South China with discussion referring to the international trade theories. Lastly, the author points out that the current trade structure in China is not very favourable from the point view of water resource allocation and efficiency because water should be but has not been regarded as a factor of production and virtual water need to be incorporated into decision makings for trading industries.

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[34] The majority of this chapter has been published in *Ecological Economics*, entitled "Assessment of Regional Trade and Virtual Water Flows in China" (Guan and Hubacek 2007), some parts of this chapter are published in ***Handbook on Sustainability Research***, entitled "An analysis of China's water problems: A long term perspective" (Hubacek et al. 2005). In addition, this chapter has been presented in the *15th International Input-output Conference*, 27 June – 01 July 2005, Beijing, China

5.1 China's trade and virtual water flows

China's economic reform has created a very competitive circumstance for domestic and foreign investors comparing to other countries in terms of cheap labour costs, huge market and low environmental standards of pollution discharge. As a result, large amount of capitals have been flowing in China, especially in northern and eastern parts, which put China to be one of the largest manufacturers and exporters in the world. This stimulated regional economic prosperity while brought huge impacts to the ecosystem and the exhaustion of water resources.

Due to the flourishing trade activities, significant amount of 'virtual water', i.e. water embedded in products or used in the whole production chain, was traded between regions or exported to other countries. The idea of virtual water was derived from the concept of 'embedded water' applied to Israel by Gideon Fishelson et al. (1989) (Gideon and Shuval 1994). Their study pointed out that exporting Israeli water embedded in water intensive crops was not sustainable. The term of virtual water was firstly proposed in London in 1994 by J.A. Allan (Allan 1996), but most studies have only emphasised on the amount of water is embedded in different agricultural products and transported through trade. There are quite a number of studies on virtual water flows with discussion on food security or related issues.

Allan (1998; 2002) defines virtual water as the water used to produce food crops that are traded internationally. He found out that a few countries characterised as water-scarce have ensured their food supply by importing water-intensive food products, rather than producing all of their food supply with inadequate water resources. Most of the studies on virtual water flows have been conducted in drought areas such as Middle East and North Africa (e.g. Knott 1998). In some of the countries with large population and scarce water resources, significant loads of food have to be imported as they cannot achieve self-sufficient supplies even if all water resources were committed to producing food for domestic consumption (Lofgren and Richards 2003). Hence, it does make sense for those countries to explicitly implementing a virtual water strategy (Yang and Zehnder 2001; Allan 2002; Yang and Zehnder 2002). Actually, the concept of virtual water is more important for the nations or regions like eastern China where is still much better off in terms of water resources in comparison to Middle East and North Africa. The limited water should be used efficiently by not allocating majority of the water resources in production of water-intensive products (e.g. crops, paper etc.) but water should be also made available for other economic purposes that can contribute more to the region by consuming the same unit of water. In many developing countries, agricultural irrigation is still occupying the majority portion of water use, which is 62% in China. However, along with the large-scale industrialisation and urbanisation since 1980, domestic, municipal, and industrial water consumption joined the competition for the limited water resources. Many industrial products also cause substantial amounts of virtual 'fresh water' as well as 'wastewater' for the productions of paper, fertiliser and cement, have been produced and transported in other regions or countries. Therefore, one can extend the concept of virtual water flow to comprise all types of commodities including agricultural goods, industrial products and services. Whilst one can distinguish the virtual water into two categories, freshwater and wastewater: the virtual freshwater is amount of freshwater is consumed during the production, and flows to other places. The virtual wastewater is amount of polluted water is discharged to the ecosystem after production, which accounts for the amount of emissions generated and left in this region in order to feed consumption in other regions or countries.

5.2 Virtual water as a factor of production

The notion of virtual water as necessary input to production and consumption activities leads to the notion of factors of production or factor endowments. Wichelns (2001) describes "virtual water as an application of comparative advantage, with particular emphasis on water resources". Allan (2003) states that "virtual water is something of a descendant of the concept of comparative advantage," while Lant (2003) suggests that "like comparative advantage, virtual water is also an application of basic principles of economic geography," which recommend that economic activities requiring inputs with low values per unit of weight should be located close to the sources of those inputs (Wichelns 2003). This chapter focuses on water as a special input to production but is also interested in the question of how production and associated trade structures affect the availability of water resources. Early economic theorists such as Adam Smith and David Ricardo were concerned with differences in factor endowment, 'the comparative advantage', as one of the main reasons for trade and regional inequalities and as a source for the wellbeing of nations. The focus shifted to the negative sides of trade; and only rather recently, scholars started to advocate re-designing trade structures from the perspectives of social and environmental sustainability. The following texts look at certain selected key publications to see how factor endowment and environmental resources have been treated in the trade literature and how that links to this research.

Heckscher (1919) and Ohlin (1933) incorporated the endowment of factors of production into the principle of comparative advantage, and consequently was referred to as the Heckscher-Ohlin (HO) theorem. The HO theory of international trade was able to explain that the differences of productivity in various countries are dependent on relative factor endowments. Leontief (Leontief 1951, 1954) calculated the labour and capital content of the exports of the United States to test the HO theory. The US seemed to be endowed with more capital relative to labour than any other country at that time. Therefore in terms of the HO theory, the US should have exported capital-intensive products and imported labour-intensive commodities. However, Leontief's test surprised the academic field as he reached a paradoxical conclusion that the US exported relatively more labour-intensive commodities and imported capital-intensive goods. These results received a great deal of attention and became known as the Leontief Paradox and have led to numerous studies discussing and critiquing the approach (see, for example, Stolper and Roskamp 1961; Bharawaj 1962).

By applying classical trade theory to environmental studies, a country may have a comparative advantage if it is endowed with certain resources or if it can produce a product with relatively low costs to the environment. Since the 1970s, numerous theoretical studies have been conducted to research the linkage of trade and the environment by adopting the principle of comparative advantage. For example, Pethig (1976), Siebert (1977), McGuire (1982) and Brander and Taylor (1997) treated a country's emission / resource management standards as factor endowment, and their results showed that countries with less stringent environmental policies could increase their comparative advantage in the production of pollution and natural resource-intensive products (quoted after Huang and Labys 2001). However this view is challenged by more recent research. Porter and van der Linde (1995) argued that strict environmental policies may not be a comparative disadvantage, in contrast, it may be an advantage to drive the producers and the whole economy to become more competitive in world markets by improving efficiency or innovating better environmental technologies. These conflicting views have led to a heated debate, and the empirical results are ambiguous (e.g. Huang and Labys 2001).

The important point to emphasise here is that environmental goods and services such as available water resources can be a factor of production and therefore a source of comparative advantage. Thus, if a region is well endowed with environmental resources such as water resources in this study, one could assume that this region's exports will have a larger share of water-intensive products. Applied to China, one would assume that water scarce North China would import water-intensive products and the water-rich South China would export products which would need lots of water inputs. The followings will test this hypothesis and investigate if these Chinese regions take full advantage of virtual water flows. This chapter will specifically build on the work of Leontief and use the input-output approach to assess regional and trade flows in China and their effects on virtual water flows.

5.3 Virtual water flows: an input-output approach

This section utilise Matrix **F** and **R** in the hydro-economic accounting framework which is described in Chapter 4, in order to quantify the virtual fresh and waste water flows respectively. This study is based on the year of 1997, therefore the required dataset for is very similar to Chapter 4. Besides, it requires the input-output table for South China which only consists of Guangdong due to the lack of data availability. However, it would not significantly influence on the results as the rest two provinces (Guangxi and Fujian) have very similar in terms of economic, social and hydrological characteristics. In addition, this chapter also requires the trade data which can be found at the "net exports" column of two regional input-output tables respectively.

5.3.1 Virtual freshwater flows

By employing Equation (4.6) with replacing the total final demand **y** by net flows $\boldsymbol{\gamma}$ – **Total Water Consumption** = $\hat{f}\,(\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{\gamma}$, one can quantify virtual freshwater flows between economic sectors triggered by trade between various regions in China and abroad. Thus one can show how much water is necessary to produce certain goods that are then exported to other regions, including both direct and indirect water consumption for producing the exports. This amount of water used in the production chain is thus not available for water consumption for other purposes within that region. Similarly, the import of certain goods into the respective region causes water withdrawal and consumption in other regions or outside of China. The calculation of virtual water flows is conducted by multiplying the net exports vector (γ) and the total fresh water consumption coefficient matrix ($\hat{f}$). The results are shown in Table 5.1 for North China and Table 5.2 for Guangdong.

The column of 'net flow of goods and services' in both Table 5.1 and 5.2 provides details of the commercial trade activities in the respective regional economy. The column of 'direct freshwater coefficient' gives the comparison of the direct water consumption levels for each production sector. For example, the coefficient for paper production measures the amount of freshwater directly consumed by paper-making industries to produce 10,000 Yuan of paper products. One can see from the tables that agriculture in both regions is the most water-intensive sector; and food processing, paper and textiles require more water per unit of output than the other industrial sectors. The column of 'virtual freshwater net exports' shows the amount of freshwater embedded in goods and services and exported to other regions or countries via trade. The term 'value added/per unit of water' in the last column of both tables assesses the amount each economic sector contributes to GDP per cubic meter of freshwater.

Based on above calculations, one can find that North China imported a number of water intensive products and services. For example, North China spent 35.89 billion Yuan to purchase extra electricity from other regions in 1997, which means a virtual import of 147.9 million cubic meters of water which is withdrawn and used up in production processes in other regions. Another example is agriculture: North China received 44.67 billion Yuan through the export of agricultural products, and with it 7,339.3 million cubic meters of virtual water have been transported to other regions.

Table 5.1: Total Water Import / Export in North China

Region: North China	Net flows of goods and services (10,000 Yuan)	Direct freshwater Coefficient (m^3/10,000 Yuan)	Virtual freshwater Net Exports (Million m^3)	Value added/Water (Yuan/ m^3)
Rainfed Agriculture	1,859,505	862.0	3,055.1	8.1
Irrigated Agriculture	2,607,575		4,284.2	
Coal mining and processing	1,359,847	5.2	2.3	441.7
Petroleum and natural gas	864,149	5.1	1.5	428.8
Metal ore mining	546,304	4.8	0.4	344.7
Non-ferrous mineral mining	-2,430,346	4.7	-12.9	256.9
Food and tobacco processing	2,944,350	10.5	57.7	111.3
Textile goods	3,060,261	12.2	67.4	84.8
Wearing	2,431,617	4.0	11.6	308.0
Sawmills and furniture	619,342	5.0	3.8	348.3
Paper and products	993,460	18.0	28.6	83.3
Petroleum processing	-1,647,543	1.1	-2.5	693.6
Chemicals	-347,419	17.8	18.8	51.4
Non-metal mineral products	2,304,248	4.5	7.2	421.9
Metals smelting and pressing	-406,689	8.8	-17	98.2
Metal products	2,443,533	2.5	5.1	416.1
Machinery and equipment	-4,825,647	7.5	-53.3	167.7
Transport equipment	-312,987	3.2	-2	237.9
Electric equipments	-1,183,115	2.1	-9.6	201.2
Telecom equipment	-2,858,957	1.9	-31.5	104.1
Instruments	-552,792	2.3	-4.3	149.4
Maintenance machinery	-1,118,056	2.1	-5.9	116.3
Other manufacturing	2,742,628	8.5	25.9	215.7
Scrap and waste	-411,395	8.5	-3.7	355.7
Electricity	-3,589,807	41.5	-147.9	45.5
Gas production and supply	-49,679	10.0	-0.6	77.2
Water production and supply	-522,085	5.7	-5.5	181.9
Construction	-2,517,219	5.0	-12.1	503.7
Transport and warehousing	260,878	3.1	0.7	470.1
Post and telecommunication	245,262	2.4	1.4	881.8
Wholesale and retail trade	-1,749,342	2.2	-4.4	428.6
Eating and drinking places	47,464	2.2	0.2	877.5
Passenger transport	295,368	3.2	1.1	746.3
Finance and insurance	3,938,707	2.2	16.6	872.4
Real estate	-203,528	2.2	-0.2	1,251.7
Social services	278,293	1.8	2.1	723.3
Health services, social welfare	-182,955	3.3	-0.5	784.9
Education and culture	-1,341,098	3.1	-5.3	1,087.7
Scientific research	-12,857	2.4	-0.4	700.6
General technical services	1,533,501	4.0	6.5	1,321.3
Public and other services	205,888	5.0	1.7	815.0
Total Exports			4545.0	
Total Imports			-319.6	
Net Virtual Freshwater Exports			**4225.4**	

***Note**: the negative figures represent the inflows (imports) for both monetary and freshwater terms, and positive figures mean outflows (exports) for both monetary and freshwater terms.*

Table 5.2: Total Water Import / Export in South China

Region: Guangdong	Net flows of goods and services (10,000 Yuan)	Direct freshwater Coefficient (m^3/10,000 Yuan)	Virtual freshwater Net Exports (Million m^3)	Value added/Water (Yuan/ m^3)
Rainfed Agriculture	-642,700.5	784.0	-228.9	8.8
Irrigated Agriculture	-982,407.5		-349.4	
Coal mining and processing	-1,507,207	4.4	-6	27.3
Petroleum and natural gas	-227,718	4.9	-9.6	223.0
Metal ore mining	-369,356	4.2	-3	96.5
Non-ferrous mineral mining	-622,501	4.0	-2.7	443.8
Food and tobacco processing	1,138,328	9.9	15.8	133.4
Textile goods	-1,827,158	11.3	39.7	112.4
Wearing	11,054,187	3.9	46.6	537.2
Sawmills and furniture	-892,070	4.9	-2.7	167.2
Paper and products	2,920,391	16.8	77.6	67.0
Petroleum processing	-2,950,551	1.3	-3.1	426.2
Chemicals	-3,848,076	16.7	0.1	42.4
Non-metal mineral products	333,439	4.9	2	383.8
Metals smelting and pressing	-6,187,180	8.2	-48.3	37.9
Metal products	1,332,070	2.7	4.7	507.0
Machinery and equipment	-1,276,310	6.9	-8.9	88.3
Transport equipment	802,771	2.9	2.7	544.7
Electric equipments	7,150,944	1.9	40.5	263.8
Telecommunication equipment	1,263,254	1.7	21.6	74.2
Instruments	2,108,399	2.1	11.3	193.8
Maintenance machinery	-8,916	1.6	0.1	413.5
Other manufacturing	-517,380	7.9	1.5	280.9
Scrap and waste	11,115	7.5	0.9	495.5
Electricity	160,907	37.9	5.3	38.9
Gas production and supply	-3,290	9.3	0	133.8
Water production and supply	-11,741	5.7	0.3	206.5
Construction	0	4.8	1.1	566.7
Transport and warehousing	-2,900,271	2.7	-11.1	331.8
Post and telecommunication	101,923	2.8	1.5	693.3
Wholesale and retail trade	-111,226	2.3	7.7	453.3
Eating and drinking places	337,216	2.3	3.9	548.3
Passenger transport	530,143	2.7	2.4	911.9
Finance and insurance	-1,289	2.1	2.5	614.6
Real estate	0	2.8	2.2	958.0
Social services	791,523	1.9	4.8	753.0
Health services, social welfare	0	3.2	-0.2	675.4
Education and culture	0	2.8	0	1,258.6
Scientific research	0	2.2	0.3	505.5
General technical services	0	3.6	0	702.9
Public and other services	0	4.6	0	592.3
Total Export			296.7	
Total Import			-444.8	
Net Virtual freshwater Export			**-148.1**	

***Note**: the negative figures represent the inflows (imports) for both monetary and freshwater terms, and positive figures mean outflows (exports) for both monetary and freshwater terms.*

However, one has to consider that much of the agricultural land is rainfed in North China, which produces about 42% of total agricultural outputs[35]. The amount of rainwater embedded in agricultural products would not be readily available for any other economic production even if crops were not grown on this land. Therefore, the effective exportation of virtual water in agricultural sector only consists of irrigated water, which is 4,284.2 million cubic meters. Annually, 4,545.0 million cubic meters of fresh water virtually flow out of North China (which is used in the production of exports) excluding rainwater in the agricultural production. On the other hand, the import of virtual water was only 319.6 million cubic meters, which reduces the net flow to other regions to 4,225.4 million cubic meters. From a water conservation point of view, North China, characterised as water-scarce, should import water-intensive products rather than produce them. According to this analysis, North China used up more than 5% of its total water resources for producing exports to other regions, mainly through the trade of water-intensive commodities such as agricultural crops, processed food, textiles and chemical products. By contrast, Guangdong is endowed with rich water resources, but virtually imported 444.8 million m^3 of freshwater, 79% of which are through the trade of water-intensive products (e.g. irrigated agricultural products). On the other hand, Guangdong exports relatively water non-intensive commodities such as electric equipment and many commercial and social services.

By summarising the virtual freshwater flows of both North and South China, one can find that the trade patterns are apparently inconsistent with the original hypothesis: water-scarce regions in China produce and export water-intensive products but import water non-intensive commodities. Meanwhile, water-abundant South China imports water-intensive goods. One of the possible explanations could be that water has not been recognised as an important factor of production in China's economy as there are very low costs associated with the utilisation of water resources for most of the production. Another reason could lie in the fact that North China has suitable climatic condition, soil and land for many agricultural crops (Heilig et al. 2000). A third reason refers to the design of economic policies: Guangdong is subject to more favourable policies and better circumstances for investments in industry and services sectors than other regions. Since the economic reform in 1978, many locations in South China (including Guangdong) have been established as "Special Economic Development

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[35] In this study, the author assumes that the amount of water required by agricultural products is same between rainfed and irrigated agriculture.

Zone", which brought many commercial opportunities and triggered a regional economic boom. This is also reflected in changing water consumption patterns. These economic incentives led to a restructuring of the regional economy to higher value added products with relatively lower levels of resource inputs. Thus Guangdong imports and exports of virtual water reflect the economic structure of the more developed regional economies within these special economic zones. On the other hand, North China has a relatively lower economic growth rate and stronger focus on low value added and high water intensive production without these special policies.

If one consider multiple factors relevant for the existing production and trade structure such as environmental endowment (e.g. soil quality), land prices and other socio-economic or political factors, one can see that North China has a 'comparative advantage' for producing and exporting agricultural products. In terms of water conservation it is important to effectively balance these factors. North China may sustain the export of rainfed agricultural goods as rainwater cannot be effectively used by other production sectors. On the other hand, North China might want to reconsider the level of exports of irrigated agricultural products in order to make the scarce water resources (e.g. surface or ground water) available for other purposes which can contribute more to the economy and society in terms of value added and jobs.

From a water efficiency point of view, North China with limited water resources, should produce and export the commodities which have high value added per unit of water. By looking at the column of 'value added/water' in Tables 5.1 and 5.2 North China has a comparative advantage in the production sectors of coal mining and processing, production of sawmill and furniture, machinery equipment, and many service sectors. Meanwhile, Guangdong has the advantage on producing agriculture, textiles, and metal products. Obviously this statement needs to be qualified by looking at other factors such as the availability of skilled labour and other essential factors of production, but the focus on water can provide a useful starting point.

5.3.2 Virtual wastewater flows

Similar to the virtual freshwater flows, wastewater is also created through trade related production. The pollutants and wastewater generated for producing exported goods will stay in or pass through the exporting region leading to negative effects in terms of water availability and quality. In other words, the exporting region virtually accepts the discharge of wastewater from other regions by exporting goods. Similarly to virtual freshwater flows, one can calculate virtual wastewater flows consumed by producing exports for both North China and Guangdong. By employing Equation (4.8) with replacing total final demand **y** with net flows γ – **Total Wastewater Generation** = $\hat{r}(\mathbf{I} - \mathbf{A})^{-1}\gamma$, one is able to quantify virtual wastewater flows triggered by imports and exports between various regions in China and abroad. The direct wastewater coefficient refers to the amount of wastewater per unit of output. The results are shown in Table 5.3 for North China and in Table 5.4 for Guangdong.

A number of pollution-intensive industries (e.g. metal mining, paper and chemical production) are concentrated in North China. Imports of North China lead to the generation of 149.7 million m^3 of wastewater in other regions where the commodities were produced while North China's exports resulted in 520.7 million m^3 of wastewater in North China, of which 32% is industrial wastewater and 68% is agricultural wastewater. Hence the net wastewater balance for North China was 371.0 million m^3. The discharge of high-concentrated pollution to surface flows from pollution-intensive production sectors (e.g. paper, chemicals and textiles) has led to the fact that many major rivers in North China no longer support any type of usage due to the low water quality levels; and more than 50% of groundwater has been seriously degraded due to the overuse of fertilizers and pesticides (Dong 2000).

Looking at the situation in the southern provinces, Guangdong virtually exports (externalises) 149.4 million m^3 of agricultural wastewater and 141.3 million m^3 of wastewater from industrial and service sectors to pollute other regions' hydrological ecosystems. The industrial wastewater is mainly contributed from paper, textiles and electric equipment production sectors. On the other hand, Guangdong accepts 213.1 million m^3 of wastewater by producing exports for other regions' consumption. Hence the water-rich Guangdong region has a net wastewater balance of 77.6 million m^3 being virtually discharged to other regions.

Thus from above figures, one can find a similar trade contradiction as with the virtual freshwater flows. The wastewater virtually flows out from water-rich region such as Guangdong which externalises the problems of wastewater production to other regions through importing wastewater intensive products and water-shortage regions such as provinces in North China are threatening their own water resources through the creation of waste water for producing exports.

Table 5.3: Total Wastewater Import / Export in North China

Region: North China	Net flows of goods and services (10,000 Yuan)	Direct wastewater Coefficient (m^3/10,000 Yuan)	Virtual wastewater New flows (Million m^3)	Value added /wastewater (Yuan/ m^3)
Agriculture	4,467,080	79.4	354.8	125.9
Coal mining and processing	1,359,847	10.2	4.7	220.8
Petroleum and natural gas	864,149	10.6	3.0	214.4
Metal ore mining	546,304	21.6	1.6	82.1
Non-ferrous mineral mining	-2,430,346	4.2	-10.4	321.1
Food and tobacco processing	2,944,350	4.2	20.1	320.0
Textile goods	3,060,261	6.9	39.9	143.4
Wearing	2,431,617	1.9	3.3	1071.3
Sawmills and furniture	619,342	1.3	2.5	539.1
Paper and products	993,460	19.2	27.2	87.7
Petroleum processing	-1,647,543	3.2	-5.0	346.8
Chemicals	-347,419	18.8	16.9	57.1
Non-metal mineral products	2,304,248	2.9	4.2	730.1
Metals smelting and pressing	-406,689	10.8	-15	111.6
Metal products	2,443,533	6.9	3.1	693.4
Machinery and equipment	-4,825,647	9.3	-49.8	179.5
Transport equipment	-312,987	4.6	-0.7	706.5
Electric equipments	-1,183,115	3.4	-5.4	357.0
Telecommunication equipment	-2,858,957	3.4	-17.7	184.7
Instruments	-552,792	5.2	-4.2	155.0
Maintenance machinery	-1,118,056	2.6	-2.3	304.6
Other manufacturing	2,742,628	6.6	18.9	295.7
Scrap and waste	-411,395	6.7	-2.7	480.0
Electricity	-3,589,807	0	0	0.0
Gas production and supply	-49,679	16.2	-1.0	47.1
Water production and supply	-522,085	16.9	-9.0	110.9
Construction	-2,517,219	8.3	-19.6	312.1
Transport and warehousing	260,878	4.4	0.6	534.2
Post and telecommunication	245,262	4.4	1.2	1002.0
Wholesale and retail trade	-1,749,342	2.5	-2.4	793.7
Eating and drinking places	47,464	2.9	0.2	1300.0
Passenger transport	295,368	2.6	0.7	1105.7
Finance and insurance	3,938,707	2.3	11.2	1292.4
Real estate	-203,528	2.1	-0.2	1854.3
Social services	278,293	2.1	1.4	1071.6
Health and social services	-182,955	2.6	-0.4	1162.8
Education and culture	-1,341,098	1.7	-3.6	1611.4
Scientific research	-12,857	2.1	-0.3	1037.9
General technical services	1,533,501	1.8	4.4	1957.4
Public and other services	205,888	2.1	0.8	1811.2
Total virtually accepted wastewater for other regions' consumption			520.7	
Total virtually generated wastewater left in other regions			-149.7	
Net virtual wastewater left for exports			**371.0**	

Note: *the negative figures represent the imports for monetary flows but the amount of wastewater is generated for producing such imports, and positive figures mean the export for monetary flows but the amount of wastewater is generated for producing such exports.*

Table 5.4: Total Wastewater Import / Export in South China

Region: Guangdong	Net flows of goods and services (10,000 Yuan)	Total wastewater Coefficient (m^3/10,000 Yuan)	Virtual wastewater New flows (Million m^3)	Value added/ wastewater (Yuan/ m^3)
Agriculture	-1,652,108	70.1	-149.4	142.5
Coal mining and processing	-1,507,207	9.5	-15.1	10.9
Petroleum and natural gas	-227,718	9.7	-23.9	89.2
Metal ore mining	-369,356	19.9	-15.8	18.4
Non-ferrous mineral mining	-622,501	3.5	-2.7	443.8
Food and tobacco processing	1,138,328	3.3	6.3	333.5
Textile goods	-1,827,158	6.4	27.0	165.3
Wearing	11,054,187	1.9	15.3	1634.9
Sawmills and furniture	-892,070	1.6	-2.5	181.2
Paper and products	2,920,391	17.3	86.7	59.9
Petroleum processing	-2,950,551	2.9	-9.3	142.1
Chemicals	-3,848,076	17.9	0.1	35.4
Non-metal mineral products	333,439	2.9	1.5	516.6
Metals smelting and pressing	-6,187,180	9.6	-53.2	34.4
Metal products	1,332,070	6.7	3.6	676.0
Machinery and equipment	-1,276,310	8.9	-8.9	88.2
Transport equipment	802,771	4.6	1.0	1510.0
Electric equipments	7,150,944	3.5	25.1	425.5
Telecom equipment	1,263,254	3.7	13.4	119.7
Instruments	2,108,399	4.9	12.0	182.8
Maintenance machinery	-8,916	2.7	0	984.5
Other manufacturing	-517,380	6.2	1.9	226.5
Scrap and waste	1,115	6.5	0.7	629.2
Electricity	160,907	0.0	0	0.0
Gas production and supply	-3,290	14.7	0	73.5
Water production and supply	-11,741	15.4	0.5	113.3
Construction	0	7.6	1.7	351.1
Transport and warehousing	-2,900,271	4.0	-9.8	377.0
Post and telecommunication	101,923	4.1	1.3	787.9
Wholesale and retail trade	-111,226	2.6	4.2	839.4
Eating and drinking places	337,216	2.7	2.6	812.3
Passenger transport	530,143	2.9	1.6	1351.0
Finance and insurance	-1,289	2.1	1.7	910.6
Real estate	0	1.9	1.5	1419.3
Social services	791,523	1.9	3.2	1115.6
Health and social services	0	2.4	-0.1	1000.5
Education and culture	0	1.5	0	1864.5
Scientific research	0	1.9	0.2	748.8
General technical services	0	1.6	0	1041.3
Public and other services	0	1.9	0	1316.2
Total virtually accepted wastewater for other regions' consumption			213.1	
Total virtually generated wastewater left in other regions			-290.7	
Net virtual wastewater left for exports			**-77.6**	

Note: *the negative figures represent the imports for monetary flows but the amount of wastewater is generated for producing such imports, and positive figures mean the export for monetary flows but the amount of wastewater is generated for producing such exports.*

5.4 Conclusion

The economic success in China has come at the expense of over exploitation of natural resources and huge impacts on the environment and especially water resources. In North China, water scarcity has become one of the bottlenecks for regional economic development. This chapter has looked at the economic and trade structure of the water-scarce northern regions of China and the water abundant southern regions of China, and assessed the implications for water resources in those regions.

This study was one of the very first to use the concept of virtual water flows not only for agricultural products but also industrial and service production. In addition this chapter accounted also for waste water flows and distinguished between rainfed and irrigated agriculture, which is of special significance with regards to water use. But one of the major shortcomings is the homogenous treatment of very different qualities of water inputs and wastewater categories.

The starting point was the assumption that from a water conservation point of view, a region/country that is endowed with vast amounts of water resources should export relatively more water-intensive/polluted products such as agricultural crops, paper and chemicals. However, the generated results of virtual freshwater flows show that water-scarce North China predominantly produces and exports water-intensive products but imports non-water intensive commodities. In comparison, water-abundant Guangdong (South China) imports water-intensive goods but exports non water-intensive products. A similar situation can be found when considering wastewater: the water-scarce North creates more waste water for export production than is virtually created through its imports; and similarly, the water-abundant South externalises waste water problems by importing waste water-intensive products from other regions.

With regards to the actual extent of the virtual water flows, the results seem to indicate that the current structure of economy and trade do not pose so much of a problem in terms of freshwater consumption as in North China only about 5% of total available water can be attributed to net virtual water flows, which is relatively minor in comparison to major water consumers such as water losses due to infrastructural inefficiencies. In other words, the water-scarce North China does not take full advantage of the possibilities of importing water-intensive products to ameliorate its own water problems. The same seems to be true for the wastewater situation.

To reflect on a more theoretical level, economic production and consumption use inputs of materials and resources from the environment, however, environmental resources are currently highly undervalued as there are often little or no costs associated with their consumption. Therefore, water usually does currently not play a sufficiently important factor in production and consumption decisions. This is also reflected in current trade theories largely ignoring the environment as a factor of production. The same is true from a policy point of view; export-oriented policies often directly conflict with water-saving policies leading to so-called perverse incentives. On the other hand, given the relative inflexibility in changing production structures in comparison to technical improvements these findings emphasise the need for increased investments in water transportation infrastructure and water treatment plants. However from a sustainability point of view it is important to emphasise that direct and indirect (virtual water) consumption needs to be incorporated in decision-making processes and public policies, especially for water-scarce regions such as North China, in order to achieve sustainable consumption and production in the future.

Chapter 6: Great Leap Forward in Consumption or Technology? – An Approach of IPAT-IO Structural Decomposition Analysis on China's CO_2 Emissions[36]

China is the most populous country in the world, accounting 22% of the world total. The recent rapid economic growth is bringing wealth and prosperity but China's energy supply are struggling to keep pace. Between 1981 and 2002, China's total final energy consumption has grown by 4.2% annually from 17,445 Petajoule (PJ) to 40,956 PJ while CO_2 emissions grew by 3.8% per year from 1,537 million metric tons (MMT) to 3,371 MMT.

In a global context, China is the second-largest contributor to CO_2 emissions emitting 17% of global CO_2 in 2004, up from 8% in 1980 (USEPA 2006), and China is predicted to become the world's largest emitter by as early as 2009 (IEA 2006).

The increasing discharge of CO_2 will directly cause global warming, which would have negative impacts on the environment, economy and society such as lowering production of rice, wheat, and cotton, raising temperature, increasing soil evaporation, and more frequent and severe storms. Particularly in recent years, the threatening to costal China from rising sea level has alarmed China's policy makers in controlling the CO_2 discharges. Over the past 50 years, China's sea level along the costal areas averagely rises up 2.5 millimetre per year, which is about 1.4 times higher than the world average of 1.8 centimetres per year (IPCC 2001). In terms of the recently released IPCC (2007) on "Impacts, Adaptation and Vulnerability", by estimation China's sea level will continue to increase by 9-38 centimetres in the next decade if China keeps the same pace in generating CO_2. In case the sea level increases by 30 centimetres, as a result, 90% of China's special economic development zones along the coast, in other words the most developed areas, will be flooded. The total flooded

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[36] The majority of this chapter is in preparation and going to be submitted to the *Proceedings of the National Academy of Science* or *Global Environmental Changes*. The last section on setting up experiments has been published in *Futures: The Journal of Policy, Planning, and Futures Studies*, entitled "Changing Lifestyles and Consumption Patterns in Developing Countries: A Scenario Analysis in China and India" (Hubacek et al. 2007); and in *Scenarios and Indicators for Sustainable Development*, entitled 90 years lifestyle changes and CO_2 emission in China and India (Hubacek et al. 2007).

land areas are equal to 2.3% of China's territory. There will also results in 21 million migrants from costal to inner China.

Therefore, understanding the key drivers behind China's growing energy consumption and associated emissions is critical for both Chinese and global climate and energy policy. In addition it is likely that other developing countries such as Vietnam and India are adopting similar growth paths as China, and the lessons learned by analysing China's changing energy consumption may provide guidance towards a low emission development way for other countries (Peters et al. 2007).

Section 3.6 gives a detailed review on both *IPAT* and structural decomposition analysis, and indicates the possibility of the combination of both models; therefore this chapter introduces the mathematical principle of the combination of the newly developed IPAT-IO SDA framework to analyse the causes of China's growth in energy consumption and associated emissions over the past 20 years.

This study is one of the very first studies to employs all major available China's IOTs including the most recent released 2002 IOT and energy data to establish structural decomposition analysis and thus allows insights into the driving forces in the most interesting period of China's economic growth since the reforms in 1978.

6.1 IPAT-IO structural decomposition analytical framework

The driving forces in many previous SDA in studying GHGs emission, which are referred to the causes of change of environmental emission (e.g. CO_2 emission in this study), usually consists of four factors: the change of CO_2 intensity, production technology improvements, people's consumption changes in terms of both patterns and volumes. The changes of population size have always been ignored. On the other hand, the driving forces of CO_2 emission in *IPAT* consist of population, affluence and technology at a much higher level of aggregation. Most of the driving forces in the two frameworks overlap. The structural decomposition can be further strengthened by combining all elements into one framework, as IPAT-IO SDA. For example, the technology in the *IPAT* can be replaced with the CO_2 intensity matrix in input-output modelling, which significantly improves the aggregation level of technology in the *IPAT* equation. Similarly the aggregation level of affluences in *IPAT* can be expanded by replacing with final demand categories in IOT. In this study, the affluence level is disaggregated into seven final demand categories with distinction of urban and rural resident consumptions in order to implement a more precise analysis in investigating the major contributor to the CO_2 emission. Furthermore, by adding the population factor in the *IPAT* equation into the SDA can make more sense for many populous countries, such as China. Therefore the IPAT-IO SDA framework can be used to evaluate the change of environmental emissions, triggered by population growth, the change of CO_2 intensity, production technology improvements, people's consumption structure changes, and per capita growth of consumption volumes.

The following sections 6.2.1 – 6.2.3 provide the theoretical background and mathematical principles for the most commonly accepted approaches in structural decomposition analysis, which are based on the studies conducted by Heokstra and van der Bergh (2003), Rørmose and Olsen (2005) and de Boer (2006).

6.1.1 IPAT-IO SDA theoretical background

The principal idea of SDA can be illustrated as shown in Equation (6.1) in the case of a two determinant multiplicative function.

$$y = x_1 \cdot x_2 \qquad \textbf{(6.1)}$$

The change of y (Δy) can be decomposed between two time points, t and $t\text{-}1$ into changes of the driving forces, x_1 and x_2. However there is no unique solution for the decomposition. For example, one can start the decomposition from the base year (e.g. $t\text{-}1$), which is referred to the Lasperyres index, whereas one can also begin the process from the target year (e.g. t), which is referred to as the Paasche index, as shown in Equation (6.2). Together using both Lasperyres and Paasche indices for decomposition analysis is referred to as so-called polar decompositions (de Boer 2006). Heokstra and van den Bergh (2003) examined that neither of the polar decompositions would lead to a complete decomposition (e.g. no residual terms), and the usual solution for this is to combine the two perspectives, so either Lasperyres-Paasche or Paasche-Lasperyres index.

$$\Delta y = y_t - y_{t-1} = \Delta(x_1 \cdot x_2)$$

or, **(6.2)**

$$\Delta y = y_{(t-1)} - y_t = \Delta(x_1 \cdot x_2)$$

Furthermore, the change of x_1 can be expressed as: $\Delta x_1 = x_{1(t)} - x_{1(t-1)}$; similarly, $\Delta x_2 = x_{2(t)} - x_{2(t-1)}$.

One of the possibilities is to decompose Equation (6.2) is by using Lasperyres-Paasche index as shown in Equation (6.3):

$$\begin{aligned} \Delta(x_1 \cdot x_2) &= x_{1(t)} \cdot x_{2(t)} - x_{1(t-1)} \cdot x_{2(t-1)} \\ &= (\Delta x_1 + x_{1(t-1)}) \cdot x_{2(t)} - x_{1(t-1)} \cdot x_{2(t-1)} \\ &= \Delta x_1 \cdot x_{2(t)} + x_{1(t-1)} \cdot x_{2(t)} - x_{(t-1)} \cdot x_{2(t-1)} \qquad \textbf{(6.3)} \\ &= \Delta x_1 \cdot x_{2(t)} + x_{1(t-1)} \cdot (\Delta x_2 + x_{2(t-1)}) - x_{(t-1)} \cdot x_{2(t-1)} \\ &= \Delta x_1 \cdot x_{2(t)} + x_{1(t-1)} \cdot \Delta x_2 \end{aligned}$$

However, the other possibility to decompose Equation 6.2 is by using Paasche-Lasperyres index as shown in Equation 6.4:

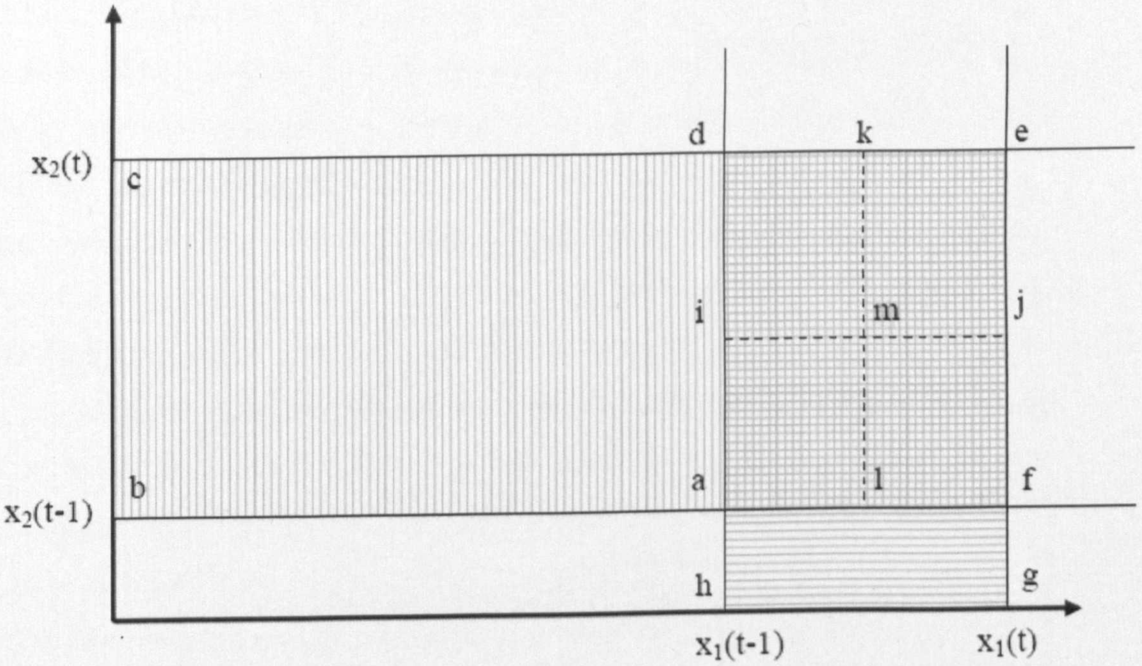
$$\Delta(x_1 \cdot x_2) = \Delta x_1 \cdot x_{2(t-1)} + x_{1(t)} \cdot \Delta x_2 \qquad \textbf{(6.4)}$$

Hereby, the core question is to examine whether the above two terms are congruent with the requirements of decomposition, which comprises the following three conditions in terms of Hoekstra and van der Bergh (2003) and de Boer (2006).

- complete, which means there are no residual terms
- "0" robust, which means it can deal with "0" values in the calculation
- time reversal, which means the decomposition produces a reverse result if the time period has been reversed, for example $\Delta y = y_t - y_{t-1} = -(y_{t-1} - y_t)$.

The method to examine the "complete" condition can be simple illustrated in Figure 6.1; Equation (6.3) covers the areas of "hdeg + bcda" with residual term "0" while the areas of Equation (6.4) covering is the "hafg + bcef" with residual term of "0"., Both decompositions cover the required areas (filled with dashed lines), which means they are qualified with the requirements of 'complete' and the condition of "0" robust for implementing calculations (Hoekstra and van der Bergh 2003; de Boer 2006). Equations (6.3) and (6.4) follow from each other by reverting base and comparison period. However neither of the above expressions satisfies the requirement of time reversal. A common approach is to take the average of these two equations to satisfy this requirement. Equation (6.3) and (6.4) is a "mirror pair" decomposition, which is the pair of permutations where the time period indication on the coefficients attached to each difference term is exactly the opposite (Dietzenbacher and Los 1998).

Figure 6.1: Additive decomposition of $y = x_1 \cdot x_2$, discrete time



Source: (Hoekstra and van der Bergh 2002; Rørmose and Olsen 2005)

As mentioned previously, either Lasperyres – Paasche or Paasche – Lasperyres index would fulfil the requirement of the "complete" requirement. The two approaches are equivalent and there is no reason why one of them should be preferred to the other (Rørmose and Olsen 2005). Therefore, the decomposition of *y* is not unique; however the result (e.g. the covered areas in Figure 6.1) is unique in this two determinants case. The problem is a so-called non-uniqueness which means that there exist a number of different decomposition forms and that it cannot be decided which one to prefer. Usually, the factors in SDA studies are more than three, Dietzenbacher and Los (1998) proved that in the case of *n* factors, the number of possible "complete" decompositions (without any residual terms) is equal to *n!*. For example, this chapter assesses five determinants in the change of CO_2 emissions, so the possible decompositions are *5! = 120*.

6.1.2 IPAT-IO SDA of CO_2 emission driving by five factors

In general, a country's energy demand and associated emissions change over time for a variety of reasons—population growth, increases in economic output, changes in trade structure, infrastructure investment, technical change and efficiency improvements, and changes in the production and consumption systems. This chapter will adopt five factors to assess the change of CO_2 emissions with application of the IPAT-IO SDA framework, and one of the *5!=120* "complete" decomposition function is shown in Equation (6.5):

$$\begin{aligned}
\Delta CO_2 &= \Delta CO_{2(t)} - \Delta CO_{2(t-1)} \\
&= p_{(t)} \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{s(t)} \cdot \mathbf{y}_{v(t)} - p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \cdot \mathbf{y}_{s(t-1)} \cdot y_{v(t-1)} \\
&\qquad \textit{One of the 120 possible decomposition is:} \\
&\dots\dots \qquad\qquad (6.5) \\
&= \Delta p \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{s(t)} \cdot y_{v(t)} + p_{(t-1)} \cdot \Delta\mathbf{F} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{s(t)} \cdot y_{v(t)} + p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \Delta\mathbf{L} \cdot \mathbf{y}_{s(t)} \cdot y_1 \\
&\quad + p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \cdot \Delta\mathbf{y}_s \cdot y_{v(t)} + p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \cdot \mathbf{y}_{s(t-1)} \cdot \Delta y_v
\end{aligned}$$

where,

p – is a scalar, population
F – is the diagonalised CO_2 emission coefficient matrix
L – is the Leontief inverse matrix, $\mathbf{L=(I-A)^{-1}}$
$\mathbf{y_s}$ – is a column vector representing per capita consumption patterns
y_v – is a scalar representing the total consumption volume

Equation (6.5) comprises five terms in total; each term represents the contribution to change in CO_2 emissions, □CO_2 triggered by one driving force with keeping the rest of factors constant, correspondingly. The first term represents population growth, p; the second term represents the aggregated changes in the emission intensities (efficiency), **F**; the third term represents changes in the production structure, **L**; the fourth term represents changes in the consumption structure, $\mathbf{y_s}$; and the fifth term represents changes in the consumption volume (GDP), y_v.

6.1.3 "Weights" in IPAT-IO structural decomposition equations

As Equation (6.5) shows, the change of CO_2 emission is decomposed into five terms, and each term represents the contribution of the changing factor ("Δfactor") of the total change of CO_2 emission. One can perceive a logical pattern that the "Δfactor" is placed at each term in turn from left to right; and the other constant factors on the left side of the "Δfactor" are in base year value (year "*t-1*"); and the ones on the right side of the "Δfactor" are in target year value (year "*t*"). Therefore, by extracting the constant values in each term Equation (6.5) can be re-written as Equation (6.6):

$$\Delta CO_2 = w^p \Delta p + w^{\mathbf{F}} \cdot \Delta\mathbf{F} + w^{\mathbf{L}} \cdot \Delta\mathbf{L} + w^{\mathbf{y}_s} \cdot \Delta\mathbf{y}_s + w^{y_v} \cdot \Delta y_v \qquad (6.6)$$

where the w^p, $w^{\mathbf{F}}$, $w^{\mathbf{L}}$, $w^{\mathbf{y}_s}$ and w^{y_v} is the so-called "weight" or "coefficient" for each "Δfactor" respectively. The calculation of these weights or "coefficients" are usually done via econometric methods; alternatively, they can be generated via a more straight forward way by deriving them with the structural decomposition method (Hoekstra and van der Bergh 2002).

As mentioned earlier, Equation (6.5) is not a unique decomposition equation, which is only one of the 120 decomposition equations by assuming the order of the driving forces of "$p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y}_{\mathrm{V}} \cdot y_s$". However, the order can also be "$\mathbf{F} \cdot p \cdot \mathbf{L} \cdot \mathbf{y}_{\mathrm{V}} \cdot y_s$" or "$\mathbf{L} \cdot \mathbf{F}\ \mathbf{y}_{\mathrm{V}} \cdot y_s \cdot p$" and so on. Although each decomposition equation would produce exactly the same result for ΔCO_2, de Haan (2001) found that the size of the contribution of each "Δfactor" significantly differs across the equations. In other words, the "coefficient" (w) of each "Δfactor" is varied in different equations.

Due to the non-uniqueness issue, Dietzenbacher and Los (1998) suggested to take the average of all the *n!* (*5!* in this case) decomposition equations. In order to do so, all the 120 equations need to be sorted into a standard order, for example, every term in the equation needs to be re-arranged to the order of "$p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y}_{\mathrm{V}} \cdot y_s$", and the "Δfactor" is in turn placed from the first factor of "p" in the first term of the equation to the last factor of y_s in the last (fifth) term. Then, all the equations have been re-arranged in the same pattern. For example, the first term of every equation contains the information of contribution of population growth (Δp) to the change of CO_2 (ΔCO_2) with keeping other factors constant. The constant values are the "coefficient" for Δp. The "coefficient" $\mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \cdot \mathbf{y}_{s(t-1)} \cdot y_{v(t-1)}$ appears 24 times, and same as the "coefficient" $\mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{s(t)} \cdot y_{v(t)}$ does. de Haan (2001) and Seibel (2003) found that each term in the equation always has $2^{(n-1)}$ different "coefficients" attached to the "Δfactor", $2^{(5-1)} = 16$ different "coefficients" to every "Δfactor" in this case.

Next one can calculate the "weights" of the "coefficients" which is attached to the "Δfactor". The easiest way is via observations, to count how many cases of "Δfactor" are attached to the same "coefficient". For example as mentioned previously, the "coefficient" $\mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \cdot \mathbf{y}_{s(t-i)} \cdot y_{v(t-1)}$ appears 24 times in the 120 equations, and therefore its weight is 24. However, the observation method could be difficult in large number of decomposition equations with more than 5 factors.

Seibel (2003) proposed a mathematic method to deal with this. Firstly, let k represent the number of subscript "*t-1*" (base year) in a coefficient; k runs from "0" to "*n-1*";

therefore, the number of subscript "*t*" (target year) would be "*n-1-k*". Secondly, for each *k*, the number of different coefficients attached to the "Δfactor" can be calculated by Equation 6.7:

$$\frac{(n-1)!}{(n-1-k)!\cdot k!} \qquad \textbf{(6.7)}$$

In this study, *n* is set to 5 (five factors). So when *k*=0 or 4, there is only one coefficient for each case; when *k*=1 or 3, the number of different coefficients are 4 respectively; when *k*=2, there would be 6 different coefficients. Thirdly, Equation (6.8) calculates how many times each of these coefficients is repeated as "weights" for each "Δfactor" term in every equation of *n!*. The results for Equation (6.7) and (6.8) are shown in Table 6.1 for the case of *n*=5.

$$(n-1-k)!\cdot k! \qquad \textbf{(6.8)}$$

Table 6.1: Subscripts for the components of "Δfactor's" coefficients and their weights

k	Subscript for the components in the coefficients				**Weight**
	first	second	third	fourth	
0	*t*-1	*t*-1	*t*-1	*t*-1	**24**
1	*t*	*t*-1	*t*-1	*t*-1	**6**
	t-1	*t*	*t*-1	*t*-1	
	t-1	*t*-1	*t*	*t*-1	
	t-1	*t*-1	*t*-1	*t*	
2	*t*	*t*	*t*-1	*t*-1	**4**
	t	*t*-1	*t*	*t*-1	
	t	*t*-1	*t*-1	*t*	
	t-1	*t*	*t*	*t*-1	
	t-1	*t*	*t*-1	*t*	
	t-1	*t*-1	*t*	*t*	
3	*t*-1	*t*	*t*	*t*	**6**
	t	*t*-1	*t*	*t*	
	t	*t*	*t*-1	*t*	
	t	*t*	*t*	*t*-1	
4	*t*	*t*	*t*	*t*	**24**

Source: Modified from (Rørmose and Olsen 2005)

Therefore, each "*w*" attached to the "Δfactor" in Equation 6.6 can be defined, for example,

$$\begin{aligned} w^{p}\Delta p = \frac{1}{120}[& (24\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)}) + \\ & (6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)}) + \\ & (6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)}) + \end{aligned}$$

$$
\begin{aligned}
&(6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{\mathbf{s}(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{\mathbf{s}(t-1)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{\mathbf{s}(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{\mathbf{s}(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{\mathbf{s}(t-1)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t-1)})+\\
&(24\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{\mathbf{s}(t)}\cdot y_{v(t)})]
\end{aligned}
$$

and it is similar to the other "*w*"s in Equation 6.6. The simplified full five factors decomposition equation with assigned weights is shown in Appendix B, which is used to generate the results in section 6.4.

6.2 Data

This study requires two-sets of data. One set are time-series input-output tables and the corresponding energy and CO_2 emission data.

6.2.1 Input-output tables

The time-series input-output tables (IOT) used in this study contain eight different years: 1981 (State Statistical Bureau of China 1983), 1987 (State Statistical Bureau of China 1989), 1990 (State Statistical Bureau of China 1992), 1992 (State Statistical Bureau of China 1996), 1995 (State Statistical Bureau of China 1997), 1997 (State Statistical Bureau of China 2000), 2000 (State Statistical Bureau of China 2002) and 2002 (State Statistical Bureau of China 2006). All the tables were in current prices.

The different years had different industry classifications – 26 sectors for 1981; 33 sectors for 1987, 1990 and 1995; 40 sectors for 1997 and 2000; and 42 sectors for 2002 – however, there was considerable overlap in the classifications. All the tables are aggregated to a uniform classification with 18 sectors. The final demand consists of 6 categories: urban households, rural household, government expenditures, fixed capitals investments, change of stock and net flows.

This study uses the classification categories of the State Statistical Bureau of 'non-peasants' for urban population and 'peasants' for rural population. Unfortunately, there are gross inconsistencies in the State Statistic Bureau's classification system for urban, rural, and city population, because the system mixes territorial and functional definitions. The definitions have also been changed over time and non-recorded migration from rural to urban areas further distorts the actual residency (Heilig et al. 2000; Hubacek and Sun 2001).

6.2.1.1 Double deflation process

For the IPAT-IO SDA, all the IOTs are converted from current price into 1997 constant prices using the double deflation method (de Boer and Broesterhuizen 1991; Durand 1994; Folloni and Miglierina 1994). This method has been widely accepted and is advocated by the United Nations (United Nations 1999). The double deflation method is described as follows,

The IOT in current prices can be represented as

$\mathbf{Z}$	$\mathbf{y}$	$\mathbf{x}$
$\mathbf{v}'$		
$\mathbf{x}'$		

where the $n \times n$ matrix **Z** denotes the intermediate deliveries between production sectors; the vector of **y** is the total final demand (including urban households, rural households, government, gross capital formation, changes in stocks, and net export); the vector **x** represents the total sectoral output; **v'** is a row vector of total value added. The IOT in constant prices obtained by using double deflation is

$\mathbf{Z}_d = \hat{\mathbf{d}}\mathbf{Z}$	$\mathbf{y}_d = \hat{\mathbf{d}}\mathbf{y}$	$\mathbf{x}_d = \hat{\mathbf{d}}\mathbf{x}$
$\mathbf{v}_d'$		
$\mathbf{x}_d'$		

The subscript d is used to indicate that the corresponding matrices and vectors are in constant prices after the deflation by using the double deflation method. Let p_i denote the ratio of the current price and the base year price, for product i. Thus, $100p_i$ is the price index. This study sets 1997 as the base year, and the price indices are adopted from official Chinese price statistics (National Bureau of Statistics 2005). The price indices are available for four agricultural sectors, 15 industrial sectors, and eight services sectors. Since there is a total of 95 sectors in the IOT, the same index is applied to similar sectors when there was not a direct correspondence. The element d_i of the vector **d** denotes the deflator in sector i, which is defined as the reciprocal price ratio ($d_i = 1/p_i$). Therefore, $\mathbf{Z_d}$ is obtained by multiplying the $\hat{\mathbf{d}}$ with $\mathbf{Z}$. One can calculate $\mathbf{y_d}$ and $\mathbf{x_d}$ in a similar way. The value added vector $\mathbf{v_d}'$ is then obtained from the balancing equation,

$$\mathbf{v_d}' = \mathbf{x_d}' - \mathbf{e}'_{(\mathbf{n})}\mathbf{Z_d}$$

where $\mathbf{e}'(\mathbf{n})$ is a row vector of ones used for summation of $\mathbf{Z_d}$.

The double-deflation method is used to compile the input-output tables in constant prices. Although the double deflation method is widely accepted, there are three drawbacks related to this approach. Firstly, by adopting this method, most sectors are assumed to produce one homogeneous product, each sector's gross output and intermediate and final demand are deflated by this sector's price index (Dietzenbacher and Hoen 1998). However, most sectors consist of more than one good, therefore to use the price index of certain goods to represent the entire sector is not always appropriate (Sevaldson 1976). Secondly, value-added is obtained as the difference between the total input and intermediate input in each sector. Consequently, it is not accurate to use value-added to balance the input-output table after the deflation (Wolff 1994). Thirdly problem arises from sectoral aggregation: a deflated IO table may be obtained in two alternative ways. The first way is to aggregate after deflation, which means that the original table is deflated first, resulting in a value added vector in constant prices, which then is aggregated. The other way, deflation after aggregation, means that the original table is first aggregated and then deflated. The two methods may produce different results unless very stringent conditions are satisfied (Kymn 1990; Dietzenbacher and Hoen 1998). However, the available constant price indices comprise 17 sectors thus the same price index is applied to similar economic sectors to match the IO tables of 18 sectors.

6.2.1.2 Treatment of the "Other" column

The Chinese IOTs follow most standard formats except for a column which is in addition to the final demand columns called "Others". This column appears in all the years except 1995. The GDP derived by summing the value added matches the GDP derived by summing final demand only if "Others" is included. The error in aggregated GDP by not including "Others" is small (<1%). However, on a sector-by-sector basis "Others" can represent up to 8% of output or even totally dominate final demand (Peters et al. 2007). This suggests considerable caution is needed if using "Others" as a final demand. Since "Others" plays a dominant role in some sectors, there is no obvious treatment of "Others" to avoid spurious results.

According to the State Statistical Bureau of China (2000) the "Others" column primarily represents different reported data, particularly related to trade. Thus, "Others" is interpreted as an estimate of an error term representing different data sources. It should not include the error in the calculation of output, thus output, $\mathbf{x}_{\mathbf{total}}$, is given as the sum of the intermediate flows and the final demand not including "Others". This output is then used to normalise the IOT and emissions data, which is described in the following section 6.3.2.

6.2.1.3 Net flows column

The later versions of Chinese IOTs separated the exports and imports. Exports are regarded as a category of final demand and imports are treated as primary inputs; this is done for the IOTs 1997, 2000 and 2002. However the earlier tables had only a "net flows" column as one of the final demand categories. According to the *information note* of China's input-output table 1992 (State Statistical Bureau of China 1996), the net flows are calculated as exports minus imports. Therefore in order to make all eight IOTs consistent for later calculations, the author manually generated the "net flows" column for IOTs 1997, 2000 and 2002. Following this approach some information would get lost. In IOA the same product can be exported and imported. From the information of "net flows", it is not possible to determine if it is the exports, imports, or both that are changing. For example, if the net trade increases between 1992 and 2002 it can hardly be known if exports have increased, imports decreased, or a combination of both. Since both exports and imports data are available for 1997-2002, section 6.3.2.5 also discusses the embedded CO_2 emission via exports, and avoided emission through imports from other countries.

6.2.2 Energy and CO_2 emission data

The energy data were extracted from "*China Energy Databook*", version 6.0 published by Lawrence Berkeley National Laboratory in June, 2004 (Lawrence Berkeley National Laboratory 2004). The complete dataset for this study consists of 18 types of fuels, heat and electricity consumption in physical unit. Then, CO_2 emissions including both the combustion of fuels and industrial processes are calculated in terms of the IPCC reference approach (IPCC 1996); the detailed method description is provided by Peters et al. (2006) generated. The energy and emissions data for all years comprise 37 production sectors and 2 households sectors (urban and rural). This requires the process of normalisation to match the sectors between IOTs and the energy and CO_2 emission data when performing the analysis.

This study follows the standard procedures for normalisation of the IOTs and the energy and emissions data,

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}_{\mathbf{total}}^{-1}$$

where **A** is the inter-industry requirements matrix which represents the technology of the Chinese economy. Since the constant price IOT has 18 sectors and the energy and emission data has 37 sectors one needs a mapping between the IO sectors and the energy sectors. To normalise the total energy and emissions data, **T**, one needs firstly aggregate the energy and emissions data to the sector classification used in the IOTs and then normalise,

$$\mathbf{F} = \mathbf{T}\left(\mathbf{P}\mathbf{x}_{\mathbf{total}}\right)^{-1}\mathbf{P}$$

where **P** represents the mapping between IO sectors and energy sectors. The post-multiplication by **P** converts **F** into an 18 sector row vector[37]. This procedure assumes that all IO sectors that map to the one energy sector have the same emission intensity. Since the IOT and energy intensities now have the same industry classification, one can perform all calculations at the 18 sector detail,

$$\mathbf{c} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$$

where **y** the final demand under investigation, **A** is the inter-industry requirements matrix which represents the technology of the Chinese economy, **F** is the emission intensity in each sector, and **c** is the energy consumption or CO_2 emissions required to produce the final demand.

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[37] In this study **F** and **T** are row vectors, but in general **F** and **T** are matrices where each row represents a different environmental stressor or value added component.

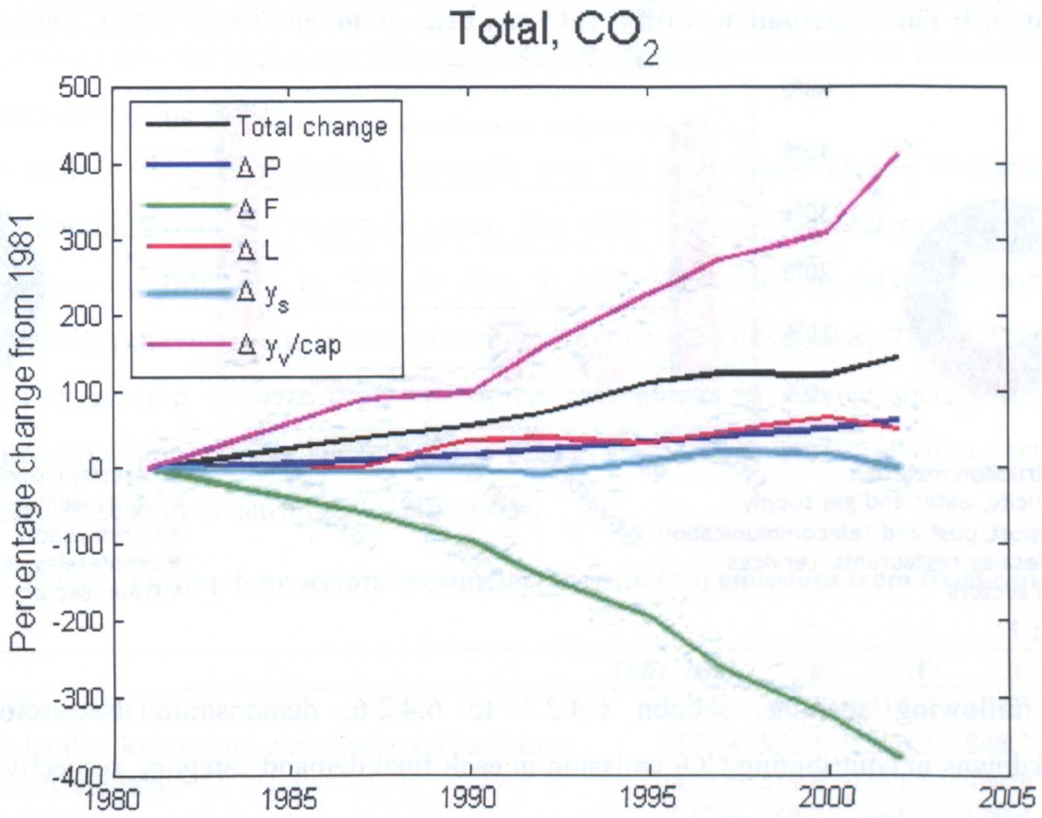
6.3 A Race between increasing consumption and efficiency gain

During the past 21 years since China opened up its economy, China has become the second largest CO_2 emitter in the world, after the U.S. China's production-related CO_2 has been increasing from 1,319 million metric tons (MMT) in 1981 to 3,209 MMT in 2002 with an growth rate of 143% overall, and 4.3% per year.

6.3.1 The contribution of the different drivers in the IPAT-IO SDA to the change of CO_2 emission

The IPAT-IO SDA results show that per capita consumption volume drives most of the increase of CO_2 emission over the past two decades. In contrast, the efficiency improvement is the strongest player in offsetting the emissions. As shown in Figure 6.2, the per capita consumption volume, "Δy_v" (pink line) would drive the increase of total CO_2 emissions by 411% if the population, efficiency improvement, economic structure and people's consumption pattern stayed constant. While the efficiency improvements (green line) would cause a decrease of total CO_2 emissions by 384% if the rest of the factors remained the same to 1981's value. The change of population (blue line) would lead to a 62% of increase of total CO_2 emission; the structure change of consumption pattern (red line) would increase 50% and the structural change of economic production (light blue line) would decrease by 1% of total CO_2 emissions. In total, by 2002 the CO_2 emissions (the black line) had increased by 143% from 1981's level. Looking at Figure 6.2, one can find that the pace of per capita consumption volume in the recent years (since 2000) is much more rapid than it in 1990s which again had been quicker compared with its 1980s' value. Meanwhile, one also notices that the efficiency gains since 1990s are more notable than during the 1980s probably due to increasing inflows of FDI and joint ventures.

Figure 6.2: The Drivers of CO_2 Emission – IPAT-IO SDA Perspective



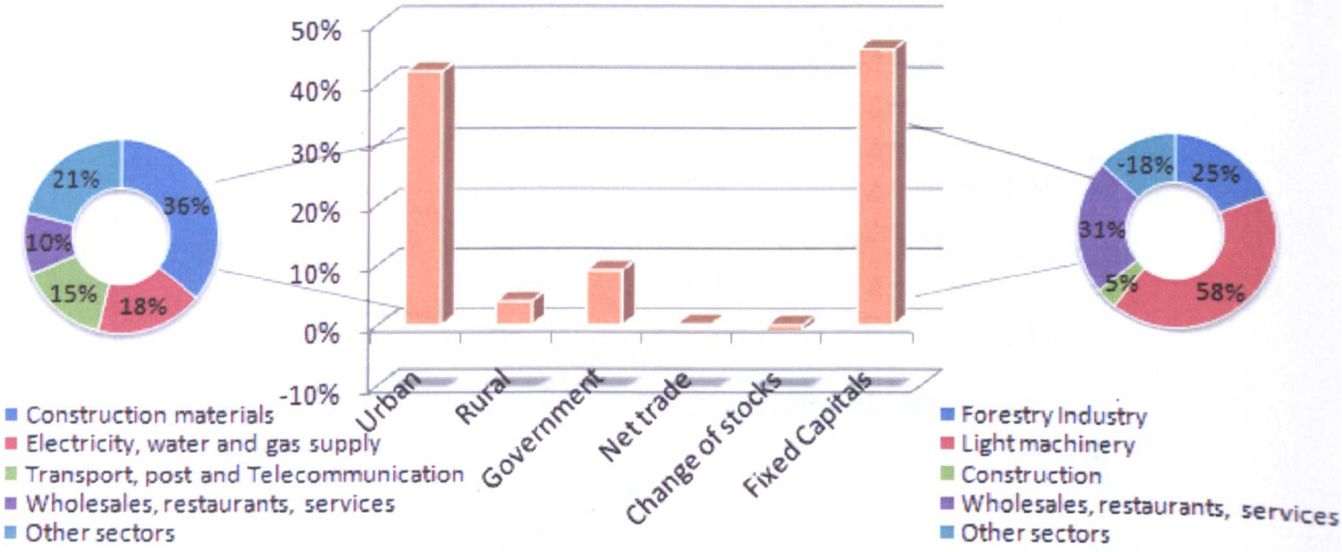
Below section 6.3.2 demonstrates the increasing fixed capital investments and urban household consumption volume are the main drivers in contributing to the increase of CO_2 emissions; and section 6.3.4 investigates whether this efficiency improvement is caused by the under-reporting of Chinese coal consumption from 1996 to 2003.

6.3.2 The contribution of final demand sectors to IPAT-IO SDA

Figure 6.3 shows an allocation of the total emission increase to the separate final demand categories. Of the 1,890 MMT (143%) increase in CO_2 emissions from 1981 to 2002, 863 MMT (46%) was due to fixed capital investments; 897 MMT (46%) was due to households with a 795 MMT (42%) is from urban households and 74 MMT (4%) is from rural households; 172 MMT (9%) was due to government expenditure; 3 MMT (less than 1%) is due to net trade, and 18 MMT (-1%) decrease in change of stocks. Figure 6.3 clearly shows the significant disparity between the urban and rural household in causing CO_2 emission over the past two decades. The urban household consumption generated more than 10 times in CO_2 emission than rural household did.

Figure 6.3 also picks the two final demand sectors – urban households and fixed capital which are most responsible for the change of CO_2 emission.

Figure 6.3: The Contribution of Different Final Demand to the Change of CO_2 Emission



The following sections, section 6.4.2.1 to 6.4.2.6, demonstrate the sectoral breakdowns in contributing CO_2 emission in each final demand category, respectively.

6.3.2.1 Fixed capitals

The right side pie chart of Figure 6.3 and Table 6.2 illustrates the top four sectors causing increases in CO_2 emissions in fixed capital investment. The referred sector which produces the capital may not necessarily be the sector that uses the capital. For instance, the light machinery produces a glass container for the purpose of laboratory experiments which is used by the chemistry sector and not the light machinery sector. Of the 863 MMT increase in CO_2 emission caused by fixed capital investment, 58% is due to the production in light machinery sector; 31% is due to wholesales, restaurants and other social services; 25% is due to forestry industry.

As Table 6.2 shows, the increased CO_2 emission from light machinery resulted from a 7,562% increase in per capita demand for light machinery products, which is mainly due to the significant growth of light machinery production triggered by foreign direct investments (FDI) in electrical and electronic production in China since the early 1990s. This figure can also indicate that many Chinese enterprises are in the process of office modernisation as a significant percentage of their fixed capital are formed by light machinery products such as computers, telephones and many other electrical appliances. Furthermore, the increase is further extended by 784% due to population growth and 1,141% due to the change of the production structure. On the other hand, the overall increase was tempered by a 6,915% improvement in efficiency due to the technology transfer by foreign direct investment especially in electrical and electronic sectors during the 1990s.

The tertiary industry excluding transport, post and telecommunication in China has been booming over the recent 20 years. The GDP share of the tertiary industry has been growing from 5% in 1981 to 16% in 2002. The share of service sectors are increasingly playing a significant role in the economy (Hubacek et al. 2007). This also leads to a rapid increase of fixed capital investments in service sectors such as computers, paper, tables and all office related products; thus the services sector is ranked as second in causing CO_2 emissions.

Table 6.2: The top four sectors causing increases in CO_2 emissions from fixed capital

Unit: %

	1981-2002	□p	□F	□L	□y_v
Light machinery	2572.0	783.6	-6914.7	1141.3	7561.8
Wholesales, Restaurants and other social services	1371.8	301.1	-2276.3	848.2	2498.8
Forestry industry	1122.9	249.6	-1871.5	732.6	2012.3
Construction	217.4	89.3	-665.1	129.4	663.8

Fixed capital formation is formed by fixed capital investments and change of stocks. However, the portion of the CO_2 contribution by "Change of Stock" is too small compared to fixed capital investments. Therefore, this chapter is not going into further detail on these investments.

6.3.2.2 Urban households

The left pie chart of Figure 6.3 illustrates the top four sectors causing increases in CO_2 emissions in urban household consumption. Of the 795 MMT increase of CO_2 emission due to urban household consumption, 36% is from construction materials, 18% from energy and water usage, 15% from transport, posting and telecommunication services, 10% from general services and the remaining 21% are from other sectors.

As Table 6.3 shows, China's urban household's demand on construction materials, mainly indirectly, would result in an increase of 7,880% in CO_2 emission over 1981 – 2002. This is due to the privatisation process of the housing sector in the early 1980s and the boost of housing construction for urban residents since the 1990s. For example, as section 2.4.2.2 discussed, the per capita net living space for Chinese urban residents was only 3.6 m^2 prior to 1978, mainly because of restrictions on private house ownership. Cities dwellers urged the development of housing. Until 1981, the commercialisation of the housing sector brought about by the Housing Reform Policy, which had been introduced to solve the problems of urban housing shortages and poor housing conditions. A great amount of money flows in housing construction sector in urban China, the total figure counts for about 7% of total GDP. As a result, many new houses have been built. City dwellers started to move from previously tiny bungalows or apartments to new multi-stories apartment blocks or even high-rise buildings, and per capita net living space increased to an average of 15.5 m^2 in 2001 (State Statistical Bureau of China 2002). The emissions have been increased mainly by population growth and change in the production structure, but largely offset by efficiency gains of 5,255%.

The extended living space for urban Chinese both direct and indirectly results in the increase of energy and water consumption that drives 3,202% growth of CO_2 emission. The direct emissions are from daily heating, cooking and the electricity usage of household appliances. For example as section 2.4.2.2 described, household electrical appliances purchased by people quickly increased in both quantity and category since 1990 (as shown in Figure 2.12). For example, purchase of refrigerator and colour TV in urban areas has both doubled in 2005 compared to 1990. Air-conditioners and personal computers have become essential household items for many urban families. Urban residents' increasing demand on electronic appliances also leads to rapid growth of indirect CO_2 emission during the production processes.

It is also interesting to look at urban residents' consumption of goods from the transport, post and telecommunication sector. Per capita demand would drive 3,906% of increase of CO_2 emission, and it is further expanded 436% by urban population growth and 956% by change of structural production, but the overall figure is offset by 3,542% in improvement of production technology. The proportion of the postal services is relatively small in this aggregated sector. In terms of transportation, the dream of owning a car is a reality for only a few households but it is still an unachievable goal for low to mid income households. But despite this fact, one can already observe a trend of the car replacing traditional ways of commuting (e.g. walking, cycling, or by bus). This would result in a boom of car production and other car-related sectors, which will inevitably cause a further increase of CO_2 emissions both from the usage of car and the increased economic production due to the structural effects of car production. In similar situation is observable for telecommunication services; for example mobile phones are popularised in urban China; every household has on average 1.37 sets in 2005 (State Statistical Bureau of China 2006). The usage of mobile phones causes direct emissions from electricity consumption, and indirect emission from production of handsets as well as from the operation of telecommunication service sector.

Table 6.3: The top four sectors causing increases in CO_2 emission from urban household

Unit: %

	1981-2002	$\square p$	$\square F$	$\square L$	$\square y_v$
Construction materials	4480.6	860.8	-5255.0	994.6	7880.2
Electricity, water and gas supply	2234.3	370.9	-1561.9	223.2	3202.1
Transport, post and Telecommunication	1845.1	435.8	-3452	955.5	3905.8
Wholesales, Restaurants and other social services	1287.6	284.6	-2149.6	802.5	2350.1

6.3.2.3 Rural household

Rural households are responsible for 75 MMT or 4% of the increase of CO_2 emission during 1981-2002. Table 6.4 illustrates the top four sectors contributing to the increase of CO_2 emissions. Of the 75 MMT, 79% are from metal and non-metal materials mining and processing sectors (mainly non-metal materials mining and processing such as limestone or marble etc), 10% from wholesales, restaurants and other social services, 6% from energy and water supplies, 4% from transport, post and telecommunication and 1% is from other sectors.

As discussed in section 2.4.2.2, rural residents rebuilt and extended their houses by using building materials, which indirectly resulted in the increase of CO_2 emission in non-metal materials mining and processing by 9,100%. The emission is tempered by 5,540% of efficiency gains and 240% of changes in the economic structure.

Table 6.4: The top four sectors causing increases in CO_2 emission from rural household

Unit: %

	1981-2002	$\square p$	$\square F$	$\square L$	$\square y_v$
Metal and non-metal materials mining & processing	4260	940	-5540	-240	9100
Electricity, water and gas supply	340	80	-330	50	540
Transport, post and Telecommunication	230	80	-630	190	590
Wholesales, Restaurants and other social services	580	150	-1090	420	1110

If one compares the increases of sectoral CO_2 emission triggered by household consumption between urban and rural China, the top sectors are very similar; the first sector is always triggered by housing improvements, followed by energy, transport and services sectors. This reflects that both urban and rural people's lifestyles have been changing in remarkably similar ways. On the other hand in terms of magnitude of the emission, urban household obviously are responsible for more than 10 times of CO_2 than rural households. However these results indicate that rural residents are progressively changing their lifestyles towards urban lifestyles, which will bring another boost of CO_2 emission in the very near future, especially considering that 57% of Chinese populations are still living in rural areas.

6.3.2.4 Government consumption

Government consumption is responsible for 172 MMT or 9% of the increase of CO_2 emissions from 1981-2002. Table 6.5 lists the top two sectors contributing to the changes in government consumption. As expected this list is topped by services, which is reflected also in increased household expenditure in these sectors.

Table 6.5: The top four sectors causing increases in CO_2 emission from government

Unit: %

	1981-2002	□p	□F	□L	□y_v
Wholesales, Restaurants and other social services	12721	2517	-19363	7019	22548
Transport, post and Telecommunication	88	53	-385	121	300

6.3.2.5 Net trade

Net trade, measured as exports minus imports, contributed very little to changes in China's overall environmental impacts, though this may vary on a regional basis (Streets et al. 2006). There is a rough balance between CO_2 emissions from the production of exports and emissions avoided by imports. Despite this balance, there has been strong absolute growth in both exports and imports since the beginning of the economic reforms. For most of the years, the IOTs only consists of net-exports, it is meaningless to see a sectoral emission breakdown for those years.

Exports and Imports: the export and imports data in IOTs are available for 1997-2002; therefore the following paragraph provides discussion on embedded CO_2 emission.

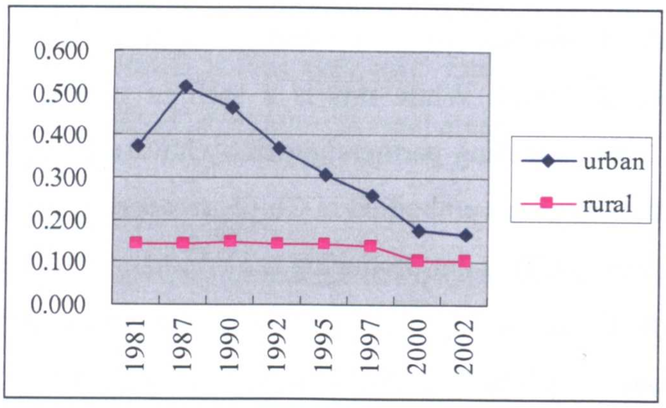
In 1997 the CO_2 emissions embodied in exports was 726 MMT, 23% of China's total emissions, but 681 MMT, 22% of the total CO_2 emissions were avoided by imports. These figures grew to 29% for exports and 31% for imports for 2002. It is interesting to point out that China had been a net CO_2 emission exporter until 1997, except for 1987; and became a net emission importer for 1997 and 2000, and switched back to an exporter in 2002. Actually, given data availability, the correct method to calculate the emissions embodied in the production of imports is through multi-regional input-output analysis (Turner et al. 2007; Wiedmann et al. 2007). Unfortunately, the necessary data is not available for China. This issue can be avoided by assuming the imports are produced with Chinese technology and then interpreting the emissions embodied in imports as the "emissions avoided in China by importing products and services" (Peters et al. 2007). While this is a shift in interpretation, it is in fact misleading. Since China's trading partners generally have a cleaner energy mix, then it is expected that the emissions embodied in China's imports are actually smaller than the emissions avoided by China not producing the imports. This is supported for 2001 where the CO_2 emissions embodied in China's exports were 26%, while the CO_2 emissions embodied in China's imports were 9% (Peters and Hertwich 2006). Consequently, China is actually a net exporter of CO_2 emissions to other countries.

6.3.3 A decrease of direct CO_2 emission

Production-related CO_2 emission represents 90-95% of total China's CO_2 emission. However, direct household CO_2 emissions such as the fuel used in daily cooking, heating, power supplies for household appliances and private transportation cannot be ignored. The amount of total direct CO_2 emissions had firstly increased from 182 MMT in 1981 to 261 MMT in 1990, and gradually decreased to 162 MMT by 2002. Figure 6.3 distinguishes the direct CO_2 emissions in per capita value between rural and urban residents, which clearly shows a significant decrease of per capita CO_2 emissions in urban China since the end of the 1980s. This is mainly caused by the gradually abandonment of coal consumption in urban areas. For example, since the end of the 1980s, urban residents started to move from bungalows, with heating and cooking based on coal, to the multi-story blocks which are supplied by district heating systems and coal- or natural- gas for cooking. These led to rapid decline of per capita coal consumption for urban residential from 348.5kg/year in 1985 to 88.2kg/year in 1999, further to 48.1kg/year by 2004 (also see section 2.4.2.4).

On the other hand, Figure 6.4 shows that per capita household CO_2 emission in rural China stayed almost constant before 1997, which indicates that the energy consumption structure in most of rural China had not been changed much. The slight decline of per capita emissions in recent years reflects a trend that the energy consumption pattern in rural China has been slowly diversified with gradually abandoning coal and biomass. In fact, this study does not consider biomass energy consumption for rural households. Stalks, bio-gases and firewood provided 85% of resident energy consumption in 1985, and the figure has been reduced to 74% by 2004.

Figure 6.4: Per capita CO_2 emission from residential energy consumption

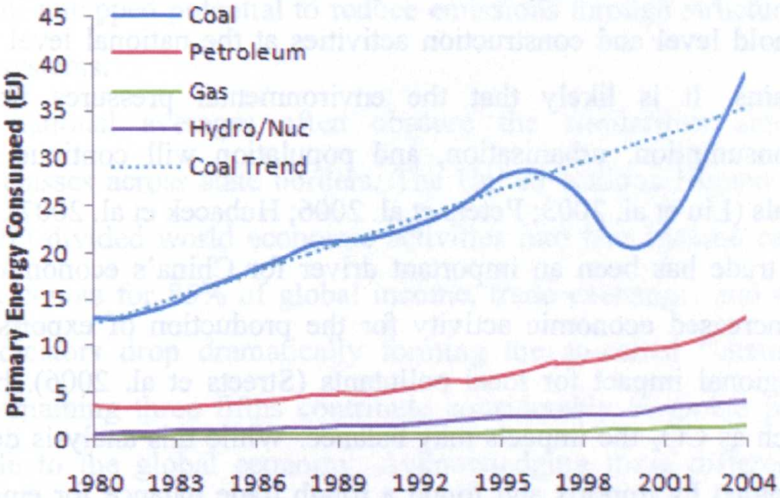


6.3.4 Under-reporting of coal consumption

Despite increases in Chinese CO_2 emissions, official energy statistics show a significant decrease in coal consumption from 1996 to 2000 (State Statistical Bureau of China 2006). According to official statistics, from 1996 to 2000 China's coal consumption declined substantially and then rapidly increased from 2000 to 2004 back to the historic trends, as shown in Figure 6.5. During this time period non coal-based energy increased in line with historical trends. Some have argued that the decrease was realistic and resulted from successful Chinese policies aimed at structural change and efficiency improvements (Sinton and Fridley 2000; Streets et al. 2001; Fisher-Vanden et al. 2004; Wu et al. 2005). However, recent satellite data suggests that there was significant under-reporting of coal consumption and that the official statistics should not be used for emission inventories (Akimoto et al. 2006). Poor statistics may be due to a number of highly dispersed users---such as smaller often rural enterprises and households---using coal from small and inefficient coal mines. Further, the policy to close these small mines has probably been less successful than thought as many continue production illegally (Horii 2001; Sinton 2001). Three of the data points in this analysis are affected by the unusual coal consumption, but only 2000 and 2002 differ substantially from the historic trend (see Figure 6.5). To account for the potential under-reporting for 2000 and 2002 the author performs a scenario which scaled up the coal consumption to reflect the historic trend.

With the modified coal data, Chinese CO_2 emissions grew 2,457 MMT (186%) from 1981 to 2002 instead of 1,890 (MMT) 143% in the un-modified data. The contribution of GDP growth to increased emissions was 427%, up from 411% in the un-modified data; efficiency improvements reduced emissions 333%, a considerable decrease from 384% in the un-modified data; and structural changes were unaffected. Despite these changes, the general form of Figure 6.2 remains unchanged suggesting that even though coal consumption was under-reported, there were still significant improvements in energy efficiency between 1997 and 2002 (Sinton and Fridley 2000).

Figure 6.5: Historical energy consumption with modified coal consumption scenario



Note: Historic coal consumption in China showing the dip in coal consumption from 1996 to 2003 which may be due to under-reporting of coal consumption. The dashed line shows the linear trend in coal consumption from 1980 to 1996.

6.4 Conclusions and Outlook

Capital investments such as in infrastructure are an important motor for economic growth in many developing countries (Yu 1998; Crosthwaite 2000), but the downside is increased pollution through the production of cement, steel and glass especially needed for building infrastructure and buildings. Since the importance of construction decreases as a country develops (Crosthwaite 2000), it is likely that the environmental impacts will decrease as well. As a country initially develops, relatively high pollution levels may be unavoidable, but once the capital stock for infrastructure is in place, decreases in construction activity may decrease related emissions. On the other hand, infrastructure may lead to increased use-phase emissions. For instance, the emissions from personal car transportation are likely to increase rapidly as infrastructure is put in place (Marcotullio et al. 2005). One potential strategy to avoid this and similar scenarios is to leapfrog straight to low emission technologies (Perkins 2003). Examples include avoiding the need for fixed telephone infrastructure by leapfrogging straight to mobile technologies (Davison et al. 2000) and moving to natural gas for transportation skipping limited efficiency improvements in gasoline or other liquid fuels.

Increases in CO_2 emissions related to household consumption are driven by a combination of urbanisation and increased expenditure of urban households. Despite a positive structural shift toward consumption of less energy-intensive services, increased consumption of energy-intensive products such as electricity and appliances at the household level and construction activities at the national level mostly offset efficiency gains. It is likely that the environmental pressures from increased household consumption, urbanisation, and population will continue with China's economic goals (Liu et al. 2003; Peters et al. 2006; Hubacek et al. 2007).

International trade has been an important driver for China's economic growth (Yu 1998). The increased economic activity for the production of exports may have a significant regional impact for local pollutants (Streets et al. 2006), but for global pollutants such as CO_2 the impacts may balance. While this analysis determined the emissions avoided by imports and found a rough trade balance for emissions, using more realistic assumptions China is a net exporter of CO_2 emissions (Peters and Hertwich 2006). This raises the question of where goods should be produced from an environmental perspective (Peters and Hertwich 2006). While Chinese production may have several advantages for the global economy due to its low labour cost structure, given its inefficiencies in terms of resource use it causes greater environmental impacts than the production of these goods in other countries (Liu and Diamond 2005).

Much of the previous research (e.g. Cole et al. 1973; Lecomber 1975; Chertow 2001) has investigated whether technology improvements are the solution to prevent environmental degradation while the economy develops, which has drawn great attention by policy makers and economic theorists alike. This section conducts a simple experiment based on Hubacek and Guan et al. (2007) to see what level of technology China would need in 2050 (e.g. $T_{China\text{-}2050}$) in order to maintain the same amount of CO_2 emission in 2000 ($CO_{2\,China-2000}$)[38] given growing population ($P_{China-2050}$) and a growing economy ($A_{China-2050}$)[39] by using the simple *IPAT* identity.

The result shows that in order to satisfy the rapid consumption increase, Chinese technology would have to be improved by 98% in the next 50 years in order to be on track with current CO_2 agreements. In comparison, historical data show that China had achieved 78% of efficiency gains over the last 40 years (1960-2000) by reducing per capita CO_2 emission (Hubacek et al. 2007). This evidence suggests technological improvements alone are unlikely to stabilise emissions. While efficiency and technology improvements will remain important, strong policies are required to capture the still-untapped potential to reduce emissions through structural changes in consumption systems.

In addition, national averages often obscure the similarities among different consumption classes across state borders. The United Nations Human Development Program (1992) divided world economic activities into five income categories. The richest fifth accounts for 85% of global income, trade exchange, and savings. After that these indicators drop dramatically forming the so-called "champagne glass" figure. The remaining three fifths contribute considerably to global population but relatively little to the global economy. Acknowledging these differences between countries Alan Durning (1992) categorised the world's population not by country but by consumption classes for 1992; he forms three broad socio-ecological classes based on consumption patterns and the degree of environmental impact (Kaza 2000). The author follows Durning's method to update the world consumption classes to 2006, as shown in Figure 6.6

Consumption has shown to be of considerable importance in this analysis. But a variety of consumption models exist. For example, in comparing income and consumption levels between Japan and the US one finds that despite relatively similar per capita income levels the average US consumes more resources as her fellow consumer in Japan. Examples of sustainable consumption and production patterns in other developed countries could therefore help the US to leapfrog to a higher level of

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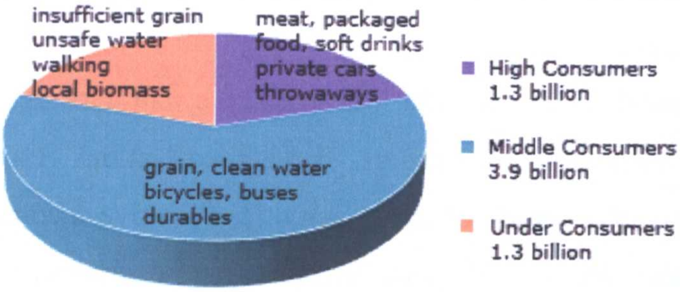
[38] Hitherto, China has not committed themselves so any international agreements to CO_2 reduction thus the author assumes that in the long-run China would want to commit to future rounds of international agreements. In the absence of these the author assumes a CO_2 level of 2000.

[39] $CO_{2\,China-2000} = P_{China-2050} \times A_{China-2050} \times T_{China-2050}$ *which is then reformulated to* $T_{China-2050} = CO_{2\,China-2000} / (P_{China-2050} \times A_{China-2050})$

well being with lower pollution and resource consumption. This might be even easier to achieve for developing countries. Wasteful infrastructure, institutions and habits have not been developed to the same extent as in the resource addictive 'North'. Similarly technological and institutional leapfrogging could help the 'under-consumers' to achieve higher level of consumptions but given the links or dependencies created through global trade, foreign direct investments and marketing in these emerging economies the possibilities for developing countries to successfully contribute to global efforts for sustainable production and consumption might be difficult.

Figure 6.6: World Consumption Classes in 2006



Source: Modified from Alan Durning (1992)

From technological and energy efficiency points of view much in this direction is already going on in some of the more advantaged areas such as the coastal areas in China driven by high levels of foreign direct investment and improved efficiency rates. With regards to the consumption side, this is much more difficult in developing or transition countries trying to emulate Western lifestyles. Even though influencing consumers is difficult but this is routinely done by companies and marketing agencies and thus why should 'green campaigns' not be able to achieve the same. On the other hand, one has to notice the huge differences in money and resources that is spent on marketing for consumption items and in comparison the miniscule amounts available for e.g. recycling campaigns, a problem shared by public agencies and non-governmental organisations (NGOs) in developed and developing countries alike.

Chapter 7: Achievements and Conclusions

This thesis studies one of the fastest growing economies – China - to explore new opportunities for quantitative research on sustainability. This thesis builds on the methodological framework of input-output analysis to assess both direct and indirect natural resources consumption and related emissions triggered by economic growth, changes of people's lifestyles, population migration, urbanisation production structures and trade patterns. This chapter firstly summaries the findings and conclusions from the above case studies (Chapter 4-6), secondly overviews methodological contribution of this PhD research to environmental input-output analysis, finally, presents some limitations of this thesis with the possibilities of further research.

7.1 Summarising thoughts on the case studies

China's economic growth, industrialisation, urbanisation and rapid increase in people's consumption volume and diversification of consumables has brought about enormous changes to China's economy and society but also left deep marks on China's ecosystems and availability of resources. On the other hand, the damaged environment would affect the continuity of development in the long run, and in some regions this has become a bottleneck to economic growth. Generally speaking, a newly industrialised country or region, initially, always engages in labour- and resources-intensive production. From the perspective of a sustainable development, it is important to ensure that an efficient economic structure and trade pattern is fostered already at the beginning of the industrialisation process, in terms of allocation of production facilities considering the availability of resources and with an effective environmental monitoring and management system.

Only very recently Chinese authorities, aware of the deterioration of the environment, have started to promote more balanced patterns of development, using concepts such as "harmonious society", "scientific development" and "circular economy". One of their core responses to these concepts is to give high priority to environmental and natural resources management with planning for national economic and social development (OECD 2006). In order to guarantee a concordant "plan", it would require a full understanding of the interrelationships between the economy and the environment, and find the major drivers damaging the environment.

Economic production and consumption use inputs of water from the environment, however, water resources are currently highly undervalued as there are often little or no costs associated with their consumption. Even North China, characterised as serious water scarce, requires 96% of its annual available water resources, mostly for the water and emission intensive sectors such as agriculture, energy generation, paper making and production of chemicals. Since agriculture was and will remain the dominating water consumer in North China, the irrigation efficiency can be improved by properly pricing the water resources with reasonable cost recovery mechanism (Hubacek et al. 2007). The preservation of irrigation will depend critically on transfers from the Yangtze, in other words, it is hard to see how these basins can survive without them (Wang et al. 1999). However, Hubacek, Guan et al. (2007) projected that the total water demand in 2020 in North China would be 1.5 times more than the total availability with the consideration of transferred water from Yangze river. A water scarce region like North China should change its economic structure by developing less water- or pollution-intensive production such as electrical and electronical appliances or services. Actually the lack of technology and investments in water transportation infrastructure and water treatment plants is the barrier to decelerate the process of economic transition in many-water shortage regions.

Similarly, by using CO_2 emissions as an environmental indicator, Chapter 6 pictures a race between per capita's consumption and efficiency gain in contributing or alleviating the growth of CO_2 emissions. Unfortunately, the pace of technology improvement has not been able to cope with the rapid increase of consumption related emissions with very important global climate implications. The results show that a boost of urban consumption is primarily responsible for the increase of CO_2 emission, which may be also true for much of the other environmental pollution in China. In the near future, it is likely that China will pursue continued economic growth in an attempt to reduce poverty and improve quality of life (Ravallion and Chen 2007). As in most countries, China has improved energy efficiency and this effectively reduced China's CO_2 emissions by 80-90% since 1960. There is the potential to reduce emissions further through efficiency changes by continued energy conservation, fuel switching, renewable energy, carbon capture and sequestration, and so on (Gielen and Changhong 2001; Pacala and Socolow 2004). However, the simple experiment at the end of Chapter 6 gives some indication that there will be a continuation of the race between increasing consumption and technology improvements for China's future CO_2 emissions. Furthermore, the required technology level can hardly be achieved by China itself, which would require extensive technology leapfrogging and imports and FDI from developed countries.

To address the (over) consumption and guide towards more sustainable consumption is more difficult in a developing country's context, where wealth is unevenly distributed. There are still large segments of the population who life under conditions of poverty (e.g. interior rural residents) and thus different sets of policies are necessary for different income classes to achieve a sustainable consumption.

7.2 Methodological achievements

This PhD thesis adopts environmental input-output analysis as the primary method to investigate the economy-environment interrelationships in China. However the author further develops the techniques in several case studies to better address the respective research questions. The methodological achievements can be summarised in the following three main points:

Hydro-economic accounting framework and analysis tool

Chapter 4 presented a new methodological accounting and analytical approach based on economic input-output modelling combined with a mass balanced hydrological model that links interactions in the economic system with interactions in the hydrological system. By following the tradition of integrated economic-ecologic input-output modelling the hydro-economic accounting framework and analysis tool allows tracking water consumption on the input side, water pollution leaving the economic system and water flows passing through the hydrological system thus enabling one to deal with water resources of different qualities in different spheres. In particular, the framework tracks water consumption on the input side including rainfall, surface and ground water; assigns qualities for wastewater leaving the economy to different hydrological sectors (e.g. surface and ground water bodies); and measures the amount of contaminated water within the hydro-ecosystems. Furthermore, Chapter 4 proposes that the traditional term of water demand needs to be modified by incorporating the ineligible water polluted by production and consumption into the water accounting framework.

Virtual Water flows

Chapter 5 evaluated the current inter-regional trade structure and its effects on water consumption and pollution via virtual water flows. Most of the studies on virtual water flows have been conducted in drought areas such as the Middle East and North Africa and have emphasised the amount of water embedded in different agricultural products related to food security, with agriculture being the largest water consumer. With increasing importance of other industrial products and services and their effects on water consumption, this study extends the concept of virtual water flows to comprise all types of commodities including agricultural goods, industrial products and services. Furthermore, the term of virtual water as used in this thesis distinguishes between freshwater and wastewater. In addition, for agriculture there are two supply sources: rain water and natural flows. Therefore, this study differentiates between rainfed and irrigated agricultural products as rain water used for agricultural products would not be readily available for any other economic production; an important distinction that has been all too often overlooked.

IPAT-IO Structural Decomposition Analysis

Chapter 6 discovered significant overlaps between the frequently used *IPAT* equation and structural decomposition analysis (SDA). Certain differences remain: *IPAT* can only account for the direct impacts to the environment created by the driving forces – population, affluence and technology. In addition, the technology term had frequently been criticised for being a catch all residual, which is difficult to interpret. Related to this point is that the technology term is too aggregated to clearly distinguish or track the sources of emissions and allocate them to particular industries. Similarly, lifestyles are only represented in the very simple A=affluence term of the *IPAT* whereas the IO tables have very detailed final demand accounts. On the other hand, many previous SDA studies ignored the factor of population growth and migration, but it is important to many populous developing countries such as China and India. The combination of the SDA and *IPAT* enriches both approaches and allows to link to the various discourses held in either one or the other 'tradition'.

7.3 Limitations and future research possibilities

Each of the results chapters of this thesis (Chapter 4 – 6) has its own sets of limitations in terms of data collection and methodological shortcomings. In the following the author firstly discusses broader sets of limitations than those already discussed in the respective chapter, and then provides the reader with some ideas or speculations to further extend and overcome these shortcomings within an input-output approach.

The author used a relatively simple mass-balanced water quality model in developing the hydro-economic accounting framework in Chapter 4. The current model is appropriate for the purpose at hand, which is to assess the water flows for a meso- and macro-level representation of the economy. But the accuracy of the framework could be further improved by combining a more sophisticated water quality model. Input-output model offers great sectoral detail of production and allows allocation of impacts to consumption and production activities. But one important limitation especially with regards to modelling pollution is the 'non-spatiality' of input-output analysis. This is of less important for a global pollutant such as CO_2 but can be very significant for water pollutants and other local and regional pollutants with the threat of contributing to hot spot pollution areas. Only a very few studies have attempted to conceptualise spatially explicit input-output models and combinations with spatially explicit datasets. In addition, this research indicates that the current methodological developments for green GNI accounting should distinguish between economic assets and environmental assets. Under the green GNI accounting framework, one can set up two sets of sub accounting systems with two sets of "prices": one is for economic achievements with monetary price; the other is for natural resources with "physical price". For example, the physical price can be defined as the amount of fresh (unpolluted) resources (e.g. freshwater) is required to upgrade (the degraded / contaminated resources). The linkage between the two sub-accounting systems would be the monetary value of per unit resource in a fresh/uncontaminated condition.

Chapter 5 investigates a "paradox" of virtual water flows via trade. Referring to international trade theories, the author points out that water resources have not been regarded as a factor of production and consumption. In fact, decision-making on supporting a certain production structure should involve a comprehensive study considering environmental factors as well as labour, capital, social economic factors. For example, in the case of North China, one can see severe water scarcity but at the same time exports of water intensive products. Thus one can observe a contradiction of water saving policies and export policies. At the same time, this region has a comparative advantage in excellent soils that are ideal for agricultural production and therefore exports of agricultural goods. However the challenge is which factor has the highest priority in the decision, and what principle one should follow to ascertain the relative importance of factors of production including non-priced environmental resources. Therefore, there is some space to test the feasibility of combining input-output analysis with multi-criteria decision analysis to support such analyses.

The experiment at the end of Chapter 6 does not use the IPAT-IO SDA framework. This is because of time constrains and many uncertainties in projecting the change for each factor, particularly the CO_2 emission coefficients and Leontief's technical matrix (**A**). For future research, the projection of CO_2 emission coefficients can use scenario of "business as usual" based on a continuation of historical data. The projection of the **A** matrix can be achieved by using RAS technique in combination of more sophisticated scenario tools (Duchin and Lange 1994; Hubacek and Sun 2001, 2005). The author conducted an analysis to evaluate the ecological and water footprints for China's 2020 using a similar combined approach, which has not been included in the write up of the thesis (Hubacek et al. 2007),

Secondly, another important aspect especially for the CO_2 case study is the discussion of whether China is a net CO_2 emission exporter or importer. The reason for this shortcoming is that it would involve knowing the economic structure and energy efficiency in producing the goods China imported from other countries. This can be done by setting up a multi-regional input-output table linking China with several regions in the world. The author is currently involved in a DEFRA funded project: UKMRIO to construct a multi-regional input-output tables linking UK with three regions – OECD Europe, OECD non-Europe and the rest of world. The assumption is to use an average or standard economic structure and energy coefficients for every region. A similar method can be applied in China and other developing countries in order to investigate on earth whether the “north” generously helps the “south” to leapfrog or sees it as a pollution heaven. A number of attempts building multi-regional world models are ongoing (e.g. the EU-projects EXIOPOL: A New Environmental Accounting Framework Using Externality Data and Input-Output Tools for Policy Analysis; MOSUS: Modelling opportunities and limits for restructuring Europe towards sustainability). These advances should make this type of analysis much easier in the future.

Chapter 8: References

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Appendix A

Appendix A-1: North China's Net Water Consumption in 1997

		Surface water (million m^3)	Ground water (million m^3)	Rainfall (million m^3)	Water Quality (COD gram/m^3)
1	Rainfed Agriculture	0.00	0.00	29,681.84	N/A
	Irrigated Agriculture	23,773.74	17,215.46	0.00	40
2	Coal mining and processing	88.98	54.54	0.00	30
3	Petroleum and natural gas	42.48	29.52	0.00	30
4	Metal ore mining	34.70	33.34	0.00	30
5	Non-ferrous mineral mining	27.47	39.54	0.00	30
6	Food and tobacco processing	267.29	594.93	0.00	30
7	Textile goods	144.91	281.30	0.00	30
8	Wearing	40.41	38.83	0.00	30
9	Sawmills and furniture	34.38	12.08	0.00	30
10	Paper and products	107.71	341.09	0.00	30
11	Petroleum processing	14.14	21.21	0.00	30
12	Chemicals	833.24	978.15	0.00	30
13	Non-metal mineral products	76.54	110.14	0.00	30
14	Metals smelting and pressing	205.28	283.48	0.00	30
15	Metal products	31.75	35.81	0.00	30
16	Machinery and equipment	137.97	256.22	0.00	30
17	Transport equipment	46.11	42.57	0.00	30
18	Electric equipments	38.28	74.30	0.00	30
19	Telecommunication equipment	73.47	101.46	0.00	30
20	Instruments	11.43	12.89	0.00	30
21	Maintenance machinery	17.70	19.18	0.00	30
22	Other manufacturing	37.93	56.89	0.00	30
23	Scrap and waste	11.95	8.31	0.00	30
24	Electricity	840.82	280.27	0.00	30
25	Gas production and supply	4.17	1.79	0.00	30
26	Water production and supply	16.03	5.06	0.00	30
27	Construction	90.42	135.63	0.00	30
28	Transport and warehousing	63.33	94.99	0.00	20
29	Post and telecommunication	11.74	17.61	0.00	20
30	Wholesale and retail trade	126.97	190.46	0.00	20
31	Eating and drinking places	14.89	22.33	0.00	20
32	Passenger transport	16.72	25.08	0.00	20
33	Finance and insurance	50.08	75.11	0.00	20
34	Real estate	15.12	22.68	0.00	20
35	Social services	31.75	47.63	0.00	20
36	Health services, social welfare	10.89	16.34	0.00	20
37	Education and culture	19.89	29.84	0.00	20
38	Scientific research	3.73	5.59	0.00	20
39	General technical services	9.73	14.60	0.00	20
40	Public and other services	33.99	50.99	0.00	20
41	Urban households	921.89	1,362.11	0.00	20
42	Rural households	209.25	3,975.75	0.00	20
	Total	**25,346.31**	**30,258.07**	**29,681.84**	

Appendix A-2: North China's Discharged Wastewater and its Quality in 1997

		Surface water (million m^3)	Ground water (million m^3)	Natural loss (million m^3)	Water Quality (COD gram/m^3)
1	Agriculture	2459.35	3689.03	1192.79	290
2	Coal mining and processing	229.63	57.41	25.26	201
3	Petroleum and natural gas	115.19	28.80	12.67	201
4	Metal ore mining	163.29	40.82	17.96	265
5	Non-ferrous mineral mining	42.89	10.72	4.72	324
6	Food and tobacco processing	272.91	26.99	17.65	469
7	Textile goods	236.90	15.12	12.83	419
8	Wearing	18.68	4.10	1.88	307
9	Sawmills and furniture	25.21	4.80	2.32	214
10	Paper and products	1131.00	215.43	104.21	1023
11	Petroleum processing	58.68	12.02	5.66	314
12	Chemicals	886.68	109.59	63.91	756
13	Non-metal mineral products	92.76	15.10	7.78	317
14	Metals smelting and pressing	387.10	43.01	26.45	317
15	Metal products	36.48	4.05	2.49	317
16	Machinery and equipment	313.17	55.27	27.54	317
17	Transport equipment	25.08	4.78	2.31	317
18	Electric equipments	59.01	4.44	3.40	285
19	Telecommunication equipment	91.70	6.90	5.28	285
20	Instruments	18.52	4.92	2.12	285
21	Maintenance machinery	12.67	1.41	0.87	285
22	Other manufacturing	56.71	12.45	5.72	346
23	Scrap and waste	12.31	2.70	1.24	423
24	Electricity	0.00	0.00	0.00	0
25	Gas production and supply	8.40	1.37	0.70	165
26	Water production and supply	29.75	4.84	2.49	105
27	Construction	127.49	8.14	6.90	423
28	Transport and warehousing	139.32	0.00	4.88	362
29	Post and telecommunication	25.83	0.00	0.90	362
30	Wholesale and retail trade	171.41	0.00	6.00	362
31	Eating and drinking places	25.12	0.00	0.88	362
32	Passenger transport	28.22	0.00	0.99	362
33	Finance and insurance	84.50	0.00	2.96	362
34	Real estate	25.52	0.00	0.89	362
35	Social services	53.58	0.00	1.88	362
36	Health services, social welfare	18.38	0.00	0.64	362
37	Education and culture	33.56	0.00	1.17	362
38	Scientific research	6.29	0.00	0.22	362
39	General technical services	16.42	0.00	0.57	362
40	Public and other services	38.24	0.00	1.34	362
41	Urban households	3777.31	0.00	132.21	362
42	Rural households	1391.87	596.51	48.72	362
	Total	**12747.15**	**4384.21**	**1761.42**	
	Average COD concentration	**426.94 (gram/m^3)**	**341.13 (gram/m^3)**		

Appendix A-3: The B Matrix: Water flows amongst hydrological sectors

	Surface water	Ground water	Natural loss
Surface water	33998 (million m^3) (coefficient: 2.76 m^3/m^3)	0	446 (million m^3)
Groundwater	0	7462 (million m^3) (coefficient: 2.14 m^3/m^3)	1494 (million m^3)
Rainfall	0	0	0

Appendix B

Each of the following function set represents the full mathematical relationship of the weight assigned to each factor on the right side of Equation 6.6.

$$
\begin{aligned}
w^{p}\Delta p = \frac{1}{120}[&(24\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(6\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(24\cdot\Delta p\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})]
\end{aligned}
$$

$$
\begin{aligned}
w^{\mathbf{F}}\Delta\mathbf{F} = \frac{1}{120}[&(24\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+
\end{aligned}
$$

$$\begin{aligned}
&(4\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(24\cdot\Delta\mathbf{F}\cdot p_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})]
\end{aligned}$$

$$\begin{aligned}
w^{\mathbf{L}}\Delta\mathbf{L}=\frac{1}{120}&[(24\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t-1)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t-1)})+\\
&(24\cdot\Delta\mathbf{L}\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{y}_{s(t)}\cdot y_{v(t)})]
\end{aligned}$$

$$\begin{aligned}
w^{y_s}\Delta\mathbf{y}_s = \frac{1}{120}[&(24\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t-1)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t-1)})+\\
&(4\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t)})+\\
&(4\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot y_{v(t)})+\\
&(6\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t-1)})+\\
&(24\cdot\Delta\mathbf{y}_s\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot y_{v(t)})]
\end{aligned}$$

$$\begin{aligned}
w^{y_v}\Delta y_v = \frac{1}{120}[&(24\cdot\Delta\mathbf{y}_s\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)})+\\
&(6\cdot\Delta y_v\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)})+\\
&(6\cdot\Delta y_v\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)})+\\
&(6\cdot\Delta y_v\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)})+\\
&(6\cdot\Delta y_v\cdot p_{(t-1)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)})+\\
&(4\cdot\Delta y_v\cdot p_{(t)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t-1)})+\\
&(4\cdot\Delta y_v\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)})+\\
&(4\cdot\Delta y_v\cdot p_{(t)}\cdot\mathbf{F}_{(t-1)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)})+\\
&(4\cdot\Delta y_v\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t)}\cdot\mathbf{y}_{s(t-1)})+\\
&(4\cdot\Delta y_v\cdot p_{(t-1)}\cdot\mathbf{F}_{(t)}\cdot\mathbf{L}_{(t-1)}\cdot\mathbf{y}_{s(t)})+
\end{aligned}$$

$$(4 \cdot \Delta y_v \cdot p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t)}) +$$

$$(6 \cdot \Delta y_v \cdot p_{(t-1)} \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t)}) +$$

$$(6 \cdot \Delta y_v \cdot p_{(t)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t)}) +$$

$$(6 \cdot \Delta y_v \cdot p_{(t)} \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t-1)} \cdot \mathbf{y}_{\mathbf{s}(t)}) +$$

$$(6 \cdot \Delta y_v \cdot p_{(t)} \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t-1)}) +$$

$$(24 \cdot \Delta y_v \cdot p_{(t)} \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t)})]$$

ECOLOGICAL ECONOMICS 61 (2007) 159–170

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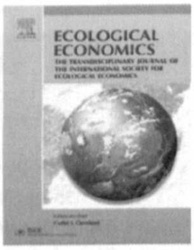

ANALYSIS

Assessment of regional trade and virtual water flows in China

*Dabo Guan, Klaus Hubacek**

Sustainability Research Institute (SRI), School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

ARTICLE INFO

Article history:
Received 29 September 2005
Received in revised form
31 December 2005
Accepted 7 February 2006
Available online 6 March 2006

Keywords:
Water accounting
Input–output analysis
China
Trade
Natural resources
Environment

ABSTRACT

The success of China's economic development has left deep marks on resource availability and quality. Some regions in China are relatively poor with regards to water resources. This problem is exacerbated by economic growth. Flourishing trade activities on both domestic and international levels have resulted in significant amounts of water withdrawal and water pollution. Hence the goal of this paper is to evaluate the current inter-regional trade structure and its effects on water consumption and pollution via 'virtual water flows'. Virtual water is the water embedded in products and used in the whole production chain, and that is traded between regions or exported to other countries. For this assessment of trade flows and effects on water resources, we have developed an extended regional input–output model for eight hydro-economic regions in China to account for virtual water flows between North and South China. The findings show that the current trade structure in China is not very favorable with regards to water resource allocation and efficiency. North China as a water scarce region virtually exports about 5% of its total available freshwater resources while accepting large amounts of wastewater for other regions' consumption. By contrast, South China a region with abundant water resources is virtually importing water from other regions while their imports are creating waste water polluting other regions' hydro-ecosystems.

1. The 'economic miracle' and virtual water flows

1.1. *Water shortage and its competing usage*

The latter half of the 20th century is considered the period of the 'economic miracle' for East Asia, achieving industrialization and urbanization in a relatively short time period. China, in particular, accelerated its economic development with an annual GDP growth rate of almost 10% after economic reforms were started in 1978. In comparison, the world average was 3.3% during the same period. By 2005, China's GDP had reached 1.13 trillion US dollars, which put China among the four largest economies in the world. China's economic reform has created very competitive and favorable circumstances for domestic and foreign investors in terms of cheap labor costs, a huge domestic market, low workers safety standards and environmental standards. These and other reasons, such as the undervalued Yuan, have led to large amounts of capital flowing into China, especially in the southern and eastern parts, which has made China one of the largest manufacturers and exporters in the world. However, Deng's 'ladder-up' strategy of economic development has increased income inequality between regions and urban and rural areas. This is also reflected in differing regional development policies, economic production structures, unequal spread of foreign direct investment, and huge differences in people's lifestyles pattern.

These developments have left deep marks on China's natural resource availability and especially with regards to water resources. China is trying to support the needs and

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* *Corresponding author*. Tel.: +44 113 343 1631.
E-mail address: hubacek@env.leeds.ac.uk (K. Hubacek).

doi:10.1016/j.ecolecon.2006.02.022

wants of a population of 1.3 billion. This amounts to 22% of the total world population with only 7% of the world's arable land, and 6% of the world's fresh water resources. Water is already considered the most critical natural resource in many parts of China in terms of the low availability of per capita volume. The average water availability is about 2300 m^3, which is roughly about 1/3 of the world's average value. But China's water resources are also unevenly distributed: North China has only about 20% of total water resources in China, but is supporting more than half of the total population. As a result, per capita water availability in North China is as little as 271 m^3 or 1/8 of the national level and 1/25 of the world average. Furthermore the rapid economic development in this region has been extracting significant amount of water from the environment, and it is also discharging pollution to the water supply sources, which further contributes to water-scarcity. Flourishing trade activities on both domestic and international levels have contributed to ever increasing levels of water consumption.

These socio-economic and environmental issues facing China in the 21st century call for careful evaluation of China's resource consumption caused by its present production and consumption and associated trade structure. Due to these trade activities, significant amounts of 'virtual water', i.e. water embedded in products and used in the whole production chain, are traded between regions or exported to other countries. Hence the goal of this paper is to evaluate the current regional economic structure and the resulting interregional trade patters in China and its effects on water consumption and pollution via 'virtual water flows'.

1.2. *Virtual water flows*

The idea of virtual water was derived from the concept of 'embedded water' applied to agriculture in Israel by Fishelson (1994). Their study pointed out that exporting Israeli water embedded in water intensive-crops was not sustainable. The term 'virtual water' was first proposed in 1994 by J. Anthony Allan (Allan, 1994). Allan defines virtual water as the water used to produce food crops that are traded internationally. He found that a few countries characterized as water-scarce have secured their food supply by importing water-intensive food products, rather than producing all of their food supply with inadequate water resources. Limited water resources should be used efficiently by not allocating the majority of the water resources to the production of water-intensive products (e.g. crops, paper etc.) but rather water should be made available for other economic purposes that can contribute more to regional value added by consuming less water (Allan, 1998, 2002).

Most of the studies on virtual water flows have been conducted for drought areas such as the Middle East and North Africa and have emphasized the amount of water embedded in different agricultural products related to food security, with agriculture being the largest water consumer.

Similarly, in China, agricultural irrigation has accounted for the majority of water use in the past, however, along with the large-scale industrialization and urbanization since 1980, domestic, municipal, and industrial water consumption joined the competition for limited water resources. Many industrial products also carry substantial amounts of virtual 'freshwater' as well as contaminated 'wastewater' from the production of paper, fertilizer and cement, which are then exported to other regions or countries.

Due to increasing importance of other industrial products and services and their effects on water consumption, we extend the concept of virtual water flows to comprise all types of commodities including agricultural goods, industrial products and services. We distinguish between two categories of virtual water: freshwater and wastewater. Virtual freshwater is the amount of freshwater consumed during the production for exports. Virtual wastewater is the amount of polluted water discharged to the ecosystem, i.e. the amount of emissions generated and left in the respective region in order to feed consumption in other regions or countries. Due to the importance of the agricultural sector in terms of water consumption we further differentiate between rainfed and irrigated agricultural products. This is based on the rationale that rain water used for agricultural products would not be readily available for any other economic production.

1.3. *Virtual water as a factor of production*

The notion of virtual water as necessary input to production and consumption activities leads us to the notion of factors of production or factor endowments. In our case we focus on water as a special input to production but are also interested in the question of how production and associated trade structures affect the availability of water resources. Early economic theorists such as Adam Smith (1909) and David Ricardo (1817) were concerned with differences in factor endowment, 'the comparative advantage', as one of the main reasons for trade and regional inequalities and as a source for the wellbeing of nations. The focus shifted to the negative sides of trade; and only rather recently, scholars started to advocate re-designing trade structures from the perspectives of social and environmental sustainability. In the following we will look at certain selected key publications to see how factor endowment and environmental resources have been treated in the trade literature and how that links to our question.

Heckscher (1919) and Ohlin (1933) incorporated the endowment of factors of production into the principle of comparative advantage, and consequently was referred to as the Heckscher–Ohlin (HO) theorem. The HO theory of international trade was able to explain that the differences of productivity in various countries are dependent on relative factor endowments. Leontief (1951 and 1954) calculated the labor and capital content of the exports of the United States to test the HO theory. The US seemed to be endowed with more capital relative to labor than any other country at that time. Therefore in terms of the HO theory, the US should have exported capital-intensive products and imported labor-intensive commodities. However, Leontief's test surprised the academic field as he reached a paradoxical conclusion that the US exported relatively more labor-intensive commodities and imported capital-intensive goods. These results received a great deal of attention and became known as the Leontief Paradox and have led to numerous studies discussing and critiquing the approach (see, for example, Stolper and Roskamp, 1961; Bharawaj, 1962).

If we apply classical trade theory to environmental studies, a country may have a comparative advantage if it

Table 1 – Extended water input–output table

	Activities intermediate demand	Final demand		Total output	Waste water
		Households and governments	Exports		
Economic activities	x_{ij}	y_{ij}	e_{ij}	x_i	r_i
Primary inputs	y_{ij}				
Imports					
Total inputs	x_j				
Fresh water (net consumption)	f_j				

is endowed with certain resources or if it can produce a product with relatively low costs to the environment. Since the 1970s, numerous theoretical studies have been conducted to research the linkage of trade and the environment by adopting the principle of comparative advantage. For example, Pethig (1976), Siebert (1977), McGuire (1982) and Brander and Taylor (1997) treated a country's emission/resource management standards as factor endowment, and their results showed that countries with less stringent environmental policies could increase their comparative advantage in the production of pollution and natural resource-intensive products (quoted after Huang and Labys, 2001). However this view is challenged by more recent research. Porter and van der Linde (1995) argued that strict environmental policies may not be a comparative disadvantage, in contrast, it may be an advantage to drive the producers and the whole economy to become more competitive in world markets by improving efficiency or innovating better environmental technologies. These conflicting views have led to a heated debate, and the empirical results are ambiguous (e.g. Huang and Labys, 2001).

The important point to emphasize here is that environmental goods and services such as available water resources can be a factor of production and therefore a source of comparative advantage. Thus, if a region is well endowed with environmental resources and in our case water resources, one could assume that this region's exports will have a larger share of water-intensive products. Applied to China, we would assume that water scarce North China would import water-intensive products and the water-rich South China would export products which would need lots of water inputs. In the following we will test this hypothesis and investigate if these Chinese regions take full advantage of virtual water flows. We will specifically build on the work of Leontief and use the input-output approach to assess regional and trade flows in China and their effects on virtual water flows.

2. Virtual water flows accounting and modeling framework

2.1. *Structure of the water input–output model*

The fundamental purpose of the input–output model is to analyze the interdependence of economic sectors. Its extensions include social institutions (Stone, 1971) and the environment (Leontief, 1970; Victor, 1972; Duchin and Lange, 1994). Frequently input–output analysis has been applied to water consumption and pollution issues (see, for example, Thoss and Wiik, 1974; Bouhia, 2001; Hubacek and Sun, 2005).

The traditional IO table is an $n \times n$ matrix describing the flows of goods between economic sectors in monetary units. We extend the table by adding 1 row in physical units[1] to measure the amounts of freshwater consumed and by 1 column to represent wastewater discharged by economic production processes.

The extended water IO table is presented in Table 1. It provides a detailed economic accounting scheme for economic activities (**x**), primary inputs (**v**), households and governmental final consumption (**y**), trade flows (**e**), net water consumption (**f**) and wastewater discharges (**r**).

As mentioned previously, water as a primary input is involved in economic production. This connection can be captured in freshwater consumption coefficients for each industrial sector. The direct freshwater consumption coefficient, f_j is calculated by dividing the total amount of consumed water of the *j*th sector by total input to that sector x_j. Therefore, the unit for the coefficient of fresh water consumption is m^3/Yuan. This coefficient represents the direct or the first round effects of the sectoral interaction in the economy (Bouhia, 2001; Hubacek and Sun, 2005). However, water is not only consumed directly but also indirectly. For instance, to produce paper necessary inputs are wood, chemicals, electricity and water (direct consumption). But also the production processes of each of these inputs need water (indirect consumption). Therefore, in order to combine both direct and indirect water consumption, we generate the total water consumption multipliers by multiplying direct water consumption coefficients f with the Leontief inverse $(\mathbf{I}-\mathbf{A})^{-1}$, which represents an indicator of the total water consumption throughout the production chain for each sector, shown in Eq. (1)

$$\text{Total Water Consumption} = \hat{f}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} \tag{1}$$

Similarly, we employ the direct wastewater coefficient r_i to represent the amount of wastewater released to produce a unit of output in the ith production sector. Therefore, we obtain Eq. (2) to measure the total amount of wastewater

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[1] For clarity, matrices are indicated by bold, upright capital letters; vectors by bold, upright lower case letters, and scalars by italicized lower case letters. Vectors are columns by definition, so that row vectors are obtained by transposition, indicated by a prime (e.g. $\mathbf{x}'$). A diagonal matrix with the elements of vector **x** on its main diagonal and all other entries equal to zero are indicated by a circumflex (e.g. $\hat{\mathbf{x}}$).

Fig. 1 - Hydro–economic regions in China. (Source: Land Use Change Group at IIASA (2001) — International Institute of Applied System Analysis, Laxenburg, Austria).

generated in an economy by increasing one unit of final consumption:

$$\text{Total Wastewater Generation} = \hat{r}(\mathbf{I}-\mathbf{A})^{-1}y \qquad (2)$$

This represents the flows from the economy to water resources (e.g. rivers, lakes or groundwater), i.e. the emissions of wastewater after production activities. These discharged wastewater flows from agricultural and industrial production can contain large amounts of noxious pollutants which damage the hydrological system.

2.2. *Hydro-economic regions and datasets*

Due to considerable regional differences in water supply and demand, and the need to assess regional trade flows, it is necessary to model water consumption on a regional level. Therefore we divide China into eight hydro-economic regions to establish water accounts for each region (shown in Fig. 1) based on watersheds and provincial level administrative boundaries[2] (see Hubacek and Sun, 2001). In this paper, we calculate and analyze the virtual water flows for two of China's regions: North China, which is characterized as water scarce, and South China which is abundant of water resources.[3]

The dataset for this study consists of two categories: detailed economic data (input–output tables) — to investigate the flow of goods and services between producers and consumers and the linkages between all production sectors; and hydrological data — comprising four sub-categories: water availability, fresh water utilization and fresh water consumption coefficients and wastewater discharge coefficients for each of the economic sectors.

2.2.1. *Economic data*

In our analysis we generate two regional input–output tables[4] (North and South China) by merging seven provincial input–output Tables[5] for 1997 in terms of the classification of hydro-economic regions (shown above, Fig. 1). The provincial input–output tables, each representing 40 economic sectors, were compiled by the State Statistical Bureau of China and published in 2000. The "value-added" categories in the table include: capital depreciation, labor compensation, taxes, and profits. "Final use" at the national level comprises six

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[2] The eight hydro-economic regions were distinguished in the "Land Use Change (LUC)" model, conducted by the LUC Group, International Institute for Applied Systems Analysis (IIASA). The eight regions are as follows: *North*, including Beijing, Tianjin, Hebei, Henan, Shangdong, and Shanxi; *Northeast*, including Liaoning, Jilin, and Heilongjiang; *East*, including Shanghai, Jiangsu, Zhejiang, and Anhui; *Central* including Jiangxi, Hubei, and Hunan; *South*, including Fujian, Guangdong, Guangxi, and Hainan; *Southwest* including, Sichuang, Guizhou, and Yunnan; *Northwest*, including Nei Mongol, Shananxi, Gansu, Ningxia, and XinJiang; and *Plateau*, representing Tibet and Qinghai.

[3] South China consists Guangdong, Fujian and Guangxi, but we had only access to the data in Guangdong. Therefore we have to use Guangdong to represent South China.

[4] Due to the lack of data, we could not construct a regional input–output table for the Plateau region.

[5] Six provincial input–output tables for North China and one in South China (Guangdong).

Table 2 – Availability of water resource distribution

Region	Total fresh water resource (10^8 m^3)	Population in 2000 (in 1000s)	Per capita water (in m^3)
North	843.5	311,100	271.1
Northeast	1529	106,334	1437.9
East	1926.2	198,149	972.1
Central	2761.2	167,256	1650.9
South	5190.8	129,942	3994.7
Southwest	6389.8	243,414	2625.1
Northwest	2115.6	111,128	1903.8
		China average	2271.0
		World average	6981.0

(Source: Wiberg, 2002 and China's Statistical Yearbook 2001).

categories: rural households, urban households, and government consumption, investment, inventory changes, and net exports.

2.3. *Hydrological data*

The dataset for water availability of different regions is generated by employing a hydrological model, *Climate and Human Activities — sensitive Runoff Model* (CHARM), developed by Wiberg and Strzepek (2000). A basic problem in modeling water use within an economic framework arises from the discrepancy between economic regions and watershed regions. Demand figures for water use are based on economic boundaries and are derived from the input–output tables. The water supply figures have to be based on hydrological conditions. The hydrological model — CHARM is used to redistribute the water resources from watershed regions to economic regions. CHARM is applied to the nine major water resource regions of China to estimate the natural available water supply which is then reallocated to the respective economic regions. The resulting water supply figures are an essential part of the regional water accounting tables and are also used to characterize the respective hydro-economic regions with regards to their water availability (see Table 2).

To calculate the water consumption side we need to know the amount of net water consumption from fresh water sources to produce a unit of output of a product or service — so-called fresh water consumption coefficients. Therefore in order to calculate the coefficients, this dataset consists of two sub-datasets: the total volume of net water consumption for each economic sector between seven regions; and the total output in monetary term for each sector correspondingly. The data of total output for each sector is given in the input–output tables. The dataset of water withdrawn for each sector was taken from *"China's Regional Water Bullets" in 1997, Regional Water Statistics Yearbook in 1999*[6] and annual reports on hydrology from various provincial hydrology-ministries. The economic sectors in the survey can be matched with the categories in the IO tables and updated to match the respective years.

In a similar fashion we proceed to calculate the effects on the wastewater side. Final wastewater discharge coefficients represent the amount of wastewater discharged to produce 10,000 Yuan of a certain product or service. The wastewater dataset is extracted from the "Third National Industrial Survey" in 1995 and "Regional Water Statistics Yearbook in 1999" and various other authoritative sources (Dong, 2000; Zhang, 2000; Li, 2003).

3. Interregional virtual water flows in China

Water problems in China have been investigated in depth in a number of studies, especially with regards to the disparities of regional water availability in China (Wang and Davis, 2000; Wiberg, 2002, 2003). Table 2 lists and compares the per capita water availability for each of the economic regions. Generally speaking, anything below one thousand cubic meters per capita is considered as a seriously water scarce region.

The northern part of China is not endowed with abundant water resources, and thus from a resource conservation point of view, North China should import more water-intensive goods such as agricultural products and export less water-intensive goods in order to maintain a favorable trade balance while optimizing the utilization of water resources. Following this idea, we will look at North China, the most water-constraint region and compare it with South China, a region with abundant water resources,[7] by tracing the virtual water flows created by the interregional trade patterns in China.

3.1. *Virtual freshwater flows*

By employing Eq. (1) — Total Water Consumption $= \hat{f}\,(I-A)^{-1}\,e$, we are able to quantify virtual freshwater flows between economic sectors triggered by trade between various regions in China and abroad.[8] Thus we can show how much water is necessary to produce certain goods that are then exported to other regions, including both direct and indirect water consumption for producing the exports. This amount of water used in the production chain is thus not available for water consumption for other purposes within that region. Similarly, the import of certain goods into the respective region causes water withdrawal and consumption in other regions or outside of China. The calculation of virtual water flows is conducted by multiplying the net exports vector (e) and the total fresh water consumption coefficient matrix ($\hat{f}(I-A)^{-1}$). The results are shown in Table 3 for North China and Table 4 for Guangdong.

The column of 'net flows of goods and services' in both Tables 3 and 4 provides details of the commercial trade activities in the respective regional economy. The column of

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[6] State Statistical Bureau (1999), State Statistical Publishing House, Beijing, China.

[7] For South China we had only the data for Guangdong province; however it will not affect the general tendency of the results as the remaining two provinces (Fujian and Hainan) are in a similar situation as Guangdong with regards to economic conditions, trade patterns and water availability.

[8] Where, $\hat{f}$ represents the diagonalized vector containing freshwater consumption coefficients. And the final demand (e) represents the net exports of goods and services.

Table 3 – Total water import/export in North China

Region: North China	Net flows of goods and services (10,000 Yuan)	Direct freshwater coefficient (m^3/10,000 Yuan)	Virtual freshwater net exports (million m^3)	Value added/ water (Yuan/m^3)
Rainfed agriculture	1,859,505	862.0	3055.1	8.1
Irrigated agriculture	2,607,575		4284.2	
Coal mining and processing	1,359,847	5.2	2.3	441.7
Petroleum and natural gas	864,149	5.1	1.5	428.8
Metal ore mining	546,304	4.8	0.4	344.7
Non-ferrous mineral mining	−2,430,346	4.7	−12.9	256.9
Food and tobacco processing	2,944,350	10.5	57.7	111.3
Textile goods	3,060,261	12.2	67.4	84.8
Wearing	2,431,617	4.0	11.6	308.0
Sawmills and furniture	619,342	5.0	3.8	348.3
Paper and products	993,460	18.0	28.6	83.3
Petroleum processing	−1,647,543	1.1	−2.5	693.6
Chemicals	−347,419	17.8	18.8	51.4
Non-metal mineral products	2,304,248	4.5	7.2	421.9
Metals smelting and pressing	−406,689	8.8	−17	98.2
Metal products	2,443,533	2.5	5.1	416.1
Machinery and equipment	−4,825,647	7.5	−53.3	167.7
Transport equipment	−312,987	3.2	−2	237.9
Electric equipment	−1,183,115	2.1	−9.6	201.2
Telecommunication equipment	−2,858,957	1.9	−31.5	104.1
Instruments	−552,792	2.3	−4.3	149.4
Maintenance machinery	−1,118,056	2.1	−5.9	116.3
Other manufacturing	2,742,628	8.5	25.9	215.7
Scrap and waste	−411,395	8.5	−3.7	355.7
Electricity	−3,589,807	41.5	−147.9	45.5
Gas production and supply	−49,679	10.0	−0.6	77.2
Water production and supply	−522,085	5.7	−5.5	181.9
Construction	−2,517,219	5.0	−12.1	503.7
Transport and warehousing	260,878	3.1	0.7	470.1
Post and telecommunication	245,262	2.4	1.4	881.8
Wholesale and retail trade	−1,749,342	2.2	−4.4	428.6
Eating and drinking places	47,464	2.2	0.2	877.5
Passenger transport	295,368	3.2	1.1	746.3
Finance and insurance	3,938,707	2.2	16.6	872.4
Real estate	−203,528	2.2	−0.2	1251.7
Social services	278,293	1.8	2.1	723.3
Health services, social welfare	−182,955	3.3	−0.5	784.9
Education and culture	−1,341,098	3.1	−5.3	1087.7
Scientific research	−12,857	2.4	−0.4	700.6
General technical services	1,533,501	4.0	6.5	1321.3
Public and other services	205,888	5.0	1.7	815.0
Total exports			4545.0	
Total imports			−319.6	
Net virtual freshwater exports			4225.4	

The negative figures represent the inflows (imports) for both monetary and freshwater terms, and positive figures mean outflows (exports) for both monetary and freshwater terms.

'direct freshwater coefficient' gives the comparison of the direct water consumption levels for each production sector. For example, the coefficient for paper production measures the amount of freshwater directly consumed by paper-making industries to produce 10,000 Yuan of paper products. We can see from the tables that agriculture in both regions is the most water-intensive sector; and food processing, paper and textiles require more water per unit of output than the other industrial sectors. The column of 'virtual freshwater net exports' shows the amount of freshwater embedded in goods and services and exported to other regions or countries via trade. The term 'value added/per unit of water' in the last column of both tables assesses the amount each economic sector contributes to GDP per cubic meter of freshwater.

Based on our calculations we find that North China imported a number of water intensive products and services. For example, North China spent 35.89 billion Yuan to purchase extra electricity from other regions in 1997, which means a virtual import of 147.9 million cubic meters of water which is withdrawn and used up in production processes in other regions. Another example is agriculture: North China received 44.67 billion Yuan through the export of agricultural products, and with it 7339.3 million cubic meters of virtual water have been transported to other regions. However, we have to consider that much of the agricultural land is rainfed in

Table 4 – Total water import/export in South China

Region: Guangdong	Net flows of goods and services (10,000 Yuan)	Direct freshwater coefficient (m^3/10,000 Yuan)	Virtual freshwater net exports (million m^3)	Value added/water (Yuan/m^3)
Rainfed agriculture	−642,700.5	784.0	−228.9	8.8
Irrigated agriculture	−982,407.5		−349.4	
Coal mining and processing	−1,507,207	4.4	−6	27.3
Petroleum and natural gas	−227,718	4.9	−9.6	223.0
Metal ore mining	−369,356	4.2	−3	96.5
Non-ferrous mineral mining	−622,501	4.0	−2.7	443.8
Food and tobacco processing	1,138,328	9.9	15.8	133.4
Textile goods	−1,827,158	11.3	39.7	112.4
Wearing	11,054,187	3.9	46.6	537.2
Sawmills and furniture	−892,070	4.9	−2.7	167.2
Paper and products	2,920,391	16.8	77.6	67.0
Petroleum processing	−2,950,551	1.3	−3.1	426.2
Chemicals	−3,848,076	16.7	0.1	42.4
Non-metal mineral products	333,439	4.9	2	383.8
Metals smelting and pressing	−6,187,180	8.2	−48.3	37.9
Metal products	1,332,070	2.7	4.7	507.0
Machinery and equipment	−1,276,310	6.9	−8.9	88.3
Transport equipment	802,771	2.9	2.7	544.7
Electric equipment	7,150,944	1.9	40.5	263.8
Telecommunication equipment	1,263,254	1.7	21.6	74.2
Instruments	2,108,399	2.1	11.3	193.8
Maintenance machinery	−8916	1.6	0.1	413.5
Other manufacturing	−517,380	7.9	1.5	280.9
Scrap and waste	11,115	7.5	0.9	495.5
Electricity	160,907	37.9	5.3	38.9
Gas production and supply	−3290	9.3	0	133.8
Water production and supply	−11,741	5.7	0.3	206.5
Construction	0	4.8	1.1	566.7
Transport and warehousing	−2,900,271	2.7	−11.1	331.8
Post and telecommunication	101,923	2.8	1.5	693.3
Wholesale and retail trade	−111,226	2.3	7.7	453.3
Eating and drinking places	337,216	2.3	3.9	548.3
Passenger transport	530,143	2.7	2.4	911.9
Finance and insurance	−1289	2.1	2.5	614.6
Real estate	0	2.8	2.2	958.0
Social services	791,523	1.9	4.8	753.0
Health services, social welfare	0	3.2	−0.2	675.4
Education and culture	0	2.8	0	1258.6
Scientific research	0	2.2	0.3	505.5
General technical services	0	3.6	0	702.9
Public and other services	0	4.6	0	592.3
Total export			296.7	
Total import			−444.8	
Net virtual freshwater export			−148.1	

The negative figures represent the inflows (imports) for both monetary and freshwater terms, and positive figures mean outflows (exports) for both monetary and freshwater terms.

North China, which produces about 42% of total agricultural outputs. The amount of rainwater embedded in agricultural products would not be readily available for any other economic production even if crops were not grown on this land. Therefore, the effective export of virtual water in the agricultural sector only consists of irrigated water, which is 4284.2 million cubic meters. Annually, 4545.0 million cubic meters of fresh water virtually flow out of North China (which is used in the production of exports) excluding rainwater in the agricultural production. On the other hand, the import of virtual water was only 319.6 million cubic meters, which reduces the net flow to other regions to 4225.4 million cubic meters. From a water conservation point of view, North China, characterized as water-scarce, should import water-intensive products rather than produce them. According to this analysis, North China used up more than 5% of its total water resources for producing exports to other regions, mainly through the trade of water-intensive commodities such as agricultural crops, processed food, textiles and chemical products. By contrast, Guangdong is endowed with rich water resources, but virtually imported 444.8 million m^3 of freshwater, 79% of which are through the trade of water-intensive products (e.g. irrigated agricultural products). On the other hand, Guangdong exports relatively water non-intensive commodities such as electric equipment and many commercial and social services.

By summarizing the virtual freshwater flows of both North and South China, we find that the trade patterns are apparently inconsistent with our original hypothesis: water-scarce regions in China produce and export water-intensive products but import water non-intensive commodities. Meanwhile, water-abundant South China imports water-intensive goods. One of the possible explanations could be that water has not been recognized as an important factor of production in China's economy as there are very low costs associated with the utilization of water resources for most production processes. Another reason could lie in the fact that North China has suitable climatic condition, soil and land for many agricultural crops (Heilig et al., 2000). A third reason refers to the design of economic policies: Guangdong is subject to more favorable policies and better circumstances for investments in industry and services sectors than other regions. Since the economic reform in 1978, many locations in South China (including Guangdong) have been established as "Special Economic Development Zone", which brought many commercial opportunities and triggered a regional economic boom. This is also reflected in changing water consumption patterns. These economic incentives led

Table 5 – Total wastewater import/export in North China

Region: North China	Net flows of goods and services (10,000 Yuan)	Direct wastewater coefficient (m^3/10,000 Yuan)	Virtual wastewater new flows (Million m^3)	Value added/wastewater (Yuan/ m^3)
Agriculture	4,467,080	79.4	354.8	125.9
Coal mining and processing	1,359,847	10.2	4.7	220.8
Petroleum and natural gas	864,149	10.6	3.0	214.4
Metal ore mining	546,304	21.6	1.6	82.1
Non-ferrous mineral mining	−2,430,346	4.2	−10.4	321.1
Food and tobacco processing	2,944,350	4.2	20.1	320.0
Textile goods	3,060,261	6.9	39.9	143.4
Wearing	2,431,617	1.9	3.3	1071.3
Sawmills and furniture	619,342	1.3	2.5	539.1
Paper and products	993,460	19.2	27.2	87.7
Petroleum processing	−1,647,543	3.2	−5.0	346.8
Chemicals	−347,419	18.8	16.9	57.1
Non-metal mineral products	2,304,248	2.9	4.2	730.1
Metals smelting and pressing	−406,689	10.8	−15	111.6
Metal products	2,443,533	6.9	3.1	693.4
Machinery and equipment	−4,825,647	9.3	−49.8	179.5
Transport equipment	−312,987	4.6	−0.7	706.5
Electric equipments	−1,183,115	3.4	−5.4	357.0
Telecommunication equipment	−2,858,957	3.4	−17.7	184.7
Instruments	−552,792	5.2	−4.2	155.0
Maintenance machinery	−1,118,056	2.6	−2.3	304.6
Other manufacturing	2,742,628	6.6	18.9	295.7
Scrap and waste	−411,395	6.7	−2.7	480.0
Electricity	−3,589,807	0	0	0.0
Gas production and supply	−49,679	16.2	−1.0	47.1
Water production and supply	−522,085	16.9	−9.0	110.9
Construction	−2,517,219	8.3	−19.6	312.1
Transport and warehousing	260,878	4.4	0.6	534.2
Post and telecommunication	245,262	4.4	1.2	1002.0
Wholesale and retail trade	−1,749,342	2.5	−2.4	793.7
Eating and drinking places	47,464	2.9	0.2	1300.0
Passenger transport	295,368	2.6	0.7	1105.7
Finance and insurance	3,938,707	2.3	11.2	1292.4
Real estate	−203,528	2.1	−0.2	1854.3
Social services	278,293	2.1	1.4	1071.6
Health services, social welfare	−182,955	2.6	−0.4	1162.8
Education and culture	−1,341,098	1.7	−3.6	1611.4
Scientific research	−12,857	2.1	−0.3	1037.9
General technical services	1,533,501	1.8	4.4	1957.4
Public and other services	205,888	2.1	0.8	1811.2
Total virtually accepted wastewater for other regions' consumption			520.7	
Total virtually generated wastewater left in other regions			−149.7	
Net virtual wastewater left for exports			371.0	

The negative figures represent the imports for monetary flows but the amount of wastewater is generated for producing such imports, and positive figures mean the export for monetary flows but the amount of wastewater is generated for producing such exports.

to a restructuring of the regional economy to higher value added products with relatively lower levels of resource inputs. Thus Guangdong imports and exports of virtual water reflect the economic structure of the more developed special economic zones. On the other hand, North China has a relatively lower economic growth rate and stronger focus on low value added and high water intensive production without these special policies.

If we consider multiple factors relevant for the existing production and trade structure such as environmental endowment (e.g. soil quality), land prices and other socio-economic or political factors we see that North China has a 'comparative advantage' for producing and exporting agricultural products. In terms of water conservation it is important to effectively balance these factors. North China may sustain the export of rainfed agricultural goods as rainwater cannot be

Table 6 – Total wastewater import/export in South China

Region: Guangdong	Net flows of goods and services (10,000 Yuan)	Total wastewater coefficient (m^3/10,000 Yuan)	Virtual wastewater new flows (Million m^3)	Value added/wastewater (Yuan/m^3)
Agriculture	−1,652,108	70.1	−149.4	142.5
Coal mining and processing	−1,507,207	9.5	−15.1	10.9
Petroleum and natural gas	−227,718	9.7	−23.9	89.2
Metal ore mining	−369,356	19.9	−15.8	18.4
Non-ferrous mineral mining	−622,501	3.5	−2.7	443.8
Food and tobacco processing	1,138,328	3.3	6.3	333.5
Textile goods	−1,827,158	6.4	27.0	165.3
Wearing	11,054,187	1.9	15.3	1634.9
Sawmills and furniture	−892,070	1.6	−2.5	181.2
Paper and products	2,920,391	17.3	86.7	59.9
Petroleum processing	−2,950,551	2.9	−9.3	142.1
Chemicals	−3,848,076	17.9	0.1	35.4
Non-metal mineral products	333,439	2.9	1.5	516.6
Metals smelting and pressing	−6,187,180	9.6	−53.2	34.4
Metal products	1,332,070	6.7	3.6	676.0
Machinery and equipment	−1,276,310	8.9	−8.9	88.2
Transport equipment	802,771	4.6	1.0	1510.0
Electric equipments	7,150,944	3.5	25.1	425.5
Telecommunication equipment	1,263,254	3.7	13.4	119.7
Instruments	2,108,399	4.9	12.0	182.8
Maintenance machinery	−8,916	2.7	0	984.5
Other manufacturing	−517,380	6.2	1.9	226.5
Scrap and waste	1115	6.5	0.7	629.2
Electricity	160,907	0.0	0	0.0
Gas production and supply	−3,290	14.7	0	73.5
Water production and supply	−11,741	15.4	0.5	113.3
Construction	0	7.6	1.7	351.1
Transport and warehousing	−2,900,271	4.0	−9.8	377.0
Post and telecommunication	101,923	4.1	1.3	787.9
Wholesale and retail trade	−111,226	2.6	4.2	839.4
Eating and drinking places	337,216	2.7	2.6	812.3
Passenger transport	530,143	2.9	1.6	1351.0
Finance and insurance	−1,289	2.1	1.7	910.6
Real estate	0	1.9	1.5	1419.3
Social services	791,523	1.9	3.2	1115.6
Health services, social welfare	0	2.4	−0.1	1000.5
Education and culture	0	1.5	0	1864.5
Scientific research	0	1.9	0.2	748.8
General technical services	0	1.6	0	1041.3
Public and other services	0	1.9	0	1316.2
Total virtually accepted wastewater for other regions' consumption			213.1	
Total virtually generated wastewater left in other regions			−290.7	
Net virtual wastewater left for exports			−77.6	

The negative figures represent the imports for monetary flows but the amount of wastewater is generated for producing such imports, and positive figures mean the export for monetary flows but the amount of wastewater is generated for producing such exports.

effectively used by other production sectors. On the other hand, North China might want to reconsider the level of exports of irrigated agricultural products in order to make the scarce water resources (e.g. surface or ground water) available for other purposes which can contribute more to the economy and society in terms of value added and jobs.

From a water efficiency point of view, North China with limited water resources, should produce and export the commodities which have high value added per unit of water. By looking at the column of 'value added/water' in Tables 4 and 5 North China has a comparative advantage in the production sectors of coal mining and processing, production of sawmill and furniture, machinery equipment, and many service sectors. Meanwhile, Guangdong has the advantage on producing agriculture, textiles, and metal products. Obviously this statement needs to be qualified by looking at other factors such as the availability of skilled labor and other essential factors of production, but the focus on water can provide a useful starting point.

3.2. *Virtual wastewater flows*

Similar to the virtual freshwater flows, wastewater is also created through trade related production. The pollutants and wastewater generated for producing exported goods will stay in or pass through the exporting region leading to negative effects in terms of water availability and quality. In other words, the exporting region virtually accepts the discharge of wastewater from other regions by exporting goods. Similarly to virtual freshwater flows, we can calculate virtual wastewater flows consumed by producing exports for both North China and Guangdong. By employing Eq. (2) — Total Wastewater Generation $=\hat{r}(I-A)^{-1}e$, we are able to quantify virtual wastewater flows triggered by imports and exports between various regions in China and abroad. The direct wastewater coefficient refers to the amount of wastewater per unit of output. The results are shown in Table 5 for North China and in Table 6 for Guangdong.

A number of pollution-intensive industries (e.g. metal mining, paper and chemical production) are concentrated in North China. Imports of North China lead to the generation of 149.7 million m^3 of wastewater in other regions where the commodities were produced while North China's exports resulted in 520.7 million m^3 of wastewater in North China, of which 32% is industrial wastewater and 68% is agricultural wastewater. Hence the net wastewater balance for North China was 371.0 million m^3. The discharge of high-concentrated pollution to surface flows from pollution-intensive production sectors (e.g. paper, chemicals and textiles) has led to the fact that many major rivers in North China no longer support any type of usage due to the low water quality levels; and more than 50% of groundwater has been seriously degraded due to the overuse of fertilizers and pesticides (Dong, 2000).

Looking at the situation in the southern provinces we see that Guangdong virtually exports (externalizes) 149.4 million m^3 of agricultural wastewater and 141.3 million m^3 of wastewater from industrial and service sectors to pollute other regions' hydrological ecosystems. The industrial wastewater is mainly contributed from paper, textiles and electric equipment production sectors. On the other hand, Guangdong accepts 213.1 million m^3 of wastewater by producing exports for other regions' consumption. Hence the water-rich Guangdong region has a net wastewater balance of 77.6 million m^3 being virtually discharged to other regions.

Thus from above figures, we can find a similar trade contradiction as with the virtual freshwater flows. The wastewater virtually flows out from water-rich regions such as Guangdong which externalizes the problems of wastewater production to other regions through importing wastewater intensive products and water-shortage regions such as provinces in North China are threatening their own water resources through the creation of waste water for producing exports.

4. Conclusion

The economic success in China has come at the expense of over exploitation of natural resources and huge impacts on the environment and especially water resources. In North China, water scarcity has become one of the bottlenecks for regional economic development. In this paper we have looked at the economic and trade structure of the water-scarce northern regions of China and the water abundant southern regions of China, and we assessed the implications for water resources in those regions.

This assessment was done by employing an extended regional input–output model for the hydro-economic regions in China. This study was one of the very first to use the concept of virtual water flows not only for agricultural products but also industrial and service products. In addition we accounted also for waste water flows and distinguished between rainfed and irrigated agriculture, which is of special significance with regards to water use. But one of the major shortcomings is the homogenous treatment of very different qualities of water inputs and wastewater categories.

Our starting point was the assumption that from a water conservation point of view, a region/country that is endowed with vast amounts of water resources should export relatively more water-intensive/polluted products such as agricultural crops, paper and chemicals. However, the generated results of virtual freshwater flows show that water-scarce North China predominantly produces and exports water-intensive products but imports non-water intensive commodities. In comparison, water-abundant Guangdong (South China) imports water-intensive goods but exports non-water-intensive products. A similar situation can be found when considering wastewater: the water-scarce North creates more waste water for export production than what is virtually created through its imports; and similarly, the water-abundant South externalizes waste water problems by importing waste water-intensive products from other regions.

With regards to the actual extent of the virtual water flows, our results seem to indicate that the current structure of the economy and trade do not pose so much of a problem in terms of freshwater consumption as in North China only about 5% of total available water can be attributed to net virtual water flows, which is relatively minor in comparison to major water consumers such as water losses due to infrastructural inefficiencies. In other words, the water-scarce North China does not take full advantage of the possibilities of importing water-intensive products to ameliorate its own water problems. The same seems to be true for the wastewater situation.

To reflect on a more theoretical level, economic production and consumption use inputs of materials and resources from the environment, however, environmental resources are currently highly undervalued as there are often little or no costs associated with their consumption. Therefore, water usually does currently not play a sufficiently important factor in production and consumption decisions. This is also reflected in current trade theories largely ignoring the environment as a factor of production. The same is true from a policy point of view; export-oriented policies often directly conflict with water-saving policies leading to so-called perverse incentives. On the other hand, given the relative inflexibility in changing production structures in comparison to technical improvements these findings emphasize the need for increased investments in water transportation infrastructure and water treatment plants. However from a sustainability point of view it is important to emphasize that direct and indirect (virtual water) consumption needs to be incorporated in decision-making processes and public policies, especially for water-scarce regions such as North China, in order to achieve sustainable consumption and production in the future.

Acknowledgements

We would like to give special thanks to Laixiang Sun for his important contributions to the data and other key aspects of this paper. We also extend our appreciations to Faye Duchin and John Gowdy for their very supportive feedback, comments and invaluable insights. We also thank the Land Use Change Team at the International Institute for Applied Systems Analysis (IIASA) and especially Guenther Fisher and David Wiberg for their support, help and opportunities during the Young Scientist Summer Program.

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