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Analysis of water consumption using a regional input–output model: Model development and application to Zhangye City, Northwestern China

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ABSTRACT

Based on a regional input–output model, we developed a method to identify the relationships between production activities and the related water consumption, as well as the relationships established between different sectors concerning water resources (i.e. indirect consumption). This method is applied to Zhangye City, an arid area of northwestern China that is characterized by water shortages. Our results confirm that although Zhangye suffers from a serious water shortage, the city's economic structure is based on sectors that consume large quantities of water. On the one hand, food production and forestry consume large quantities of water, reflecting the large scale of these water-intensive forms of land use. On the other hand, the industrial and service sectors use a smaller amount of water directly in production, but to produce the intermediate inputs that they incorporate into their production processes, a high consumption of water is often necessary. At present, there is no evidence that the city alleviates its water scarcity by importing virtual water in the form of economic inputs produced in other regions, suggesting that planners should include both direct and indirect water consumption in their resource allocation planning.

1. Introduction

Water shortages have become an increasingly serious problem in China, especially in the arid zones of the northwest (Ma et al., 2005). Although this problem has been extensively studied from hydrological and engineering perspectives (Lu et al., 2003; Zhang et al., 2004; Wang et al., 2005; Ji et al., 2006; Chen et al., 2007; Zhang et al., 2007), there has been little economic analysis of water use and management in this area (Huang et al., 2005; Zhang, 2007). Consequently, little is known about how to use and manage the available water resources effectively, because no commonly accepted concepts have been established to describe the socio-economic processes that relate to water use. However, any attempt at conceptualizing sustainable development of water resources must involve a consideration of the interactions between water use and the economy (Khouri, 2003; Mehta, 2007).

Studies that relate the economic system to the natural system and the environment date back to the 1960s (Velázquez, 2005). In earlier studies, a rigorous approach to these problems suggested feasible solutions that consisted of recognizing the necessity to develop a system of national accounts that provides information about the actual relationships between the economy and the environment (Hellsten et al., 1999). To encourage the integration of international environmental accounts, several international organizations (United Nations et al., 1993) developed an ambitious system known as the System of Integrated Environmental and Economic Accounts (SEEA). These efforts were advanced by the National Accounting Matrix including Environmental Accounts (NAMEA), developed in the Netherlands based on the SEEA indicators (Keuning et al., 1999). However, although these accounts managed to integrate the economic and environmental relationships within the production system in macroeconomic terms, their analysis only considered direct effects, since no industrial interdependencies were considered.

A parallel methodology that analyzes economic and environmental accounts together is the extended input–output model. Standard input–output tables consider inter-industry relationships in an economy, and thereby depict how the output of one industry is captured by another industry, where it serves as an input. Combining input–output analysis with environmental factor data

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makes it possible to quantify the environmental loads for all productive processes from raw material extraction to manufacturing and use, and then to ultimate disposal (Jesper et al., 2005). In recent decades, this methodology has been extensively used to calculate the environmental burdens caused by the normal activities of an economy (Lenzen, 1998, 2002, 2003; Proops et al., 1999; Hubacek and Sun, 2001; Giljum et al., 2004; Suh et al., 2004; Wiedmann et al., 2006; Hikita et al., 2007).

Water consumption analysis dates from 1950s, but the first models were abandoned due to operational difficulties and the methodological problems that arose when some variables had to be introduced into an input–output model (Velázquez, 2005). In input–output analysis, it is assumed that monetary transactions are proportional to physical transactions, whereas in the case of water transactions, this assumption is not correct because use prices vary considerably between production sectors. This difficulty was overcome in the work of Lofting and McGauhey (1968) who, in order to evaluate the water requirements of the California economy, introduced water inputs as a production factor (measured in physical units) in a traditional input–output model. Within this framework, Chen (2000) studied the supply and demand balance for water resources in Shanxi Province of China. One year later, Bouhia (2001) developed a hydroeconomic model by incorporating the water industries into the input–output table. Duarte et al. (2002) evaluated the internal effect and the induced effect of water consumption in Spain using a Hypothetical Extraction Method based on an input–output analysis. Velázquez (2005) then established a number of indicators of water consumption and studied the intersectoral water relationships in the economy of Andalusia. Based on this foundation, we advanced the existing analytical methods by integrating the analysis of intersectoral water relations so as to trace the sources of indirect water consumption in production processes. The objectives of this paper were thus to develop a regional input–output model of water consumption following the approach taken by Velázquez (2005); and to apply the model to Zhangye, an arid area of northwestern China, to analyze the structural relationships between economic activities and their physical relationships with the region's water resources.

2. Materials and methods

2.1. Description of the area

The Heihe River, the second-longest inland river in China, originates in the Qilian Mountains, which lie mainly in Qinhai province, and ends in Juyanhai Lake in Inner Mongolia. Our study area is Zhangye City, in Gansu province, which is located along the middle reaches of the Heihe River (Fig. 1). The city covers 42 000 km^2 in six counties: Ganzhou, Shandan, Minle, Linze, Gaotai, Sunan Yugur. The climate of this region is arid, with annual precipitation ranging from 100 to 300 mm, and potential annual evapotranspiration reaching 2000 mm.

Although located in one of the driest zones in the world, Zhangye consists of many oasis ecosystems that are mainly watered by the Heihe River. Water use in midstream areas accounts for about 93% of all water use from the river, with 94% of this water used for agriculture (Cheng, 2002). According to the Zhangye Statistical Yearbook, the irrigated area in Zhangye was about 68 667 ha in 1950s, but by 2002, had expanded to almost 266 000 ha, including 212 000 ha of farmland and 41 000 ha of forest and grassland. Based on irrigated farming, Zhangye has become an important center for the production of commodity grains.

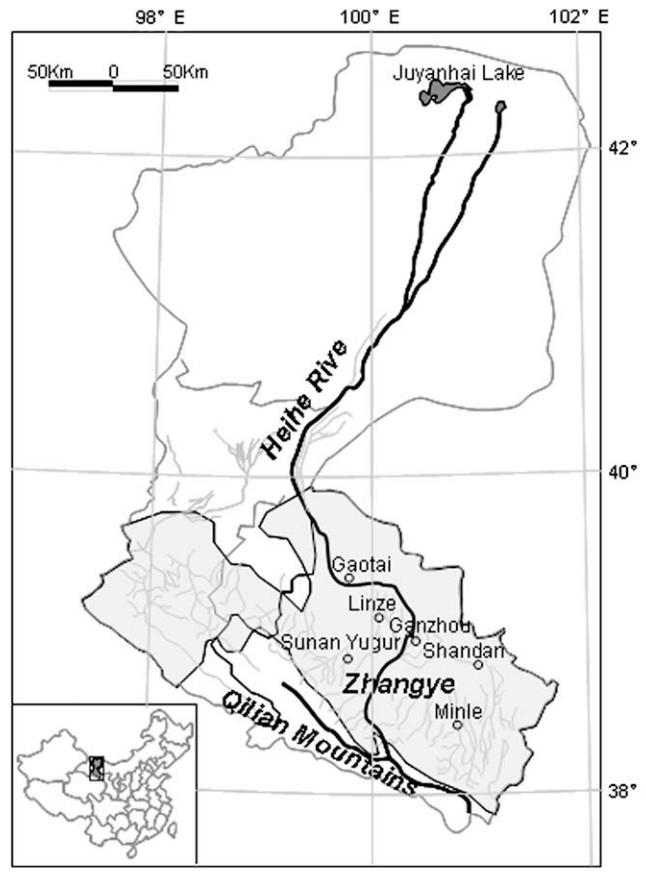

Fig. 1. Study area and the Heihe River Basin.

Since the Chinese national economic reforms that began in 1978, new industrial sectors have arisen, such as mining (including coal production), production of building materials, electric power, metallurgy, machinery assembly, transportation, and services. In recent years, Zhangye has experienced considerable economic growth as a result of these changes. The gross domestic product (GDP) was 6.9 billion yuan (RMB) in 2001, which was 8% greater than that in 2000. In 2002, 2003, and 2004, the GDP increased to 7.6, 8.4, and 10.0 billion yuan, respectively, representing annual increases of 10, 11, and 12%, respectively, over the values in the previous year (GSB, 1979–2006). Rapid economic growth and increasing population pressure have resulted in excessive use of the region's water resources, causing environmental degradation and generating tensions in the eco-economic system (Feng and Cheng, 2001).

2.2. Methods

2.2.1. The extended input–output model of water consumption

The starting point or our analysis is to define an indicator of direct water consumption intensity for each sector (w_j^{d*}):

$$w_j^{d*} = w_j^d / x_j \tag{1}$$

where w_j^d is the amount of water consumed directly by sector j; and x_j is the output of sector j in monetary terms.

In addition to this physical water consumption, other goods and services are required by the production processes of sector j. Consequently, in order to produce the inputs generated by other sectors, another requirement of water is also necessary. For sector j, this is the indirect water consumption. Direct consumption plus indirect consumption together amount to the total water consumption. By analogy with the input–output model, the calculation of total water consumption depends on the direct water consumption and the intersectoral dependence:

$$w_j^{t^*} = w_j^{d^*} + \sum_{i=1}^{n} w_i^{t^*} \cdot a_{ij} \tag{2}$$

where $w_j^{t^*}$ and $w_i^{t^*}$ are the total water consumption intensity of sectors j and i, respectively, and n represents the number of sectors. a_{ij} is the technical coefficient of production, which is defined as the purchases that sector j makes from sector i per total effective output of sector j. In the input–output tables, i represents sectors listed in rows, and j represents sectors listed in columns.

On the right side of Eq. (2), the first part represents the direct water consumption intensity of sector j, and the second part represents the sum of total indirect water consumption intensity of sector j. In matrix notation, and expressed for the economy as a whole, this becomes:

$$W^{t^*} = W^{d^*} + W^{t^*} \cdot A \tag{3}$$

where $W^{t^*} = [w_1^{t^*}, w_2^{t^*}, \ldots, w_n^{t^*}]$, $W^{d^*} = [w_1^{d^*}, w_2^{d^*}, \ldots, w_n^{d^*}]$, which represent the coefficient vectors of the total and direct water consumption intensities, respectively; and $A = [a_{ij}]_{n \times n}$ is the technical coefficient matrix of production. The solution for W^{t^*} is available as follows:

$$W^{t^*} = W^{d^*} \cdot (I - A)^{-1} \tag{4}$$

where $(I - A)^{-1}$ is known as the Leontief inverse matrix, which represents the total production that every sector must generate to satisfy the final demand of the economy (Leontief, 1966).

It is important to clarify this expression and its meaning because it can capture both the direct and indirect effects of any change in the exogenous final demand vector. Manresa et al. (1998) clearly summarize the importance of this fact: if the production vector is replaced by this expression in the input–output model, then the matrix describing only the specific direct requirements of the production sectors is replaced by the matrix $(I - A)^{-1}$, which expresses the total requirements of each sector in terms of both the direct and indirect inputs. By decomposing Eq. (4), one can separate the direct from the indirect water consumption required to sustain production by the economy (Gay and Proops, 1993):

$$W^{t^*} = W^{d^*} + W^{d^*}A + W^{d^*}A^2 + \cdots + W^{d^*}A^n + \cdots \tag{5}$$

In Eq. (5), W^{d^*} is the water requirement for one unit of outputs from all sectors, I. This represents the direct water consumption. $W^{d^*}A$ is the water required to allow the production of $A \cdot I$. This is the "first-round" indirect water consumption. $W^{d^*}A^2$ is the water necessary to allow the production of $A(A \cdot I)$. This is the "second-round" indirect water consumption. $W^{d^*}A^n$ is the water needed to produce the goods $A(A^{n-1} \cdot I)$. This is the "nth-round" indirect water consumption. Clearly, the total indirect water consumption is the sum of all rounds of consumption.

2.2.2. The water consumption multiplier

The input–output analysis also accounts for the "drag" effect, which has this name because it indicates how the evolution of a given sector can exert a drag upon the total economic production. Following Velázquez (2005), this drag effect can be measured by dividing the total water consumption per unit output by the direct water consumption per unit output (defined earlier):

$$m_j^d = w_j^{t^*} / w_j^{d^*} \tag{6}$$

where m_j^d is the water consumption multiplier that expresses the total quantity of water consumed by the whole economy per unit of water used directly to satisfy the demand of sector j.

After the multiplier m_j^d has been defined, it is easy to obtain a multiplier of indirect water consumption (m_j^{id}), simply by subtracting one from them_j^d.

$$m_j^{id} = m_j^d - 1 \tag{7}$$

In this way, the indicator yields an estimate of the quantity of water used indirectly by sector j for each unit of water that is consumed directly.

2.2.3. The matrix for intersectoral water relationships and associated matrices

Eq. (4) provides a row vector in which each element determines the total water consumption if the output of any given sector changes by one unit. Based on this equation, we will proceed to formulate a matrix for intersectoral water relationships (W^*) by changing the form of W^{d^*} and subtracting the direct water consumption from the total water consumption:

$$W^* = \widehat{W}^{d^*}\left[(I - A)^{-1} - I\right] \tag{8}$$

where ^ indicates that the vector's elements should be placed along the diagonal of the matrix. The elements w_{ij}^* of W^* indicate the additional quantity of water consumed by the whole economy for each unit of additional output in sector j. Thus, the sum of all the elements of column j expresses the indirect water requirements per unit output of sector j. This matrix can be converted into a matrix of water transaction coefficients whose elements are defined as:

$$\beta_{ij}^W = w_{ij}^* / w_j^{d^*} \tag{9}$$

where β_{ij}^W indicates the additional quantity of water that sector i will consume if the demand for water by sector j increases by one unit. Therefore, this new matrix reflects the dependence established between one sector and other sectors concerning water resources.

2.3. Data collection

In our analysis, we used two primary data sets: the quantity of water consumption for production sectors (in biophysical units) and the input–output tables (in monetary value units). The water data used in this paper was obtained from the Gansu Water Resource Official Reports, published every year by the Gansu Provincial Bureau of Water Resources (GPBWR, 2003). At the most detailed level, water-intensive agricultural water use is divided into four categories: farming, forestry, animal husbandry, and fisheries. Other productive use categories include mining and processing, manufacturing, production and supply of electric power and heat, construction, transportation and communications, and services. Thus, in this analysis, we used 10 categories of productive consumption of water.

For the economic data, the basic input–output table for Zhangye in 2002 was constructed by the Office of the Input–Output Survey, Gansu Statistical Bureau. This input–output table classification is based on 17 sectors, and its framework centers on the supply and use tables for products, including the structure of the intermediate consumption of production sectors, final consumption, and exports and use of imported goods at current prices. To make the complete data set consistent, a few adjustments to the basic input–output table were necessary due to limitations of the water consumption data. As a result, we integrated the 7 of the 17 sectors into the other sectors and created a simplified 2002 table for Zhangye that represents a 10 sector by 10 sector input–output table, whose classification of economic sectors is consistent with our division of the 10 water use categories.

3. Results and discussion

3.1. Characteristics of water consumption

The data on direct water consumption (Table 1) reveal that the amount of water consumed directly by the agricultural sectors (farming, forestry, animal husbandry, and fisheries) is much greater than that consumed by the industrial and service sectors, with agricultural consumption exceeding 2 billion m^3, and the latter only consuming a small fraction of this amount (about 69 million m^3). This finding confirms the well-known fact that agriculture is the main consumer of water resources in Zhangye, and is responsible for 95% of the total water consumption in the region. In comparison, the volume of water consumed directly by the industrial and service sectors is nearly negligible.

However, when indirect water is considered, it becomes obvious that water consumption by the industrial and service sectors increased greatly. This is often unnoticed in analyses that focus exclusively on the lower values for direct water consumption by these sectors, as shown in Table 1. This means that although these sectors use only a small amount of water directly in production, in order to produce the inputs (generated by other sectors) that they incorporate into their production processes, a high consumption of water is necessary. Thus, it appears that the industrial and service sectors also consume large amounts of water indirectly, as the detailed analysis later in this section will show. In this sense, indirect consumption seems to make up a significant part of the water consumption in the study area. Combining previously known aspects of the study region with the data on total water consumption obtained from this research, it is easy to conclude that Zhangye is a region which, despite its water shortage, possesses an economic structure that is based on sectors that consume large quantities of water.

As water consumption is related to the quantity of goods produced by any of these sectors (the x values in Table 1), one can note that the water consumption intensity of the agricultural sectors is considerably greater than that of the other sectors because of the greater water consumption in these sectors. Per unit output, water consumption was highest in the fisheries sector at 1294 m^3 per thousand yuan (Table 1). Water use was more efficient for economic sectors that produced higher-value products. This is true, for example, of the farming sector. Even though this sector consumed 85% of the physical water resources, its direct water consumption per unit output remained less than 1000 m^3 per thousand yuan. Forestry and animal husbandry also had a relatively high intensity of direct water consumption. Therefore, these agricultural sectors play a decisive influence on use of the region's limited water resources. Although indirect water use by the industrial and service sectors revealed that their total water use was higher than that has been traditionally assumed, their water consumption intensities remained lower than those of the agricultural sectors.

Some interesting observations can be made by examining the composition of total water consumption (i.e., by comparing direct versus indirect consumption). In all agricultural water use categories except animal husbandry, water consumption was primarily direct. As shown in Table 2, direct consumption accounted for 83% of the total consumption in forestry, 81% in farming, and 77% in fisheries. This indicates that the water used in their production processes is primarily "real" water that originates from the available surface and underground water resources. In this sense, slight increases in production of these sectors would greatly increase the consumption of real water. However, it should be noted that the output value for forestry has increased from 2.4 million yuan to 124.1 million yuan between 1978 and 2002 in constant 1978 prices, representing an increase to 52 times the 1978 value. The outputs of farming and fisheries also increased remarkably during the same period, with increases from 136.0 million yuan to 3205.3 million yuan and from 0 to 12.0 million yuan, respectively, during this period (GSB, 1979–2006). As a result, the massive expansion of agricultural activities during this period has inevitably resulted in increasing use of water resources, and is likely to be responsible for the observed environmental degradation in the middle and lower reaches of the Heihe River. These results clearly reveal why some agricultural sectors impose such a significant pressure on natural freshwater resources and the environment in the Heihe River Basin: the magnitude of the production in these sectors, combined with their high direct water use per unit of production, results in a high pressure on the available resource and correspondingly large impacts on the environment. This conclusion strongly suggests the need to propose changes in the productive specialization in this region, based on exhaustive studies that account for economic, social, and environmental factors. A broadened economic policy should account for not only productive criteria but also on social and environmental factors.

Contrary to the situation in the agricultural sectors, most industrial and service sectors (construction, transportation and communications, services, mining and processing, and manufacturing) are characterized by relatively high ratios of indirect water consumption to total water consumption. With the exception of the production and supply of electric power and heat,

Table 1
Indicators of direct (w^d) and total (w^t) water consumption, direct (w^{d^*}) and total (w^{t^*}) water consumption per unit of output, and sectoral output (x) in Zhangye City in 2002.

Sectors	w^d ($\times 10^3$ m^3)	w^t ($\times 10^3$ m^3)	x ($\times 10^6$ yuan)	w^{d^*} ($m^3/10^3$ yuan)	w^{t^*} ($m^3/10^3$ yuan)
1. Farming	1 890 380.0	2 324 951.2	3205.3	589.8	725.3
2. Forestry	106 002.5	127 209.6	124.1	854.2	1025.1
3. Animal husbandry	93 289.5	320 288.6	1038.4	89.8	308.5
4. Fisheries	15 519.5	20 246.9	12.0	1294.2	1688.5
5. Mining and processing	4018.2	48 387.4	741.4	5.4	65.3
6. Manufacturing	37 526.2	660 796.5	4052.5	9.3	163.1
7. Production and supply of electric power and heat	15 127.4	32 054.4	367.3	41.2	87.3
6. Manufacturing	37 526.2	660 796.5	4052.5	9.3	163.1
7. Production and supply of electric power and heat	15 127.4	32 054.4	367.3	41.2	87.3
8. Construction	5010.9	243 907.1	2723.3	1.8	89.6
9. Transportation and communications	1208.1	65 971.7	1050.5	1.2	62.8
10. Services	6050.0	153 627.6	3379.9	1.8	45.4

Note: the data for w^d were taken from the Gansu Water Resource Official Reports (GPBWR, 2003); the data for x were collected from the Zhangye input–output table created by the Office of the Input–Output Survey of Gansu Statistical Bureau.

Table 2
The ratios of the direct and indirect water consumption to the total water consumption and the water consumption multipliers for Zhangye City in 2002.

Sectors	Ratio			
	w^{d^*}/w^{t^*} (%)	$(w^{t^*} - w^{d^*})/w^{t^*}$ (%)	m^d	m^{id}
1. Farming	81.3	18.7	1.2	0.2
2. Forestry	83.3	16.7	1.2	0.2
3. Animal husbandry	29.1	70.9	3.4	2.4
4. Fisheries	76.7	23.3	1.3	0.3
5. Mining and processing	8.3	91.7	12.0	11.0
6. Manufacturing	5.7	94.3	17.6	16.6
7. Production and supply of electric power and heat	47.2	52.8	2.1	1.1
8. Construction	2.1	97.9	48.7	47.7
9. Transportation and communications	1.8	98.2	54.6	53.6
10. Services	3.9	96.1	25.4	24.4

more than 90% of the total water consumption in these sectors is attributable to indirect water consumption (Table 2). Thus, these sectors appear to have a large drag effect on the water consumption of the whole economy. This can be confirmed by examining the values of the indirect water consumption multiplier (m_j^{id}; Table 2). For each cubic meter of water consumed directly in the transportation and communications sector, satisfying an increase of production requires the consumption of an additional 53.6 m^3 of water by other production sectors. Similarly, in the construction sector, each cubic meter of water consumed directly requires the indirect consumption of an additional 47.7 m^3 of water by the other sectors. The levels of indirect water consumption were also high for mining and processing, manufacturing, and services. These results show that the sectors with the highest indirect consumption of water are those that are normally considered to be the driving forces behind Zhangye's economy due to the strong influence that demand for their respective products exerts on the production of the remaining sectors. In other words, increases in the production of these leading sectors require additional inputs from other sectors, locally or nationally.

3.2. Intersectoral water relationships and product trade balances

Table 3 shows the intersectoral water transaction coefficients. This new matrix shows that most water transaction coefficients are relatively low, indicating that most water transactions between sectors can be disregarded, since only a few sectors dominate these transactions. As shown in Table 2, construction, transportation and communications, and services are the sectors characterized by relatively high ratios of indirect water consumption to total water consumption, and the matrix of intersectoral water transaction coefficients (Table 3) shows that their indirect water consumption is mainly derived from the farming sector. Table 3 thus reveals that for each cubic meter of water consumed directly by the transportation and communications, construction, and services sectors, satisfying this water demand requires an additional 39.5, 35.2, and 15.5 m^3 of water, respectively, to be consumed by farming.

Allan (1997, 1998) introduced the term "virtual water" to indicate the water consumed during the process of production that cannot be detected as direct consumption. He defined the volume of virtual water "hidden" or "embodied" in a particular product to be the volume of water that is used, both directly and indirectly, in the production of that product. This definition conveys the idea that the water consumed in the present study is first embodied in farming products, and then incorporated into other sectors as an intermediate input. Thus, the farming sector is the main supplier of indirect (virtual) water consumption. Apart from the farming sector, other agricultural sectors (such as animal husbandry and fisheries) are also important suppliers of virtual water because of the high water content in their products. These results reveal an important fact: that despite the high direct water consumption by the agricultural sectors, most of the water is first embodied in its products and then flows to other sectors in the form of virtual water. However, because of limited knowledge about the relationship between the overall production structure and physical water use in Zhangye, the indirect consumption of water is always neglected by water policy and environmental planners. Finally, it should be pointed out that industrial sectors such as manufacturing and the production and supply of electric power and heat also supply a certain amount of virtual water to Zhangye's economy, embodied in large quantities of imports from outside the region (Table 4).

Virtual water can be seen as an alternative source of water, and using this additional source can be an instrument for achieving regional water security. More firmly stated – and this is the political argument that has been put forward by Allan (1997) from the beginning of the virtual water debate – trading virtual water can be an instrument for solving geopolitical problems and can even potentially prevent wars over water. Next to the political dimension, there is also an economic dimension that has been equally stressed by Allan (1997, 1998) and Allan and Olmsted (2003). The economic argument behind the virtual water trade is that, according to trade theory, nations or regions should export products in which they possess a comparative advantage in production, but should import products in which they possess a comparative disadvantage. Consequently, a region with low supplies of water should import products that require a lot of water to produce (water-intensive products) and should export products or services

Table 3
The water transaction coefficients for the 10 sectors of Zhangye in 2002.

Sectors	Sectors									
	1	2	3	4	5	6	7	8	9	10
1. Farming	0.21	0.04	2.32	0.24	6.51	14.12	0.57	35.19	39.46	15.53
2. Forestry	0.00	0.16	0.01	0.01	0.14	0.12	0.01	0.35	0.59	0.71
3. Animal husbandry	0.02	0.00	0.05	0.00	0.27	0.60	0.02	1.44	1.67	0.67
4. Fisheries	0.00	0.00	0.01	0.05	0.27	0.13	0.02	0.64	1.28	3.09
5. Mining and processing	0.00	0.00	0.00	0.00	0.25	0.06	0.02	0.40	0.25	0.11
6. Manufacturing	0.00	0.00	0.02	0.00	0.66	0.56	0.06	3.61	3.81	1.40
7. Production and supply of electric power and heat	0.00	0.00	0.02	0.00	2.77	0.93	0.40	5.53	5.54	2.37
8. Construction	0.00	0.00	0.00	0.00	0.03	0.02	0.01	0.19	0.28	0.18
9. Transportation and communications	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.07	0.21	0.07
10. Services	0.00	0.00	0.00	0.00	0.11	0.06	0.01	0.26	0.52	0.26
Sum	0.23	0.20	2.43	0.30	11.04	16.61	1.12	47.68	53.61	24.39

Note: created by the authors using data of the direct water consumption for production sectors (GPBWR, 2003) and the Zhangye input–output table.

Table 4
The product trade balances in Zhangye City in 2002.

Sectors	Products ($\times 10^6$ yuan)		
	Exports[a]	Imports[a]	Net exports
1. Farming	1179.9	12.1	1167.8
2. Forestry	22.8	38.2	−15.4
3. Animal husbandry	381.0	93.2	287.8
4. Fisheries	5.4	77.4	−72.0
5. Mining and processing	210.2	139.6	70.6
6. Manufacturing	285.2	1642.3	−1357.1
7. Production and supply of electric power and heat	0.0	877.2	−877.2
8. Construction	868.9	982.8	−113.9
9. Transportation and communications	251.4	111.6	139.7
10. Services	549.8	876.8	−327.0

[a] Data were collected from the Office of the Input–Output Survey of Gansu Statistical Bureau.

that require less water (water-extensive products). This is called the "import of virtual water" (Allan, 1997), and net import of virtual water in a water-scarce nation can relieve the pressure on its water resources. However, this does not currently seem to be happening in Zhangye.

As we noted above, the production of most industrial and service sectors (and especially of the construction, transportation and communications, and services sectors) causes a high consumption of physical water by the farming sector. This means that these sectors require large quantities of products produced by the farming sector as intermediate inputs to satisfy the demand created by their production. But it is important to note that in our study area, these inputs from the farming sector are supplied only locally, not by other regions. In fact, Zhangye is an important producer of commodity grains for Gansu province, exporting large volumes of farm products every year to other regions (Table 4), in addition to meeting its own demand. Consequently, outside agricultural products, with a high virtual water content, cannot currently enter Zhangye via a trade in merchandise in large quantities. On the contrary, the product trade balances in Zhangye (Table 4) indicate that the products of farming and animal husbandry, which are characterized by relatively higher virtual water contents, show a strongly positive net export balance. That is, large amounts of virtual water flow from Zhangye to other regions every year in the form of exported agricultural products. In contrast, products such as those of the manufacturing, production and supply of electric power and heat, construction, and services sectors show strong positive net imports. That is, the virtual water imports are lower due to the low total water consumption in the production processes of these sectors. As a result, it appears that the trade structure of exports and imports is inconsistent with a virtual water strategy designed to maximize the value of Zhangye's limited water resources. The significant pressure imposed on Zhangye's water resources by economic production is currently not transferred to other regions with more abundant water resources.

3.3. Limitations of our analysis

Although input–output analysis offers one of the most robust methodologies for measuring the environmental impacts of economic production, the limitations of the input–output model should be recognized. In particular, regional input–output tables such as the one used in the present study are not readily available in most cases, and this either restricts the applicability of this method to very small economies or requires large labor inputs to generate this table. The data required to create such an input–output table (e.g., data on the use of intermediate goods by firms involved in different activities or on the goods consumed by households) are not often available on a regional level. This is particularly true for data on regional exports and imports, which are neither collected by national statistical offices nor easily retrievable even by regional producers themselves. Moreover, surveys to fill gaps in the existing secondary data are very costly. Therefore, various methods have been applied to derive such tables from their national counterparts using all available information about a regional economy. For example, in this study, the technical coefficients matrix (A) for Zhangye was derived from the Gansu provincial input–output table in 2002 (GSB, 1979–2006) using a location quotients method (Fritz et al., 2003), and other data in the input–output table were estimated by the Office of the Input–Output Survey of Gansu Statistical Bureau based on a large survey of regional firms. Although this approach may not be ideal, it makes use of the best available data.

Another potential problem is that the linearity of the model's structure requires constant prices, fixed-proportion production, and linear demand, and ignores the effects of economies of scale (Leontief, 1966). In this sense, there is no substitution in consumption or input use, and the amounts of purchased inputs and water resources are determined solely by the level of output (Spörri et al., 2007). Therefore, the model may overstate the water consumption multipliers because it ignores the potential substitution of virtual water for physical water resources in production processes.

In addition, the information used to create the input–output table is for a given point in time. That is, it only shows a "picture" of the economic system at a certain moment, and therefore, represents a static analysis of that system. In this study, the input–output table used in our analysis was for the year 2002, and the present economic structure might be different from that of 2002. This problem imposes certain limitations on the analysis of our results. These limitations might be alleviated somewhat by an approach that performs calculations for several years to reveal temporal trends, with the caveat that these trends may change in the future.

4. Conclusions

In this paper, we developed a regional input–output model that allowed us to quantify the amount of water consumed by individual sectors of an economy. The proposed method provided indicators and matrices that could be used to distinguish between direct and indirect water consumption, and to trace the sources of indirect water consumption. We applied this methodology to the city of Zhangye in northwestern China, and showed that water-intensive industries dominated the city's economy and that the city currently does not make use of the option to import virtual water in the form of economic inputs. But given the limitations on the available water resources and the importance of water security criteria at a regional level, virtual water should be seen as an alternative source of water in the future. From the point of view of sustainable regional development, switching from water-intensive, low-valued crops to higher-valued crops that require smaller diversions of irrigation water, maximizing the value of water-intensive products, and reducing the export of virtual water appear to be necessary strategies for this arid area.

We are aware that this paper is merely an incomplete initial approach to estimating the pressure of economic activities on Zhangye's water resources and that the study could be completed with a more detailed analysis of water consumption and other economic variables, such as value added and the employment generated by each sector. Doing so would provide a clearer picture of the interactions between the economic activities and water resources. Moreover, it seems clear that our work could also be improved in the coming period by using a new input–output table and by considering changes in the composition and proportion of inputs over time. These are just a few of the potential future lines of research revealed by our study.

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