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Published paper

Guan, D. and Hubacek, K. (2008) *A new and integrated hydro-economic accounting and analytical framework for water resources: A case study for North China*, Journal of Environmental Management, Volume 88 (4), 1300 - 1313.

A New and Integrated Hydro-Economic Accounting and Analytical Framework for Water Resources: A case study for North China

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Abstract

Water is a critical issue in China for a variety of reasons. China is poor of water resources with 2,300 m³ of per capita availability, which is less than 1/3 of the world average. This is exacerbated by regional differences; e.g. North China's water availability is only about 271 m³ of per capita value, which is only 1/25 of the world's average. Furthermore, pollution contributes to water scarcity and is a major source for diseases, particularly for the poor. The Ministry of Hydrology (1997) reports that about 65%-80% of rivers in North China no longer support any economic activities.

Previous studies have emphasized the amount of water withdrawn but rarely take water quality into consideration. The quality of the return flows usually changes; the water quality being lower than the water flows that entered the production process initially. It is especially important to measure the impacts of wastewater to the hydro-ecosystem. 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.

In this paper we present 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. We thus follow the tradition of integrated economic-ecologic input-output modelling. Our 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 us to deal with water resources of different qualities.

Following this method, the results illustrate that North China requires 96% of its annual available water, including both water inputs for the economy and contaminated water that is ineligible for any uses.

Keywords:

input-output analysis, hydro-economic accounting, water consumption, wastewater, water quality, China

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1 INTRODUCTION

1.1 Competitive Usage of Scarce Water Resources

Traditional economic analysis rarely takes natural resources into consideration and thus water is usually not recognised as a factor of production. But in reality water is a primary input to all goods and services either directly or indirectly; the available quantity and quality can affect the production of goods and services and thus influences the level of economic activities especially in quickly transforming societies, from agricultural based towards industrialized and modernizing economies, such as China.

Economic growth and people's lifestyle changes have left deep marks on China's water resource availability. China is trying to feed 1.3 billion inhabitants and their wants, i.e. 22% of total world population with only 7% of the world's arable land, and 6% of fresh water resources (Fischer et al. 1998). Water is already considered the most critical natural resource in some regions in China. China's water resources are unevenly distributed: North China has only about 20% of the 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 m³ or 1/8 of the national level and 1/25 of the world average. Table 1 lists and compares the per capita water availability for China's regions. Anything below one thousand cubic meters per capita is considered as serious water scarce. The total fresh water resource in North China is 84,350 million m³, surface water accounts for 65% of the total, 55,151 million m³; and groundwater provides the rest 35%, 45,252 million m³.

Table 1 here

Furthermore the rapid economic development and urbanisation has led to the extraction of significant amounts of water and to discharge of often toxic waste water further reducing the amount and quality of appropriate water supply. Many of 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 enormous demand for total water consumption in the northern basins and great impacts on local hydro-ecosystem, especially in the Haihe River, Huanghe River and Huaihe River Basins. In 1997, the total treatment rate of wastewater in North China was only 22% (Li 2003). The pollutants disperse and contaminate other fresh water resources and thus further contribute to water-scarcity. The severe water

shortages have become one of the bottlenecks for the development of the regional economy such as in North and Northwest China². However, many countries and regions including China do not have an integrated water accounting system that can effectively capture the linkages and interactions between economic production and consumption, water resource depletion and hydro-ecosystem degradation.

Thus the objectives of this paper are to firstly review environmental input-output models and its application on water. Then we propose an integrated economic-hydrological model by merging the regional input-output tables with a mass balanced hydrological model to establish water accounts. The proposed framework creates the links and interactions between the economy and the hydro-ecosystem, which enables us to quantify environmental impacts triggered by economic activities. In particular, we 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. We illustrate the model with a numerical example for North China which has been considered as one of the most water scarce regions in the world.

2 REVIEW OF INPUT-OUTPUT ANALYSES: FROM ADDING A WATER COEFFICIENT ROW TO INTEGRATED ECONOMIC-ECOLOGICAL MODELS

An appropriate and efficient water accounting method has a vital role in policy decision-making. It is essential to analyse the interdependences within the production system of an economy, and to seek the main contributors to water resource exhaustion and the polluters of the hydro-ecosystem. Input-output analysis is a quantitative framework to investigate the interdependences within an economy, which was developed by Wassily Leontief in the late 1930s. Since the 1960s, input-output analysis has been extended to account for environmental pollution generation and abatement associated with inter-industry activities (Cumberland 1966; Daly 1968; Leontief 1970). Leontief added a row vector of pollution to represent the amount of emission each economic sector generated for its production. Its delivery to final

² In 2003, the South- North Water Transfer project was launched to improve the hydro-conditions in North of China to sustain economic usage.

demand is the amount of pollutants households are willing to accept. In order to balance the table, he added an 'anti-pollution' column 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) and Chen (1973). But it was also criticized for its sole focus on the emission side and for ignoring the material balance principle (Victor 1972; Forsund 1985). However, this simple method of adding a row vector in input-output table has been widely adopted for investigating environmental emissions or resource consumption triggered by economic developments or trade in both single-country and multi-regional levels (e.g. Duchin et al. 1993; Julia and Duchin 2005; Peters and Hertwich 2006), as well as estimating future environmental challenges (e.g. Duchin and Lange 1994; Hubacek and Sun 2000; 2001)

In order to better reflect the effects and feedback of economic activities to natural ecosystems, the 'Economic-Ecological' model has been created to allow modelling of interactions both within economic and environmental systems. Daly (1968) and Isard (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 (Miller and Blair 1985). In both Daly's and Isard's 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 today. However these early models suffered to a larger extent of lacking data (Richardson 1972; Victor 1972). Victor (1972) limited the scope of Daly and Isard's models to account only for flows ecological commodities (free goods called in Victor's model) from the environment into the economy and of the waste products from the economy into the environment. His work was the first study in which comprehensive estimates of material flows are 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. Building on the idea of Isard's (1972) and other later authors Jin et al. (2003) developed an economic-ecological model for a marine ecosystem 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 of New England. They linked the workings of an economy, represented by a matrix of economic exchanges, with three ecological resource multipliers

(fishing harvesting, fishing and habitat destruction and marine ecosystem interaction) depicting flows between ecological sectors.

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 a water allocation study conducted by Harris and Rea (1984) for the US. The study aimed to effectively allocate water resources among the economic sectors in order to maximize value added, and determined the marginal value of water for different users. 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; Leistriz et al. 2002; Wang et al. 2005). Only a handful input-output studies were conducted with regards to water issues in China. For example, 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 based on 1992's national data. They matched watershed boundaries with regional input-output boundaries. Guan and Hubacek (2006) extended regional input-output tables by adding coefficients for freshwater consumption and wastewater discharge to account for trade of virtual freshwater and virtual wastewater respectively.

Nevertheless, 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 a very few exceptions including water degradation into input-output frameworks. For example, Ni et al. (2001) conducted a regional study on one of the fast-growing economy zone, Shenzhen, South China; they added a pollution sector into the input-output tables, aimed to adjust the economic structure for minimizing the COD (Chemical Oxygen Demand) level in industrial wastewater by giving a predicted maximized 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, followed the definition in Miller and

Blair (1985, pp.236)³, which allow accounting of water flows throughout economic and hydrological systems.

3 A HYDRO-ECONOMIC ACCOUNTING FRAMEWORK

The core of the structure of our model is the combination of a water quality model with an economic input-output model. In order to set up the framework of such a water accounting model, it is important to understand how water flows through the hydro system.

3.1 Hydrological Balance and Water Demand

Water in nature can be perceived as a balanced system, as shown in Figure 1. Water is mainly extracted from two sources: surface water from rivers, lakes, streams 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 infiltrating the soil.

Figure 1 here

Traditionally, the term ‘water demand’ comprises the amount of net water consumed⁴ for economic production and domestic usage; however the flows of polluted water resources, i.e. the degradation, 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 diffuse through the water bodies causing pollution in the same economic region or further downstream affecting other economic regions. For example, the polluted wastewater infiltrates into the groundwater or mixes with surface water and flows 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

³ “Economic-Ecological models result from extending the inter-industry 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)

⁴ We use the term consumption rather than intake as this refers to water that is embodied in the intermediate or final product and thus not available for alternative users within the accounting period.

purify the waste, but this ability is determined by conditions of the hydro system and biological, physical or chemical characteristics 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 1. We assign the name of ‘unavailable 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.

$$\textit{Extended Water Demand} = \textit{Net Water Consumption} - \textit{Discharged Wastewater} + \textit{Unavailable Water} \quad (1)$$

In an input-output framework, the accounting period is usually for a year. In this paper we use the year of 1997 for China’s regional water budget, to match the availability of economic and hydrological data.

3.2 Structure of the Integrated Hydrological-Economic Water Input-output Model

The traditional input-output table is an $n \times n$ matrix describing the flows of goods between economic sectors in monetary units. We extend the matrix to $(n + m) \times (n + m)$ by adding water sectors in physical units⁵. 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 2).

Table 2 here

Matrix **A** ($n \times n$) represents the technical coefficients in production 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

⁵ 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 \mathbf{x} on its main diagonal and all other entries equal to zero are indicated by a circumflex (e.g. $\hat{\mathbf{X}}$).

production wastewater is discharged into the ecosystem. The following sections 3.3 – 3.6 give detailed description for the linkages within and between the four matrices.

3.2.1 The Economic System

The key part of the static Leontief's input-output model is the following algebraic equation:

$$\mathbf{y} = (\mathbf{I} - \mathbf{A})\mathbf{x}; \quad (2)$$

where \mathbf{x} represents sectoral production output; \mathbf{y} represents total final demand; \mathbf{I} is the $n \times n$ identity matrix; and \mathbf{A} is a $n \times n$ matrix of technical coefficients. The \mathbf{A} -matrix represents the components of intermediate demand, where the coefficients a_{ij} refer to the amount of input from sector i required by the sector j for each unit of output.

Hence, a_{ij} (unit: Yuan/Yuan) are technological coefficients, defined as Equation (3),

$$a_{ij} = \frac{x_{ij}}{x_j} \quad (3)$$

where the x_{ij} (unit: Yuan) represents the monetary flows from i^{th} sector to j^{th} sector. x_j (unit: Yuan) is the total economic output of j^{th} sector in monetary term. If the $(\mathbf{I}-\mathbf{A})$ is not singular, we can convert Equation (2) as,

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}; \quad (4)$$

The matrix $(\mathbf{I}-\mathbf{A})^{-1}$ gives the so-called Leontief multiplier matrix which accounts for the total accumulative effect on sectoral output (\mathbf{x}) by the changes in final demand (\mathbf{y}).

3.2.2 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 $m \times n$ \mathbf{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 (5):

$$f_{kj} = \frac{g_{kj}}{x_j} \quad (5)$$

where g_{kj} (unit: m^3/year) is the amount of water supplied from the k hydrological sectors consumed in economic sector j ; x_j (unit: Yuan) is the total input of the j^{th} sector. This coefficient represents the direct or the first round effects of the sectoral interaction in the economy. However, water is not only consumed directly but also indirectly. For instance, to produce paper necessary inputs are fiber, 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 have to generate the total water consumption multipliers matrix (\mathbf{F}) by multiplying the diagonalized matrix of direct water consumption coefficients \hat{f}_k ($k = \text{surface, ground or rainfall water}$) with the Leontief multiplier matrix $(\mathbf{I}-\mathbf{A})^{-1}$, which represents an indicator of the total amount of water used up throughout the production chain for each sector. By pre-multiplying the water consumption matrix \mathbf{F} with final demand (\mathbf{y}) we receive Equation (6) describing the direct and indirect effects of water inputs by increasing a unit of final consumption, named as ‘Net water consumption’:

$$\text{Net Water Consumption} = \hat{f}_k (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} \quad (6)$$

3.2.3 Flows from the Economic to the Hydrological System

The wastewater after the production and domestic discharge will leave the economy and flow back to the original water resources (e.g. rivers, lakes or groundwater), which usually get degraded. Often the discharged wastewater carries large amounts of noxious pollutants dissolved into surface or ground water. The output (wastewater) of each production sector to the water supply sources shall be captured in the \mathbf{R} matrix with dimensions $n \times m$. Similarly to the process of determining fresh water consumption coefficients, the direct wastewater coefficient r_{il} – the amount of wastewater released to the l^{th} hydrological sector in order to produce a unit of economic output in the i^{th} production sector. The calculation is shown in Equation (7).

$$r_{il} = \frac{h_{il}}{x_i} \quad (7)$$

By multiplying the diagonalized matrix of direct wastewater coefficients \hat{r}_l ($l = \text{surface, ground or natural loss water}$) with the Leontief multiplier matrix $(\mathbf{I}-\mathbf{A})^{-1}$, we will obtain the total wastewater coefficient matrix (\mathbf{R}) which identifies the total contribution of each production sector to the environment by discharging sewage into natural water resources. Multiplying the matrix \mathbf{R} with final demand (\mathbf{y}), we get Equation (8) representing the total amount of wastewater generated in an economy by final consumption, referred to as ‘Discharged wastewater’:

$$\text{Discharged Wastewater} = \hat{r}_l (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} \quad (8)$$

3.2.4 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 infiltrate into the groundwater, a series of complex physical and biochemical processes occur. For our purpose we can summarize them 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, the receiving water body, and the layers (e.g. soil or rocks) in between. 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) may be reduced. The **B** matrix identifies the water flows within the hydrological ecosystem and the impacts of discharged wastewater to the freshwater resources. In other words, it measures the natural water losses (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). For illustrate purpose, we use COD (Chemical Oxygen Demand) as water quality indicator measured in $gram/m^3$. The following linear formulation is developed to capture the impacts to the hydro-ecosystem when contaminated wastewater enters the water bodies as well as the natural evaporation process.

$$h_k = \sum_l v_{kl} + e_k, \quad k = 1, \dots, m; \quad l = 1, \dots, m \quad (9)$$

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, we further decompose the freshwater needed for diluting pollution (v_{kl})

$$v_{kl} = b_{kl} h_l \quad \text{alternatively,} \quad b_{kl} = \frac{v_{kl}}{h_l} \quad (10)$$

where b_{kl} (unit: m^3/m^3) is the hydro-ecosystem exchanges coefficient⁶, 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

⁶ 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.

the amount of pollution discharged to the l^{th} hydrological sector. Therefore we obtain Equation (11) by combining Equations (9) and (10),

$$h_k = \sum_l b_{kl} h_l + e_k, \quad k = 1, \dots, m; \quad l = 1, \dots, m \quad (11)$$

The Equation (11) can be also rearranged and re-written in matrix notation:

$$(\mathbf{I} - \mathbf{B})\mathbf{h} = \mathbf{e} \quad (12)$$

where \mathbf{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; \mathbf{e} is a $m \times 1$ vector denoting the natural losses in the ecosystem; \mathbf{B} is a $m \times m$ matrix referred to as the hydro-ecosystem exchange matrix. The above Equation (12) can also be re-arranged as followed,

$$\mathbf{h} = (\mathbf{I} - \mathbf{B})^{-1}\mathbf{e} \quad (13)$$

If we combine the Equation (6), (8) and (13) to formulate the relationship as shown in Equation (1), the water demand can be described as,

$$\text{Extended Water Demand} = (\hat{f}_k - \hat{r}_l)(\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} + (\mathbf{I} - \mathbf{B})^{-1}\mathbf{e} \quad (14)$$

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

Equation (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 \mathbf{B} , b_{kl} concerns physical water flows in nature. In the following, section 3.3 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 16) provides the simple 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 \mathbf{B} matrix.

3.3 Mixing Pollution in Water Bodies

We employ the following water quality model which is constructed based on a mass balance approach (Equation 15). 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.

$$c_{mixed} = \frac{1}{1 + k_1 \frac{v}{q}} \left(k_2 \frac{q_0}{q} c_0 + \frac{q_p}{q} c_p \right) \quad (15)$$

$$q = q_0 + q_p$$

Parameters:

- c_{mixed} – pollutant concentration after mixture processes
- c_0 – initial pollutant concentration in the water body
- c_p – pollutant concentration in wastewater
- q – runoff rate after completion of the mixing process⁷
- q_0 – initial runoff rate
- q_p – wastewater discharge rate
- v – volume of freshwater in the water bodies
- k_1 – Total reaction rate of pollutants after entering the water bodies
- 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 we replace the c_{mixed} by $c_{standard}$, the Equation 15 can be re-written as follows:

$$v \geq \frac{1}{k_1 c_{standard}} (q_0 c_0 + k_2 q_p c_p - q c_{standard}) \quad (16)$$

$$q = q_0 + q_p$$

Hereby, the scalar v is the amount of freshwater in the hydro-ecosystem that has been used 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.

⁷ Runoff is categorized as surface runoff and sub-surface runoff for surface and ground water respectively.

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 in this study, we ignore air borne emission to water bodies; their treatment would be beyond the scope of this paper.

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 also estimated the parameters for above simplified one-dimensional water quality model. Similarly, another group of hydrologists, Zhang et al. (2003) measured the groundwater self-purification parameter which allows us to calculate the pollution discharged into groundwater bodies. 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 types⁸.

The advantage of this simple water quality model is to require much less hydrological data, which is always difficult to obtain, so that the feasibility of many macro-level water studies can be significantly enhanced. On the other hand, this model can only represent an individual pollutant or pollution indicator (e.g. COD/BOD⁹) each time so that it adequately reflect the interactions between the pollutants. However, a more sophisticated water quality model can be easily incorporated into our accounting framework to replace the current one-dimensional mass balance model.

3.4 Hydro-economic Regions and Datasets

Due to considerable regional differences in water supply and demand and for the purposes of this paper, it is necessary to model water consumption on a regional level. Therefore we divided China into eight hydro-economic regions to establish water accounts for each region (shown in Figure 2) based on watersheds and provincial level administrative boundaries¹⁰ (see Hubacek and Sun 2001; 2005). In this paper, we calculate and analyze the water demand for

⁸ We employ the result of loess soils as k_2 in Equation 16 as there are over 75% of area are covered by loess soils in North China Plain.

⁹ BOD: Biological Oxygen Demand

¹⁰ 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)..

North China which is characterized as seriously water scarce. 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 consumption coefficients for each of the economic sectors; wastewater discharge coefficients for each of the economic sectors; and the hydrological parameters in the water quality model (e.g. k_1 and k_2 in Equation 16).

Figure 2 here

3.4.1 Economic Data

In our analysis we 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 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 1. The “value-added” categories in the table include: capital depreciation, labor 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.

3.4.2 Hydrological Data

The dataset for water availability is extracted from “*China’s Regional Water Bulletins*¹¹” 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*¹² and annual reports on hydrology from various provincial hydrology-

¹¹ Published annually by the Ministry of Hydrology in China

¹² State Statistical Bureau (1999), State Statistical Publishing House, Beijing, China

ministries. The data of total outputs for each economic sector is given in the input-output tables.

The calculation of final wastewater discharge coefficients involves 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 our case, COD (gram/m³), was not available for all economic 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, we are able to calculate the average concentration of COD level in discharged wastewater for each economic sector.

4 HYDRO-ECONOMIC ACCOUNTING FOR NORTH CHINA

In this section, we use North China as a case study and employ the above method to perform the water accounting as described above.

4.1 Economic Flows

By employing Equation 3, we calculate the technical coefficients for North China’s economy in 1997. The dimension of the technical coefficients matrix (**A**) is 40×40. It allow us to generate the Leontief multiplier matrix - (**I-A**)⁻¹.

4.2 Water Inputs to the Economy

By employing Equation 6 – **Net Water Consumption** = $\hat{f}_k (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}$, we are able to quantify the total amount of water that is consumed in the production chain and is thus not available for other purposes within that region.

As shown in Appendix 2, 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), which accounts for 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 sector¹³. Moreover in this study, agriculture is distinguished in rainfed and irrigated agriculture. Rainfall is regarded as the water input for rainfed agriculture only.

Figure 3 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 m³. The total households’ net water consumption is 6,469 million m³, 35% from urban households and 65% from rural households (Ministry of Hydrology 1997). Hence overall net water consumption is 55,634 million m³ (excluding precipitations for rainfed agricultures) in comparison to the total freshwater availability of 84,350 million m³. In other words, about 66% of available fresh water resources are used up. As shown in Figure 3, 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 consumption, and construction, energy generation and all services sectors shared the remaining 4% of net water consumption.

Figure 4 distinguishes the net water consumption by water supply sources. Groundwater supply plays an important role in North China’s economy, especially in the service sectors and for rural household 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

¹³ In this paper, we assume 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/m³ of COD level for irrigated agriculture; 30gram/m³ for industries; and 20gram/m³ for services and domestic usages.

seriously damage the underground hydro-ecosystem through depletion and salt water intrusion in the costal areas.

Figure 3 & 4 here

4.3 Discharged Wastewater

Equation 8 – **Discharged Wastewater** = $\hat{r}_l(\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}$, allows us 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 household sectors¹⁴, as shown in Appendix 2. Columns stand for economic sectors; the rows of wastewater flows stands for the amount of wastewater discharged from the corresponding economic sectors; and the column of wastewater quality stands for the concentration of COD levels in the discharged wastewater, measured in gram/m³.

Figure 5 & 6 here

Pollution can further contribute to water scarcity and is a major source for diseases, particularly for the poor. Figure 5 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 m³. 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 2). Furthermore, about 60% of agricultural wastewater infiltrates under ground (Zhang et al. 2003). The majority of wastewater from industries and households is released into surface water bodies, as shown in Figure 6.

¹⁴ The statistics of households wastewater discharge only consists of urban areas. Therefore in this paper we assume that per rural resident wastewater discharge is 1/3 of urban residents' level as rural person consumed 87 liters of freshwater per day in comparison of 220 liters per day for every urban resident. The COD concentration of discharged wastewater from rural households is assumed to be same as urban households' level.

4.4 Water Exchange within the Hydrological Ecosystem

By employing Equation (10), we are able to form the **B** matrix and define its elements – the hydrological exchange coefficients, b_{kl} , which refer 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. Due to lack of data, we are not able to quantify the mutual pollution exchanges between the surface and ground water bodies. In this paper, we assume 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 (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 (16) and considering the water bodies self-purification capability, $k_1=3.64$, (Xie 1996), we can estimate that the hydro-ecosystem would provide about 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 (12,301 million m^3), we therefore obtain the *surface-surface* exchanges coefficient, $b_{surface-surface}$ which was $2.76m^3/m^3$ (see Appendix 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 rounds of 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 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 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), we are 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 $b_{surface-surface}$, we get the *ground-ground* exchange coefficient, $b_{ground-ground}$ which was calculated to be $2.14 m^3/m^3$.

Applying all elements into Equation 14, we 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. Our 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) no longer support any economic activities”.

5 CONCLUSION

China is currently under a situation of fast changes in economy and society. 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. Many previous water studies have only emphasized either supply or demand side of events, which hardly allow for effective allocation and management of the limited water resource.

This study 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, we have developed a hydro-economic accounting framework following in the tradition of economic-ecological input-output 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 be not available from statistical agencies. Our 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.

We applied the hydro-economic accounting framework to the region of North China which has been characterized as water scarce. The result shows that North China consumed up to 55,634 million m³ of freshwater and discharged 15,787 million m³ of wastewater (after evaporations) that contaminated 41,461 million m³ of freshwater in the hydrological environment. In 1997, the extended water demand for North China was 81,308 million m³, which occupies 96% of its total annual water availability. Agriculture, energy generation and households were the relatively largest 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).

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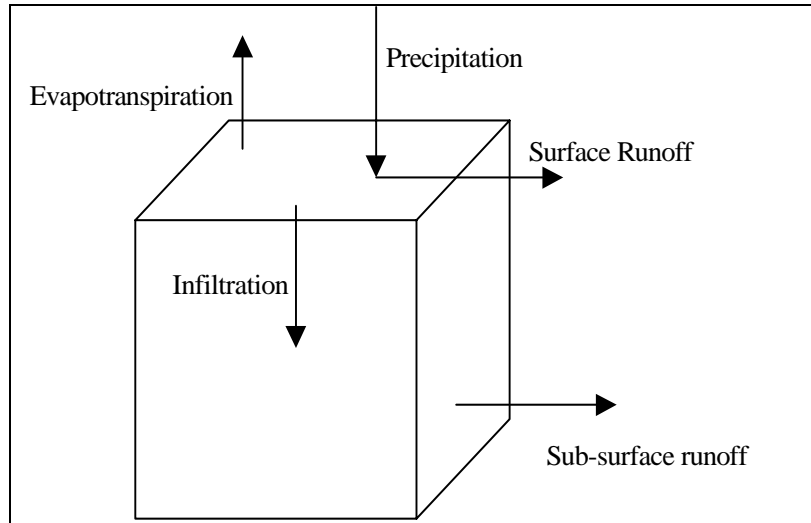
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Figures:

Fig. 1 – Hydrological Balance



(Source: Wiberg (2002))

Fig. 2 – Hydro-economic regions in China.



(Source: Land Use Change Group at IIASA (2001) — International Institute of Applied System Analysis, Laxenburg, Austria).

Fig. 3

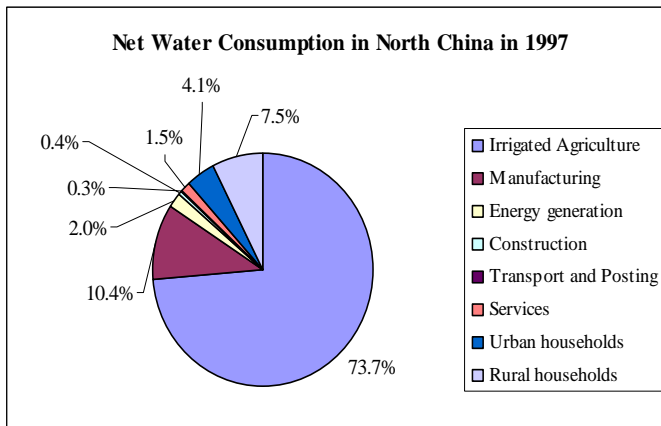
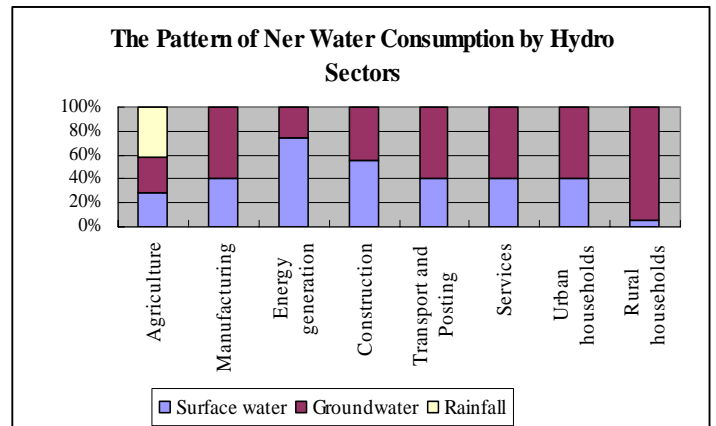


Fig. 4



Note: aggregation is based on 40 production sectors and 2 final demand sectors as shown in Appendix 2.

Source: Own calculation

Fig. 5

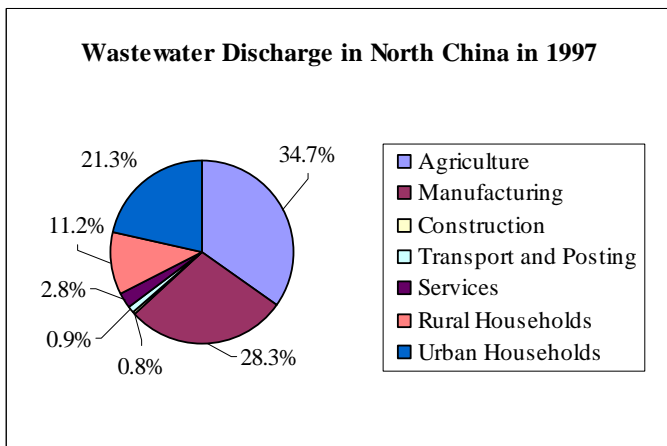
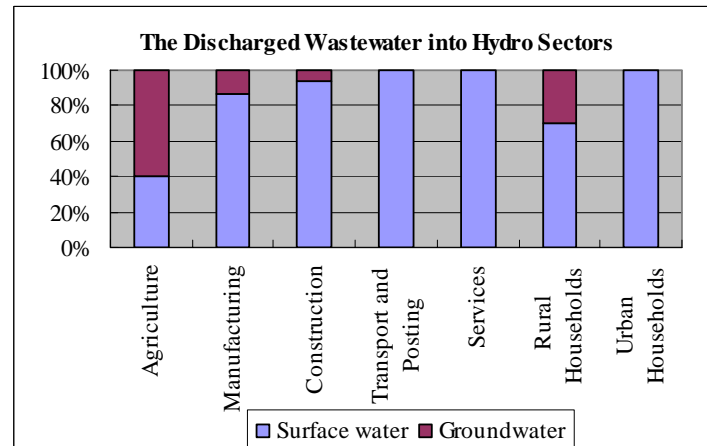


Fig. 6



Note: aggregation is based on 40 production sectors and 2 final demand sectors as shown in Appendix 2.

Source: Own calculation

Tables:

Table 1: Availability of Water Resources in China

<i>Region</i>	<i>Total fresh water resource (10⁸m³)</i>	<i>Population in 2000 (in 1000s)</i>	<i>Per capita water (in m³)</i>
<i>North</i>	843.5	311,100	271.1
<i>Northeast</i>	1,529	106,334	1,437.9
<i>East</i>	1,926.2	198,149	972.1
<i>Central</i>	2,761.2	167,256	1,650.9
<i>South</i>	5,190.8	129,942	3,994.7
<i>Southwest</i>	6,389.8	243,414	2,625.1
<i>Northwest</i>	2,115.6	111,128	1,903.8
		<i>China Average</i>	2,271.0
		<i>World Average</i>	6,981.0

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

Table 2: Extended Hydro-economy Input-output Table

Units in "()"		Activities Intermediate Demand	Final Demand		Total Output	Hydrological system			
			Household & Governments	Exports		Surface water	Ground water	Natural losses	
Economic Activities	x_{ij} (Yuan)	Matrix A	y_{ij} (Yuan)	w_{ij} (Yuan)	x_i (Yuan)	Matrix R			
Primary Inputs	s_{ij} (Yuan)								
Imports									
Total Inputs	x_j (Yuan)					h_l (m ³)			
Water inputs	Surface water	Matrix F			g_k (m ³)	Matrix B			
	Ground water								
	Rainfall								

Appendix 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	Crude petroleum and natural gas products	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	Manufacture of food products and tobacco processing	267.29	594.93	0.00	30
7	Textile goods	144.91	281.30	0.00	30
8	Wearing apparel, leather, furs, down and related products	40.41	38.83	0.00	30
9	Sawmills and furniture	34.38	12.08	0.00	30
10	Paper and products, printing and record medium reproduction	107.71	341.09	0.00	30
11	Petroleum processing and coking	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 equipment and machinery	38.28	74.30	0.00	30
19	Electronic and telecommunication equipment	73.47	101.46	0.00	30
20	Instruments, meters, cultural and office machinery	11.43	12.89	0.00	30
21	Maintenance and repair of machinery and equipment	17.70	19.18	0.00	30
22	Other manufacturing products	37.93	56.89	0.00	30
23	Scrap and waste	11.95	8.31	0.00	30
24	Electricity, steam and hot water production and supply	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, sports and social welfare	10.89	16.34	0.00	20
37	Education, culture and arts, radio, film and television	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 administration and other sectors	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 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	Crude petroleum and natural gas products	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	Manufacture of food products and tobacco processing	272.91	26.99	17.65	469
7	Textile goods	236.90	15.12	12.83	419
8	Wearing apparel, leather, furs, down and related products	18.68	4.10	1.88	307
9	Sawmills and furniture	25.21	4.80	2.32	214
10	Paper and products, printing and record medium reproduction	1131.00	215.43	104.21	1023
11	Petroleum processing and coking	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 equipment and machinery	59.01	4.44	3.40	285
19	Electronic and telecommunication equipment	91.70	6.90	5.28	285
20	Instruments, meters, cultural and office machinery	18.52	4.92	2.12	285
21	Maintenance and repair of machinery and equipment	12.67	1.41	0.87	285
22	Other manufacturing products	56.71	12.45	5.72	346
23	Scrap and waste	12.31	2.70	1.24	423
24	Electricity, steam and hot water production and supply	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, sports and social welfare	18.38	0.00	0.64	362
37	Education, culture and arts, radio, film and television	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 administration and other sectors	38.24	0.00	1.34	362
41	Rural Households	3777.31	0.00	132.21	362
42	Urban Household	1391.87	596.51	48.72	
	Total	12747.15	4384.21	1761.42	
	Average COD concentration	426.94 (gram/m ³)	341.13 (gram/m ³)		

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

	Surface water	Ground water	Natural loss
Surface water	33,998 (million m ³) (coefficient: 2.76 m ³ / m ³)	0	446 (million m ³)
Groundwater	0	7,462 (million m ³) (coefficient: 2.14 m ³ / m ³)	1494 (million m ³)
Rainfall	0	0	0