Virtual Water Flow at County-Level of the Heihe River Basin in China

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Contents

Abstract

Water scarcity in arid regions can be addressed by using the virtual water concept in water resources management. This chapter used a compiled county-level input–output table to analyze virtual water flows for the Heihe River Basin in 2012 by applying a multiregional input–output (MRIO) model. The results showed that the Heihe River Basin is a net virtual water exporter at a scale of

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1.05 billion m^3, which accounts for one third of the total amount of the basin's water resources. The midstream area of the basin imports 96.31% of virtual water (2.04 billion m^3) and exports 88.84% of virtual water (0.94 billion m^3). In contrast, the upstream and downstream parts have limited virtual water flows. The agricultural sector largely consumes water in each county; maize or wheat production accounts for approximately 50% of the total water consumption. For most sectors, the virtual water content from surface water is greater than that from groundwater. The ratio of virtual surface water to virtual groundwater ranges from 1.20 to 2.91. The results for the water stress index indicated that most counties experienced water stress due to maize production. Greater attention needs to be paid to the adaptation and assessment of virtual water strategies in arid regions.

Keywords

Virtual water · Multi-regional input–output model · Water stress index · Heihe River Basin

Introduction

Arid land covers approximately 41% of the world's land surface. Water scarcity in arid and semi-arid regions has been severe (Vörösmarty et al. 2010). In water-scarce regions, water resource sustainability, ecosystem health, and socioeconomic development are dependent on water, which is the central determining factor (Palmer et al. 2015). The sharp conflict between freshwater demand and available freshwater resources is one of the largest threats to sustainable water supply in China and throughout the world. To address water shortage issues, management interventions have been made. These interventions include water diversion projects (such as China's South–North Water Transfer), implementing the use of water-saving technology, industrial structure adjustments, and using virtual water strategies. Virtual water was defined by Allan (1997) as "the water embedded in internationally traded goods" based on economic theory. According to virtual water principles, water-scarce regions with spatial mismatches in water and arable land availability can improve their food security by purchasing a portion of their food requirements through agricultural trade (thus acquiring virtual water) and cutting local food production (thus using less local water). A flourishing literature has been inspired on dealing with water scarcity through virtual water trade, whereas it is still under debate (Ansink 2010; Antonelli and Sartori 2015; Jia et al. 2017).

To mitigate water stress, some researchers believe that food trade to increase virtual water in water-scarce regions is an efficient use of water resources (Dalin et al. 2012; Chen and Li 2015). Different crop trades save or lose different volumes of blue and green water. Nevertheless, others have argued that the virtual water trade strategy as a solution to water scarcity is fallacious (Jia et al. 2017; Hoekstra et al. 2017). In practice, producing grain in some arid regions has a competitive advantage over humid regions. Input and output of virtual water trade depend on social-economic structure and water use efficiency rather than scarcity degree of water resources. The application of virtual water trade to improve water use efficiency in water-scarce regions was biased for several reasons: (1) no enough trade capital for traditional agricultural regions, (2) considering water as the only production factor while neglecting land, (3) lack of consumption pattern and production allocation in economic system. Furthermore, virtual water flows have varied effects on water stress for the water-receiving regions and the water-exporting regions. The key to mitigate water stress is improving water use efficiency, whereas the efficiency benefits will be highly compensated by the increased water demand caused by developed economy.

Social equity and adaptability can in theory result in the allocation of virtual water. Virtual water use is highly unequal, and is almost completely explained by social development status rather than water scarcity (Suweis et al. 2011). Urbanization leads to a change in the requirements from industry, which in turn leads to changes in urbanization rates and urban poverty rates. In addition, if a country (or region) is scarce in water resources but rich in socioeconomic resources, its social adaptability would lead to an industrial structure with relatively richer virtual water resources (Ohlsson and Turton 1999). Agricultural water use dominates national water demands and cannot be completely compensated for virtual water transfers. Virtual water strategies can increase social transactions, which should give priority to guaranteeing people’s purchasing power. The implementation of the virtual water strategy could lead to a lot of agricultural surplus labor force, and the unemployment status of agricultural labor force. As a consequence, two important indicators should be considered when solving the problem of agricultural surplus labor force with the application of the virtual water strategy, i.e., employment multiplier and “learning effect” of nonagricultural sectors. Economic efficiency and water use efficiency should be considered equally. Water price and quality should be driven by both supply and demand, since water is an economic good. Water use efficiency or water productivity represents the crops’ economic value. In general, agriculture sector largely consumed water resources with low additional value, and the only feasible approach is to save water resources by improving the water use efficiency. The theory of comparative advantage in implementing virtual water strategy could be used to learn the economic attractiveness of virtual water import and export (Wichelns 2010). The economic level in a country (region) can be reflected with the proportion of economic sectors (e.g., agriculture, industry, services) in the total GDP. Moreover, the virtual water strategy implementation will reduce the pressure of ecological water shortage and thereby change the regional food production mode (Vörösmarty et al. 2010; Hoekstra 2009). In general, the agriculture sector largely consumed water resources with low water productivity, and the only feasible approach is to save water resources by improving the water use efficiency. On the other hand, agricultural water use can be saved by introducing the virtual water strategy and reasonably decreasing the agricultural land area, thus indirectly increasing the ecological water use. Seeking a balance between agricultural production and ecological conservation is of important value to guiding the ecological sustainability in the ecologically fragile water-scarce regions (Hoekstra 2009). Virtual water concept brings global insights across countries for improving water and land management, fostering adaptation strategies to trans-boundary resource management.

Previous studies focused primarily on national-level and provincial-level virtual water issues. Only a few studies have addressed virtual water flows at the county level, and have addressed the feasibility of inter-basin virtual water strategies (Jia et al. 2017; Chen and Li 2015). Thus, the aims of this chapter are to address this knowledge gap by: (1) assessing the virtual water flows at the county level, river basin level, and sector level for the Heihe River Basin; (2) distinguishing between surface water and groundwater flows in virtual water import and export; and (3) evaluating the water stress status of the Heihe River Basin. This chapter will provide policy implications for water resources management from the perspective of virtual water and industrial structures in arid regions.

Virtual Water Flows in the Heihe River Basin

The Heihe River Basin, located in the arid regions of Northwest China, is the second largest inland river basin in China with an area of 116,000 km^2 and a mean runoff of 2800 Mm^3/a. In Northwest China, alternating high mountains and basins lie in the inland river basin. Runoff flow from the mountains is the determining ecological factor for the inland river basin. The oases cannot survive and become desertified without water. The main stream of the Heihe River originates from the Qilian Mountain, which is mainly located in Qinghai Province. The river flows through the Hexi corridor of the Gansu Province and terminates in the Juyanhai Lake on the Inner Mongolia Plateau (Fig. 1). The Heihe River Basin has been divided into upstream, midstream, and downstream areas by the boundary lines of two hydrological stations (Yingluoxia and Zhengyixia). The mountainous areas, usually distributed in the upstream areas of river basins, are water consumption areas and often undergo much more precipitation, snowmelt, and glacier melt. The historical mean annual precipitation declines sharply from approximately 338 mm in the upstream area to 127 mm in the midstream area, and 49 mm in the downstream area (China Meteorological Administration). Precipitation is scarce in the midstream and downstream areas of inland river basins, the midstream and downstream areas are water consumption areas.

There are relatively abundant water resources in the upstream areas compared to the other two areas, especially the downstream area. Hills dominate the terrain in the upstream area, where animal husbandry is the main income source for farmers. The midstream area consists of broad, flat plains that are suitable for irrigated agriculture, which accounts for the majority of the water consumption in the basin. In contrast, the downstream area is mainly desert. Discharge in the downstream area has decreased significantly, and more than 30 tributaries, as well as the terminal lakes, have dried up. The Heihe River Basin is an exemplary region in China experiencing water scarcity. With the rapid population growth, economic expansion, abrupt water

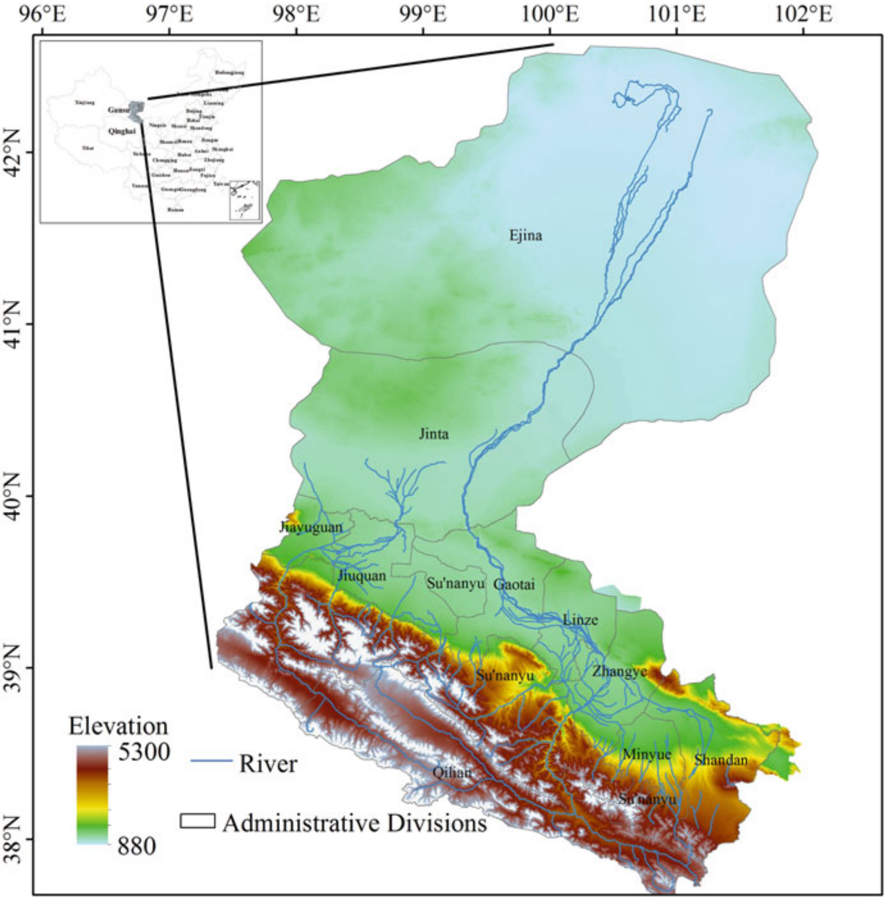

Fig. 1 Map of the study area (Reprinted from Zhang et al. (2017) with permission of Water)

exploitation, and irrational water allocation in the upstream and midstream areas of the river basins, the consumption of water increases dramatically and diminishes the water available for ecological processes, thus accelerating ecological degradation over the last five decades (Cheng et al. 2014). The terminal lakes dry up, sandstorms become more common, and the Populus euphratica forests die, causing a series of severe ecological disasters (Department of Geoscience, CAS).

Data and Methodology

Data Sources

The IO table at the county level of the Heihe River Basin was compiled and cited from the research project “the National Natural Science Foundation of China (Grant

No. 91325302).” With the support of “National Natural Science Foundation of the Heihe River Basin major research program,” the ecology-hydrological process and human disturbance on water resources were studied and explored in the Heihe River Basin. The IO table on water consumption at the sector level for 11 counties was obtained by the combination of survey methods and nonsurvey methods. The IO technical coefficients of key sectors at the county level were determined by survey methods and nonsurvey methods. Survey methods were applied to compile the input and consumption information of production in key sectors. Nonsurvey methods were adopted to obtain the technical coefficients of nonkey sectors from IO table at province level. The statistical data depicting regional economic structure, development speed, and technology improvement were reliable although the errors of these statistics exist. Total output values of sectors were derived from the Statistics Yearbook in 2012. The volumes of surface water and groundwater were collected from the Bulletin of first national census for water, which was conducted by the Ministry of Water Resources.

The Water Use Coefficients

The input–output model can quantitatively analyze the water use efficiency of each sector in the national economic system from two perspectives of input and output, and guide the regional industrial structure adjustment according to the calculation results of the key indicators of water use efficiency.

The direct water use coefficient of each sector can be expressed as:

$$q_j = w_j / X_j \tag{1}$$

For the first sector of the total output, the departments of the direct water consumption coefficient of q_j represents the direct water consumption coefficient for j sector; w_j is direct water consumption for j sector; X_j is the total output for j sector; the direct water consumption coefficient q_i in each sector constitutes line vector of water consumption coefficient $Q = (q_1, q_2, \ldots, q_n)$.

The line vector of water consumption coefficient Q in each sector premultiplication Leontief inverse matrix equals the total water demand vector H^d as follows:

$$H^d = Q\left(I - A^d\right)^{-1}. \tag{2}$$

$(I - A^d)^{-1}$ is Leontief inverse matrix, which means that the coefficient matrix is fully needed related to the final use. A^d represents direct consumption coefficient matrix $\left(A_d = x_{ij}^d / X_j\right)$. The total water demand vector $H^d = \left(h_1^d, h_2^d, \ldots, h_n^d\right)$ includes direct and indirect water demand in the production process. In other words, the amount of each economic sector is needed when the final consumption (use) increases one unit.

After introducing the direct water consumption coefficient and the total water demand coefficient, we need to calculate the direct water consumption and the total water demand. The amount of physical water consumed by the sector j is the direct water consumption of the sector j by multiplying the total output of the sector, which is derived from Eq. (1):

$$w_j = q_j x_w^d. \tag{3}$$

Local total water demand is total water demand coefficient h_j of sector j by multiplying the final use $y_i^d (i = j)$, as follows:

$$tw_j^d = h_j^d y_i^d (i = j). \tag{4}$$

tw_j^d represents local total water demand in sector j, which means that the direct and indirect water demand in all sectors of economic system in the production process of the final use of the product.

Multi-regional Input–Output Model

The multi-regional input–output (MRIO) model is a useful tool for capturing the economic relationships among different regions and sectors, and is based on the input–output (IO) table method formulated by Leontief. The MRIO model has the ability to trace the spatial transfers of ecological and environmental damage, and has been widely used to investigate virtual water footprints (Dalin et al. 2015; White et al. 2015; Mubako et al. 2013). This chapter applies the MRIO model at the county level for the Heihe River Basin. In the MRIO table, the Heihe River Basin consists of 11 counties, and the sectors have been aggregated into 48 sectors (Table 1). Input–output analysis has been subsequently further developed and applied in a large number of studies, and is adopted as an analytical framework developed by Wassily Leontief in the late 1930s (Miller and Blair 2009).

In the basic IO model, economic output can be expressed as the sum of intermediate consumption and final demand. The Leontief IO relationship is as follows:

$$x = (I - C)^{-1} y \tag{5}$$

where x is the vector of economic output, I represents the identity matrix, C is the direct IO coefficients matrix, and y is the vector of the final demand. $(I - C)^{-1}$ is recognized as the Leontief inverse matrix, representing the total production that each sector must satisfy the final demand of the economy, and expressing the total requirements of each sector in terms of both the direct and indirect inputs. The water resource is divided into groundwater and surface water in the IO table.

In this chapter, a MRIO model was employed to extend the standard IO matrix to a larger economy in which each sector in each county is assigned a separate row and column. The input–output (IO) method was developed by Wassily Leontief in the late 1930s. The IO model is based on data contained in national input–output tables. An IO table represents the flows of goods and services between economic sectors. Each sector of the economy in the IO table has one row and one column. Each entry in the i-th row and j-th column illustrates the flow from the i-th sector to the j-th

Table 1 The MRIO table at county level in the Heihe River Basin

	Middle use					Final use						Total output
Intermediate input	A^{11}	A^{12}	...	...	A^{1i}	F^{11}	F^{12}	...	...	F^{1i}	X_1
	A^{21}	A^{21}	...	...	A^{2i}	F^{21}	f^{21}	...	...	F^{2i}	X_2
	...	...	11 counties	...	...	...	...	11 counties	...	...	...
	...	...	...	Outside the basin	...	...	...	...	Outside the basin	...	...
	A^{i1}	A^{i1}	...	...	A^{ii}	F^{i1}	F^{i2}	...	...	F^{ii}	X_i
Surface water	W_{a1}	W_{a2}			W_{ai}						
Groundwater	W_{b1}	W_{b2}			W_{bi}						
Land	L_1	L_2			L_i						
Value added	V_1	V_2			V_i						
Total input	X_1	X_2	...	...	X_i						

sector. Equation (5) can thus be generalized to include imports from other counties, as formulated in Eq. (6):

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & \cdots & C_{11} \\ C_{21} & C_{22} & \cdots & C_{21} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{n1} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} \sum_s y_{1j} \\ \sum_s y_{2j} \\ \vdots \\ \sum_s y_{nj} \end{pmatrix} \tag{6}$$

where x_j indicates the total output of production and consumption in region j, y_{ij} indicates each sector's output produced in region i and consumed in region j, and C_{ij} reflects the intermediate consumption; each column denotes the input from each sector in region i required to produce one unit of output from each sector in region j. Vector x reflects total output of all economic sectors (x_j) in each county. Final demand (y matrix) exhibits the sum of household consumption, government expenditure, capital formation, changes of inventory, and international export.

Virtual water flows (VW) are calculated as:

$$VW = k_c\,(I - C)^{-1}y \tag{7}$$

where k_c is a row vector of water consumption per unit of sectorial output.

Water Use Structure and Water Use Coefficient in the Heihe River Basin

According to the annual report of the Heihe River Basin in 2012, the total water consumption of the Heihe River Basin in 2012 is 2.548 billion m^3 (Table 2), of which the irrigation water, the ecological water consumption, the industrial water consumption, and urban and rural living water are 2.154 billion m^3, 236 million m^3, 0.81 m^3, and 78 million m^3, respectively.

Table 2 Water use in sectors of the Heihe River Basin in 2012 (10^4 m^3)

Counties	Life	Industry	Irrigation	Artificial ecology	Total water use	Natural ecology
Qilian	582	236	1145	106	2069	–
Sunan	334	571	640	180	1725	–
Shandan	841	1950	12,465	–	15,256	–
Minle	943	600	34,139	265	35,947	–
Ganzhou	2653	2152	76,758	2671	84,234	–
Linze	713	614	38,209	3421	42,957	–
Gaotai	769	783	45,515	2693	49,760	–
Ejina	165	660	–	4201	5026	65,674

From the regional distribution of water use in the basin, the water consumption is mainly concentrated in the middle reaches of the Heihe River Basin. The total water consumption of various sectors is 2.282 billion m^3, accounting for 89.5% of the total water consumption in the basin with is 2.071 billion m^3 of the irrigation water, 9 million m^3 of the ecological water consumption, 61 million m^3 of industrial water consumption, and 59 million m^3 of domestic water consumption. In the downstream area, water consumption is 229 million m^3, accounting for 9.0% of the total water use of the basin, while in the upstream area, water consumption is 38 million m^3, accounting for 1.5% of the total water consumption.

The Heihe River Basin is a resource-based water scarce area, and regional water resources is difficult to meet the local economic and social development and ecological water needs. According to the recent management planning of the Heihe River Basin, the future utilization of water resources in the Heihe River Basin needs to be further adjusted. The adjustment should include the control of irrigated area size, the adjustment of the industrial structure and agricultural planting structure, the development of characteristic agriculture and efficient agriculture, and the establishment of industrial structure and economic layout to adapt to Heihe River Basin water resources condition. Agriculture is the main water consumption sector in the Heihe River Basin, and there is a huge water saving space. According to the plan, the irrigated area of farmland in the middle reaches of the irrigation area decreased from 276 million acre to 254 million acre, and the water saving area increased from 53.85 million acre to 84.87 million acre. The farmland irrigation quota is reduced from 629 m^3/acre to 580 m^3/acre in 2020. Agricultural irrigation water demand from the current situation of 1.827 billion m^3 reduced to 1.546 billion m^3 in 2020 to achieve the goal of 280 million m^3 in agricultural water saving. Agricultural water savings are mainly transferred to the industrial and ecological sectors.

From the perspective of water use structure, direct and total water consumption coefficients of virtual water in the primary industry of the Heihe River Basin were the largest, while the smallest coefficients lied in the tertiary industry in 2012. The direct consumption of virtual water is from direct water use in the primary industry, and about 80% of the total water consumption coefficient is the direct water consumption coefficient. The proportion of the direct water consumption coefficient in the total water consumption coefficient of the secondary industry is only 30%, while the proportion of the tertiary industry is lower, only about 3%. This indicated that the second and tertiary industries mainly consumed indirect water. Obviously, the direct water-based industry consumes a lot of local water resources, while indirect water-dominant industrial sector can rely on imports or transfers to the water resources to increase the middle input, thus reducing the local water resources pressure. Table 3 listed the industrial water use coefficients in 48 sectors at county level in upstream, midstream, and downstream of the Heihe River Basin.

From a regional perspective, the difference in water use coefficients between regions is also significant. One of the smallest water use coefficient of the first industry is Ejin County, and the highest water use coefficient is Qilian County, with a difference of about 4 times. Gaotai County, Shandan County, Linze County, and Jinta County in the secondary industry take relative advantages on water resources

Table 3 Industrial water use coefficients at county level in upstream, midstream, and downstream of the Heihe River Basin

	Qilian County		Ganzhou County		Ejina County	
Sectors	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)
1	0.508424	5591.421	0.248759	2806.447	0.67112	7213.539
2	2.144524	23376.64	2.777295	30195.84	2.830771	30334.05
3	0.116855	1313.316	0.036387	475.6144	0.154249	1685.305
4	0.052801	573.086	0	41.97869	0.069698	741.9691
5	0.106518	1274.239	0.125702	1475.173	0.140604	1614.307
6	0.100226	1204.171	0.097356	1166.717	0.132299	1523.545
7	0.025291	681.4308	0.008297	428.5772	0.033384	764.6911
8	0.001034	206.6601	0	174.6717	0.001365	206.2758
9	0	181.5959	0	158.0077	0	177.6036
10	0.003383	342.0981	1.71E-05	265.0259	0.002771	327.9451
11	0.006443	288.9741	0	201.3893	0.005277	274.2446
12	0.00477	813.1379	0.003557	806.6113	0.003907	817.0885
13	9.81E-05	540.2689	0	536.3931	8.04E-05	545.0521
14	3.1E-05	351.2956	0	338.2182	2.54E-05	352.8515
15	0.002674	308.2184	0.005076	314.9515	0.00219	302.929
16	0.002956	342.343	0.004778	362.1138	0.002421	337.4972
17	7.07E-05	158.6914	0	147.8354	5.79E-05	158.2439
18	0.001145	329.009	0.001143	312.6067	0.000938	325.3912
19	0.003169	285.6216	0.001876	250.3703	0.002595	276.477
20	0.000269	272.8811	0	240.07	0.00022	268.0431
21	0.000182	291.4947	0.000449	266.7404	0.000149	286.4705
22	6.23E-05	222.7203	0	206.307	5.1E-05	220.1607
23	1.46E-05	202.9099	1.82E-05	194.3161	1.2E-05	201.5226
24	1.22E-05	232.5284	3E-05	218.1696	1E-05	230.2491
25	0	138.4506	0	133.528	0	137.1626
26	0	155.9327	0	150.5488	0	154.932
27	1.52E-06	329.102	3.75E-06	309.5311	1.25E-06	329.6299
28	0	30.88341	0	28.95183	0	30.59677
29	0.001856	574.4165	0.004387	504.3368	0.00152	548.3893
30	0.002622	171.974	0	138.888	0.002147	166.7323
31	0.569246	6041.75	0.625713	6557.857	0.46624	5000.156
32	5.42E-05	224.9238	3.49E-05	213.3527	4.66E-05	223.9351
33	6.9E-06	165.0326	0	155.104	7.19E-06	168.1274
34	0	102.8449	0	97.84684	0	103.2037
35	9.85E-05	105.0619	0	96.6537	1.32E-05	103.3423
36	0.000135	107.9574	7.05E-05	100.0391	5.55E-05	107.1323
37	0.000322	415.1455	0.000271	397.3486	0.000262	417.7359
38	0.000124	80.82765	0.000101	73.55852	6.88E-05	80.40831

(*continued*)

Table 3 (continued)

Sectors	Qilian County		Ganzhou County		Ejina County	
	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)
39	0.000105	47.69626	3.29E-05	41.78797	1.95E-05	47.90766
40	0.000237	197.9627	2.54E-05	184.4088	2.53E-05	196.4059
41	0.00281	216.6228	0	180.6458	0	188.9788
42	0.00064	115.164	0.000576	109.0575	0.000325	112.6899
43	0.018955	437.674	0.010423	360.7073	0.019309	444.099
44	0.000267	185.3946	3.42E-07	179.9219	2.08E-05	183.7729
45	0.001762	148.0615	0.002648	145.3635	0.001746	147.1065
46	0.000848	242.6886	0.000708	236.9535	0.000766	241.4216
47	0.000516	208.9176	4.92E-06	196.1031	1.5E-05	204.5231
48	8.57E-05	128.4303	1.72E-05	116.3538	3.45E-05	128.3258

utilization, with lower water coefficient below 0.1. The tertiary industry's water use coefficient is generally low, and lowest direct water use coefficients exist in Shantan County and Sunan County.

To sum up, the Heihe River Basin is facing gradual water shortage. The local government should put the appropriate restrictions on the primary industry by increasing the water saving within the agricultural transformation, improving the proportion of efficient water-saving crops and agricultural production technology level. In the meanwhile, increasing the proportions of secondary and tertiary industry could ease water scarcity of the Heihe River Basin. In addition, it is necessary to fully combine the characteristics of the industrial structure of the water resources within the basin to rationalize the industrial layout of the river basin.

Virtual Water Flows at the River Basin Level

For thousands of years, sufficient water has been available to support grazing and agriculture in the Heihe River Basin. Land use patterns have been altered to support blooming populations. However, the Heihe River Basin, as China's northwestern arid region, has experienced a common challenge recently. The Heihe River Basin was divided into three areas: upstream, midstream, and downstream. Each area has distinct characteristics in terms of water resources, economic structure, household income, and consumption patterns (Table 4).

The total amount of virtual water imported into the Heihe River Basin was 1.06 billion m^3, and the total amount of virtual water exported was 2.11 billion m^3. Based on the research results of Cai et al. (2012), in the Gansu province, which occupied the majority part of the Heihe River Basin, the net virtual blue water export accounted for 10% of the total natural runoff through food trade in the basin, and

Table 4 Socioeconomic characteristics of the Heihe River Basin (Reprinted from Zhang et al. (2017) with permission of Water)

Counties	Population (10^4)	Urbanization rate	GDP (Billion Yuan)	Industry structure (Primary industry: Secondary industry: Tertiary industry)
Qilian	4.70	–	0.52	24:38:38
Ganzhou	51.60	37.00	7.67	25:36:40
Sunan	3.64	30.80	0.94	21:61:18
Minle	24.00	13.90	1.92	37:33:31
Linze	14.70	16.00	2.18	32:43:25
Gaotai	15.80	16.00	2.09	41:37:22
Shandan	19.80	34.80	2.22	22:42:36
Suzhou	40.64	43.50	6.20	13:54:34
Jinta	14.70	23.80	2.40	30:30:40
Jiayuguan	18.59	88.90	14.40	1:82:17
Ejina	1.65	70.00	2.04	3:61:36

accounted for 25% of the total blue water use. Thus, the Heihe River Basin is a net virtual water exporter of 1.05 billion m^3, accounting for one third of the total water resources in this region. The upstream area (Qilian County) had small virtual water flows to and from the rest of the basin (Fig. 2). In this area, the vegetation has been seriously degraded by deforestation, overgrazing, and grassland reclamation since the 1950s. The glacier area in the Heihe River Basin has decreased by 29.6% over the past 50 years (Wang et al. 2011). The midstream area, which covers most areas of Ganzhou, Sunan, Minle, Linze, Gaotai, Shandan, Suzhou, Jinta, and Jiayuguan Counties, exported 96.31% of virtual water (2.04 billion m^3) to outside the basin, and imported 88.84% of their virtual water (0.94 billion m^3) from outside the basin. Rapid agricultural development accounted for increased water consumption in the midstream area of runoff from the mountainous areas. In the Heihe River Basin, the agricultural land increase of 75 million m^2 led to the increasing water consumption of about 5 million m^3. As a consequence of rapid agricultural development, both water use patterns and land use types underwent dramatic changes (Cheng et al. 2014). As with the upstream area, the downstream area (Ejina County) also had limited virtual water flows. The amount of physical water entering the downstream area decreased significantly from the 1950s to the 2000s as a result of the large expansion of irrigated farmlands in the midstream area.

Over 2004–2006, the water footprint of the Heihe River Basin was million m^3 $yr.^{-1}$, of which 960 million m^3 $yr.^{-1}$ were green and 800 million m^3 $yr.^{-1}$ were blue. Agricultural production is the sector with the largest water consumption, accounting for 96% of the water footprint (92% of crop production and 4% of livestock production). The remaining 4% was for industrial and domestic sectors. The water footprint of the "blue" (surface water and groundwater) component is 8.11 million m^3 $yr.^{-1}$. This indicates that blue water accounts for 46%, well above the world average and the Chinese average, mainly due to the water scarcity in the Heihe River Basin and high dependency on crop production. However, even in such

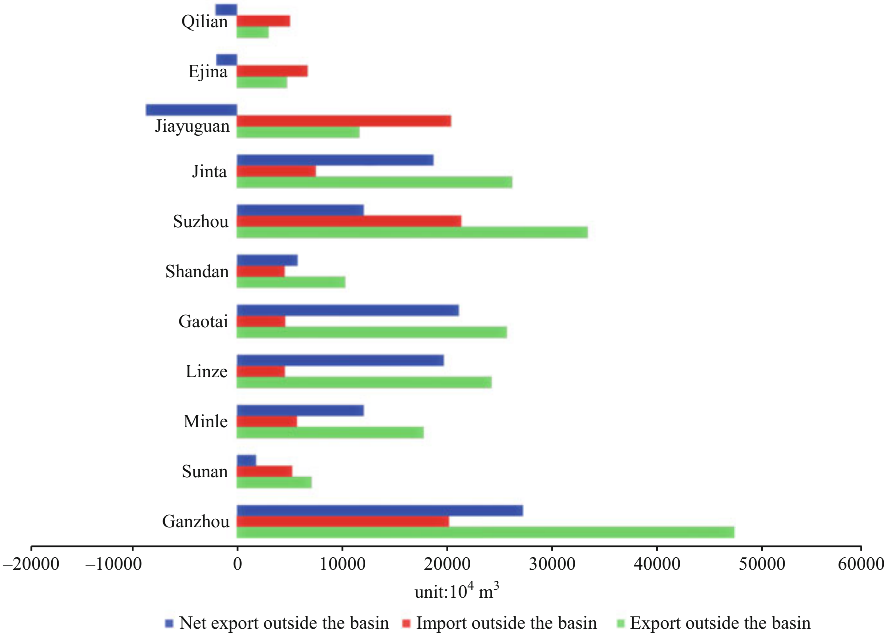

Fig. 2 Virtual water flows between different counties in the Heihe River Basin (Reprinted from Zhang et al. (2017) with permission of Water)

a river basin, the blue water footprint is still less than the “green” (soil water) water footprint, indicating the importance of green water (Zeng et al. 2012).

Virtual Water Flows at the County Level

Compiling a multi-regional IO table at county level is crucially vital to making appropriate policy for balancing economic development and water resources management at county level. An extended input–output table at county level is divided into three parts of sectors in the primary industry, secondary industry, and tertiary industry, respectively. From the perspective of policy-making, the output value of the tertiary industry to the provincial primary industry is more than that of the county level, which is estimated by the different proportion of other inputs in the tertiary industry’s output to the primary industry (Deng et al. 2014).

The agricultural sector consumed the largest amount of water in each county in the Heihe River Basin (Table 5). The water consumption of the secondary and tertiary industries was less than that of agricultural production. Water consumption structures at the county level in 2012 showed that regions with grain production had high levels of water consumption; corn or wheat production accounted for the largest proportion (almost 50%) of total water consumption. For example, the water use for corn production in Ganzhou County accounted for 54.53% (449.07 million m^3) of

Table 5 Water consumption for key sectors at county level of the Heihe River Basin (10^4 m^3) (Reprinted from Zhang et al. (2017) with permission of Water)

Counties	Total water consumption	Agricultural sector	Corn production	Wheat production
Qilian	1694.21	1416.75	594.46	6.47
Ganzhou	82,351.67	79,302.18	5972.51	44,906.67
Sunan	11,780.58	11,434.79	4248.49	5050.66
Minle	26,248.54	25,456.54	9865.74	1891.69
Linze	40,860.99	40,027.45	721.33	23,529.22
Gaotai	42,757.56	42,029.49	5656.42	18,328.82
Shandan	14,949.32	13,731.75	6664.54	419.14
Suzhou	19,267.03	16,484.47	3087.09	1572.70
Jinta	10,337.30	2925.42	548.73	278.52
Jiayuguan	14,355.89	13,655.25	2556.02	1301.01
Ejina	1617.38	1010.80	114.83	376.62

total water consumption, while the proportion of consumption for wheat was 44.58% (66.64 million m^3) in Shandan County. The water consumption results can be captured in consumption coefficients for each sector. The coefficients in the agricultural sector of Zhangye city (including Ganzhou, Sunan, Minle, Linze, Gaotai, and Shandan Counties) was 0.15 m^3/yuan in 2012, which was 0.05 m^3/yuan higher than that of Jiayuguan County, and 0.02 m^3/yuan higher than that of the national level for China in 2002 (Chen et al. 2017).

In this chapter, the MRIO model was applied to quantify the amount of imported and exported virtual water at the county level for the Heihe River Basin in 2012 (Fig. 3). Qilian, Ejina, and Jiayuguan Counties are the primary importing counties, while Ganzhou, Sunan, and the remaining counties are the virtual water exporting counties. Table 2 presents the details for the amounts of imported and exported virtual water at the county level for the Heihe River Basin. Ganzhou County stands out as the county which contributed significantly to both imported (0.20 billion m^3) and exported virtual water (0.47 billion m^3). The intercounty virtual water flows in the basin showed that the top three exporters of virtual water are Ganzhou, Linze, and Gaotai Counties with amounts of 0.91, 0.71, and 0.66 million m^3, respectively. The largest receiver of virtual water from other counties was Suzhou County (1.13 million m^3). Ganzhou County was the next biggest receiver of virtual water (0.92 million m^3) from counties within the basin. The key to mitigating severe water consumption in the Heihe River Basin is to adjust industry structures, and thus to optimize water consumption structures.

Virtual water import implies increased water availability and might be one way to alleviate regional water stress. In contrast, the export of virtual water indicates increased water consumption, which contributes to water stress on local water resources (Bulsink et al. 2010; Zhang et al. 2011). A previous study on water consumption in the Hetao irrigation district showed that the export of virtual water contributed more pressure to water scarcity than local production (Liu et al. 2017). The interbasin virtual water flows (blue water) indicated that the total amount of

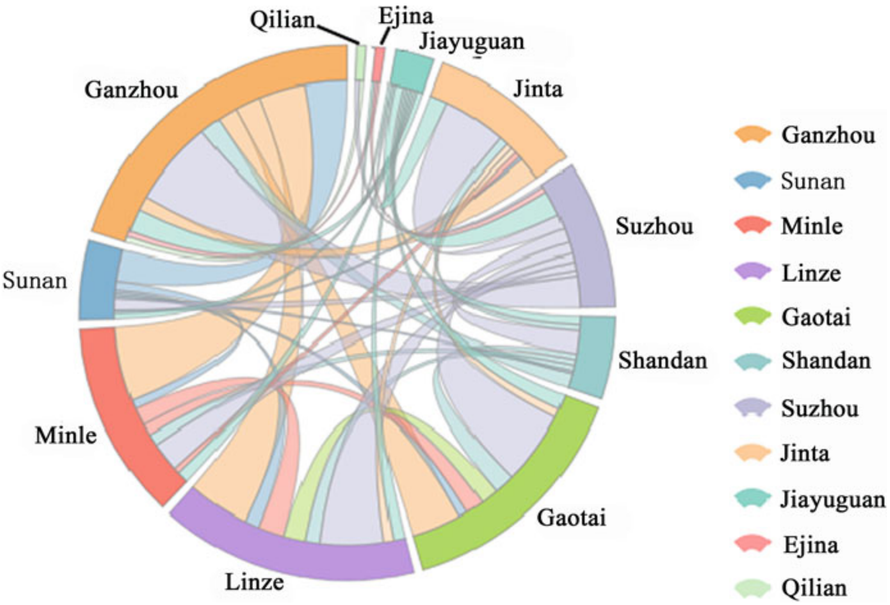

Fig. 3 Virtual water imports and exports at the county level for the Heihe River Basin. The color of the links refers to the counties (Reprinted from Zhang et al. (2017) with permission of Water)

Table 6 An account of the virtual water import and export at county level of the Heihe River Basin (unit: 10^4 m^3) (Reprinted from Zhang et al. (2017) with permission of Water)

Counties	Other counties in the Basin (Exporters)	Other counties in the Basin (Receivers)	Export outside the Basin	Import outside the Basin	Net export outside the Basin
Qilian	2.36	6.89	3043.54	5077.05	−2033.51
Ganzhou	91.19	92.57	47,302.46	20,123.45	27,179.01
Sunan	22.74	28.07	7096.40	5285.61	1810.79
Minle	54.77	37.96	17,769.94	5735.70	12,034.24
Linze	70.77	27.68	24,215.79	4571.68	19,644.11
Gaotai	66.12	26.08	25,678.01	4614.42	21,063.59
Shandan	21.87	30.24	10,309.50	4558.34	5751.16
Suzhou	42.10	112.98	33,327.96	21,301.00	12,026.96
Jinta	43.63	20.02	26,163.75	7503.92	18,659.84
Jiayuguan	9.73	37.93	11,665.25	20,318.16	−8652.91
Ejina	0.65	8.49	4763.28	6727.54	−1964.26

virtual water imported into the Heihe River Basin was 4.29 million m^3 and total virtual water exported from the basin was 4.26 million m^3 (Table 6). This indicates that there was 0.03 billion m^3 of virtual water imported specifically through interbasin transfers. This reinforces our observation that interregional trade makes little contribution to alleviating water stress in water-scarce regions.

Virtual Water Flows by Sectors

Figure 4 shows the virtual water flows at county level by sector in the Heihe River Basin (only amounts above 1.5 million m^3 are shown). Of the 48 aggregated sectors, only 23 sectors revealed both the import and export of virtual water. When all the counties were considered, the sectors with the highest virtual water import and export were the food manufacturing and tobacco processing industries in Jiayuguan County with 73.57 and 119.33 million m^3, respectively, while the sector with the lowest virtual water import and export for all counties was the textile industry with

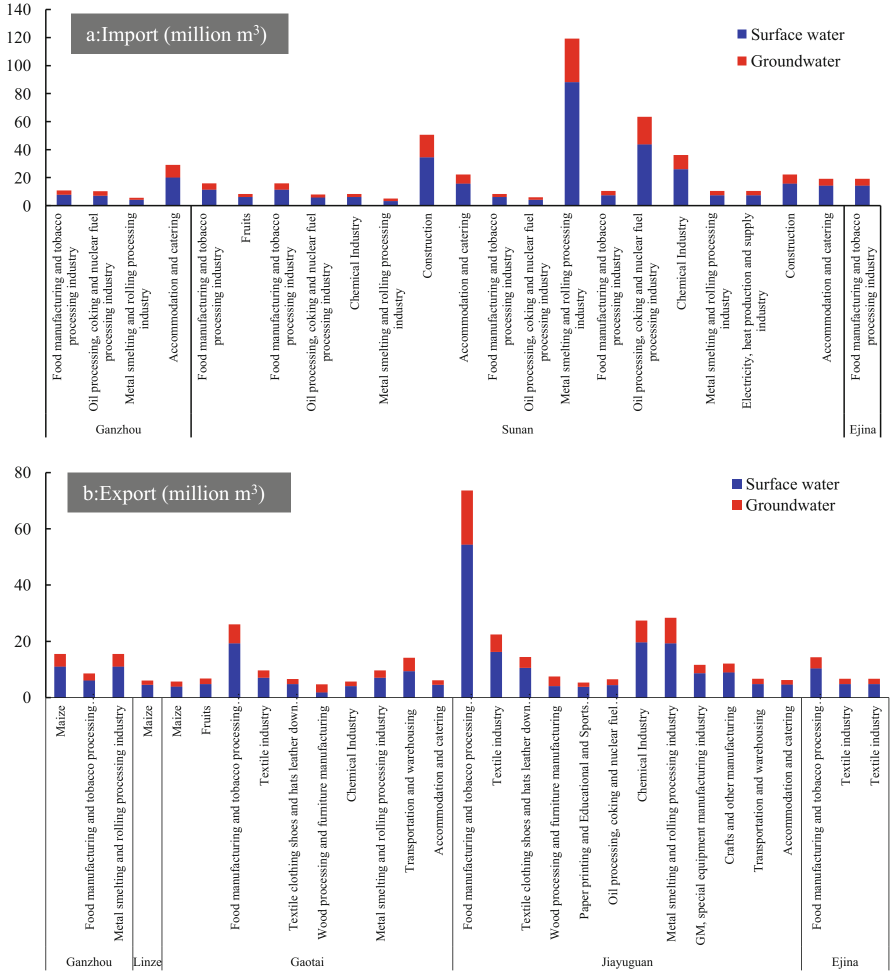

Fig. 4 The interbasin virtual water flows at the county level by sector in the Heihe River Basin. (**a**) virtual water import; (**b**) virtual water export (Reprinted from Zhang et al. (2017) with permission of Water)

1.44 and 0.20 million m^3, respectively. The sectors mainly responsible for virtual water import are the chemical industry, accommodation and catering, the food manufacturing and tobacco processing industries, and the metal smelting and rolling processing industries (Fig. 4a). In contrast, the sectors that mainly export more virtual water than they import are maize production; the textile industry; transportation and warehousing; and textiles, clothing, shoes and hats, leather down and its products (Fig. 4b). By making full use of the water saving effect of imported trade, water scarcity in China can be alleviated. First, agriculture and other sectors of imports including general machinery, equipment manufacturing industry, and petrochemical industry should be expanded. These industries in China's import and export trade has a high virtual water intensity. To strengthen the import of goods in these sectors, the tensions of China's water consumption can be better alleviated. China imported virtual water through three sectors: agriculture, petrochemical industry, general machinery, and equipment manufacturing industry (Chen et al. 2017).

In Ganzhou County, maize production dominated the largest contributor to the regional water stress, with a net virtual water export of 11.04 million m^3. The studies on virtual water at the sector level inhibited that food and agriculture are crucial sectors affecting virtual water trade interregionally (Zhang and Anadon 2014). The service sector's influence on water stress varied from county to county. For instance, the virtual water export by leasing and business services in Suzhou and Jiayuguan Counties was around 16.00 million m^3, while the virtual water import in Jiayuguan County (31.34 million m^3) was almost triple that of Suzhou County (11.19 million m^3). The leasing and business services sector in Jiayuguan County were presented to relieve the water shortage. Overall, the Heihe River Basin imported a small portion of virtual water (raw and processed food products) during the 10 years from 1997 to 2007 (Jin et al. 2016).

Most previous assessments of global water resources have focused on surface water. However, humans are overexploiting groundwater in many large aquifers that are critical to agriculture, especially in Asia and North America (Gleeson et al. 2012). Figure 4 also provides virtual water flows by distinguishing between surface water and groundwater. Clearly, almost all the sectors experienced more virtual water flows from surface water than that from groundwater, with the ratio of surface water to groundwater virtual water ranging from 1.20 to 2.91. An exception was the wood processing and furniture manufacturing sector in Suzhou County, where virtual water flows from groundwater exceeded those from surface water. This is possibly a result of Suzhou county having the highest utilizable groundwater resources (about 0.25 billion m^3) among all the counties. However, it should be noted that more than 50% of groundwater has been seriously degraded as a result of the overuse of fertilizers and pesticides (Dong et al. 2009). The discharge of high-concentrated pollution to surface flows from intensively pollution-generating production sectors (e.g., paper, chemicals, and textiles) has led to many major rivers in North China no longer being able to support any type of beneficial use because of their poor water quality. Water consumption in different sectors damaged water quality to some extent, which is vital for water-scarce regions. Policy about industry structure adjustment suggested that the sectors affecting water quality and consuming large amounts of water should be transferred to less-polluted and less-consumed sectors.

Over the past 6 years, the sum of virtual water imports in two sectors including agriculture and electric and water industry accounted for about 64% of China's total virtual water resources. The virtual water intensity of the exports of the sectors such as agriculture; electric and water industry; food, beverage, and tobacco products; textile, garment, and leather products industry in China is quite strong. Agriculture and services industry have no significant pull on the export of virtual water in China. However, agriculture and electric and water industry exported the most virtual water in China. Over the past 6 years, the total amount of virtual water exports in these two provinces accounted for about 80% of China's total virtual water exports. The sector of manufacturing industry is the main industry that drives China's virtual water exports. Food, beverage, and tobacco products; textile, garment, and leather products; petrochemical industry; general machinery; and equipment manufacturing industry exported virtual water of 387.3 billion tons in total among 2000, 2002, 2005, 2007, 2010, and 2012, accounting for 72% of the total amount of virtual water exports (Chen et al. 2017).

Water Stress and Water Scarcity

According to the United Nations, as of 2050, it will face a water problem of 2–2. 7 billion people, and per capita water will be reduced by more than one third over the next two decades. In these countries, China's water scarcity is the most serious, in which per capita available water resources is only 2300 m^3, lower than the world per capita of one-fourth population, ranked the 110th in the world, and is one of the world's 13 most water-scarce countries. China is well-known covering a temperate south and an arid north. There are also a large number of regional diversity in North and South China. The per capita available water resources in southern China are about 3600 m^3. The North China Plain exhibits the highest water scarcity, where per capita water availability is under 150 m^3, much lower than that in North China. In Northern China, water scarcity largely attributes to water use conflicts between upstream and downstream areas in the river basin, and between agriculture and the municipal and industrial sectors as well. In addition, more than 400 cities face water resources shortage in supply among China's 699 cities, and 110 cities face severe scarce water resources. This situation severely limits the sustainable development of China's national economy (He et al. 2011; Chen et al. 2017). Agriculture sector has been growing fast, and is the largest water consumer. Besides, water stress has given rise to deterioration of fresh water resources in terms of quantity (aquifer over-exploitation and dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.) (Cai 2008).

Water Stress Index Adjustment

Over the past few decades, the problem of water scarcity has increasingly been seen as a global systemic risk due to increased water demand and limited water supply

(Mekonnen and Hoekstra 2016). At present, various methods such as water resources vulnerability index, water stress index, international water management institute index, the water poverty index, and critical ratio are used to assess regional water shortage, water resources, acquisition, and capacity. Water stress is defined as the ratio of total annual freshwater withdrawals to total freshwater availability. In addition to that, the researchers should consider other different perspectives to learn more about water scarcity. Moreover, global water shortages were evaluated from a production perspective and demonstrated a mean annual basis for irrigation agriculture (A/Q), the domestic and industrial sectors (DI/Q), and their combinations (DIA/Q). Other researchers also took into account the large amount of water consumption and calculated the water scarcity associated with food production (Porkka et al. 2016; Liu et al. 2017). The Falkenmark indicators may be based on per capita usage of the most widely used water stress measures, which classified water resources in one area as no water stress (per capita 1700 m^3/y), water stress (per capita 1000–1700 m^3/y), water scarcity (per capita 500–1000 m^3/y), and absolute water scarcity (per capita <500 m^3/y) (Falkenmark et al. 1989).

This chapter adopts the water stress index (WSI) as defined by Pfister et al. (2009) and adjusts it for virtual water. The WSI concept represents the portion of water consumption that transfers freshwater to other users, thus indicating the pressures on renewable water resources. The *WSI* is expressed as:

$$\mathrm{WSI} = \frac{WC + VW_{ex} - VW_{im}}{Q} \tag{4}$$

where WC refers to water consumption. VW_{im} is virtual water import, and VW_{ex} is virtual water export. Q is renewable freshwater availability. Water stress is defined as moderate and extreme above a threshold of 0.4 and 0.8, respectively.

Water Stress at the County Level in the Heihe River Basin

Physical and virtual water use varied in different streams of the Heihe River Basin. The WSI formula was modified to accommodate virtual water flows. The results showed that physical water use, virtual water net imports, and renewable freshwater availability were the main causes of changes in water stress. Incorporating virtual water flows into water stress analysis permits a better understanding of what is causing water stress. Most of the 11 counties in the Heihe River Basin have experienced water stress, and had WSI values >0.4 in 2012 (Table 7). The areas with extremely high water stress included Sunan and Jiayuguan counties in the midstream area, and Qilian County in the upstream area. The WSI values for Sunan, Jiayuguan, and Qilian counties were 3.02, 2.17, and 1.69, respectively. However, Ejina County in the downstream area did not experience water stress and had a WSI value of 0.09. In fact, the physical water consumption and net virtual water import in the upstream and downstream areas were similar. This indicates that the large difference in water stress is driven by renewable freshwater availability (Table 7).

Table 7 Water stress index (WSI) at the county level in the Heihe River Basin (Reprinted from Zhang et al. (2017) with permission of Water)

Streams	Counties	Renewable freshwater resources (Billion m^3)	WSI
Upstream	Qilian	0.02	1.69
Midstream	Ganzhou	0.80	0.69
	Sunan	0.03	3.02
	Minle	0.40	0.36
	Linze	0.43	0.49
	Gaotai	0.34	0.63
	Shandan	0.13	0.70
	Suzhou	0.65	0.11
	Jinta	0.36	−0.23
	Jiayuguan	0.11	2.17
Downstream	Ejina	0.41	0.09

National-level studies on virtual water have revealed that several economically advanced provinces, such as the cities of Beijing, Tianjin, Shandong, Shanghai, Zhejiang, and Guangdong, have imported huge amounts of virtual water from outside to alleviate their water stresses (Dalin et al. 2015; Zhang et al. 2012; Wang et al. 2013). This is especially applicable to the city of Beijing. Other researchers found that virtual water was exchanged and traded from arid regions to wet regions, and from north to south (Zhang and Anadon 2014; Guan and Hubacek 2007). However, only about 5% of the total available water use can be attributed to net virtual water flows in north China (Guan and Hubacek 2007). Moreover, surface water has been polluted by highly polluting production sectors (e.g., paper, chemicals, and textiles), and groundwater has been seriously degraded by agricultural activities. Thus, groundwater overexploitation in the midstream areas of the Heihe River Basin should be highly valued.

The middle oasis area is the main social and economic development gathering place of the Heihe River Basin, among which Zhangye oasis agriculture district in the middle reaches played important roles. Eighty percent planting area of the basin are concentrated in the city of Zhangye. Zhangye City is located in the middle reaches of the Heihe River Basin, which belongs to the typical arid oasis of agriculture. It is an oasis area with relatively high historical development, rapid economic development, and relatively high development potential in the Hexi corridor. It is known as the place with South China-type scenery and golden Zhangye. Zhangye City exhibits a low level of urbanization, weak economic base, big agricultural proportion. The county's economic level varies a lot. In 2012, about 1.21 million people existed in Zhangye City, of which the urban population of nearly 450,000 people with the urbanization rate of 35.98%. Agricultural is the main production sector in Zhangye oasis, while industrial process is still in its infancy and thus economic development is lagging behind. In the allocation of water resources, agricultural water consumption accounts for more than 95% of total water consumption, while water use efficiency is only 40–50%.

The counties in Zhangye City have different regional economic differences due to terrain, agricultural infrastructure, and socioeconomic infrastructure differences. The city's nearly half of the output value is from Ganzhou County. Ganzhou, Linze, and Gaotai Counties are characterized with higher GDP because it is the core area of the Heihe oasis. However, Shandan and Minle Counties are covered with the piedmont plain, so their regional economic foundations are very weak. Sunan County is mainly located in the grassland pastoral areas with the less population by gathering of ethnic minorities, in which animal husbandry is the key economic sector.

Since the implementation of the water reallocation program, the water environment in the middle reaches has been slightly adversely affected. The surface water recharge decreased, and the groundwater exploitation increased, leading to the gradually decreased middle water level. However, the water supply in the middle reaches has barely changed. The amount of available water in the middle reaches is about 10^8 m^3. The ratio between surface water and groundwater utilization remained stable among Ganzhou, Liyuan River irrigation area. Nevertheless, in Linze and Gaotai irrigation areas, groundwater exploitation increased dramatically. For example, groundwater exploitation in Linze and Gaotai Counties increased by 505% and 40% respectively from 2000 to 2008 (Cheng et al. 2014).

Virtual Water Strategy Application Facing Challenges

Over the past 50 years, China's surface water and total water resources were reduced by about 5% and 4%, respectively (Liu 2013), while the inland river basin in China occupies one third of the total land area. Water issue becomes the crucial issue of socioeconomic development and environmental protection in inland river basins due to congenital water shortage and unreasonable use (Feng et al. 2007). With the population booming and the rapid economic development in the upstream and midstream areas of the Heihe River Basin, the consumption of water increases dramatically and diminishes the water available for ecological processes, thus causing a series of severe ecological disasters. Nowadays, water use capacity of the Heihe River Basin is about 3.36 billion m^3, among which agricultural water use accounts for 95% and extremely squeezes ecological water use. The competition for water between economy and ecosystem is also getting more intense. Therefore, the Heihe River Basin experiences multidimensional drives of human activities involving ecology, animal husbandry, agriculture, and industry.

From the viewpoint of water resource characteristics, water not only has natural properties but also possesses socioeconomic and ecological properties. Information about water scarcity only considers the water supply aspect, and neglects the water demand aspect (Dalin et al. 2015; Deng et al. 2014). That said, industrial structure's effect on water demand should be considered. Agricultural irrigation has a large water demand, while service industries need less water. Much research has been done on virtual water trade for relieving water stress (Feng et al. 2012; Hoekstra et al. 2012; Deng and Zhao 2015; Fracasso et al. 2016).

In 1999, Professor Allan suggested that a country could implement a virtual water trade strategy to import water-intensive products from another country and reduce the export of high water consumption products in order to import (virtual) water resources, thus saving water resources. Import or export of physical water is very expensive, so the trade of virtual water could overcome this shortcoming and is an effective way to deal with water scarcity in countries with water shortages (Allan 1999). Over the past two decades, trade flows and trade in virtual water have doubled in all countries (Dalin et al. 2012). With the rapid development of China's international trade, the virtual water trade strategy will alleviate the problem of water shortage to a large extent, adjust China's foreign trade structure, reduce the export of virtual water, and increase the import of virtual water. However, the application of virtual water strategies to improve water use efficiency was challenged due to comprehensive capacities of economic level, social equity, infrastructural construction, and potential eco-environmental effect.

The implementation of the virtual water strategy can lead to a lot of surplus agricultural labor force, and the unemployment status of agricultural labor force. As a consequence, two important indicators should be considered when solving the problem of surplus agricultural labor force under the virtual water strategy, i.e., employment multiplier and "learning effect" of nonagricultural sectors. The social distribution equity could be represented with the Hoover coefficients, which provided a more straightforward interpretation of inequality than the Gini coefficient.

Implementation of the virtual water strategy will reduce the pressure of ecological water shortage and whereas change the regional production mode and the local biodiversity. Consequently, two indicators should be involved in the suitability assessment of the virtual water strategy, e.g., constraint of water resources on the ecological conservation, impacts of the virtual water strategy on biodiversity. The water resource is one of the limiting factors of ecological conservation and sustainability in water-scarce regions, especially where there is serious ecological degradation. However, if the high water agriculture is replaced by urbanization rather than low water agriculture, it may lead to the decline of vegetation coverage, consequently causing desertification, soil erosion, and ecological degradation.

Water has to be considered as a social, economic, as well as an ecological good. Social-economic-ecological systems have powerful reciprocal feedbacks and act as complex adaptive systems. The core of implementing virtual water trade is selecting an appropriate route to develop the secondary and tertiary industries that leads virtual water flow to industry and service sectors by dint of positive feedback loop. The positive feedback loop is efficient due to the driving mechanism of putting virtual water in the secondary and tertiary industries. Nevertheless, when the feedback loop evolves, adaptability of the feedback loop should be considered by adding compensation mechanism of industrial transition. Consequently, integrating social, economic, and ecological systems is a vital step to determine whether the virtual water trade is appropriate or not. There has been no standard index applied to tell the application boundary of virtual water trade in the world. The establishment of standard index for water-scare regions is also critical for the mechanism of water price and water right of surface and ground water.

Summary

Water scarcity in arid and semi-arid regions has been severe. In the Heihe River Basin, water resource sustainability, ecosystem health, and socioeconomic development are dependent on water. According to virtual water concept, water-scarce regions with spatial mismatches in water and arable land availability can improve their food security by purchasing a portion of their food requirements through agricultural trade and cutting local food production. A flourishing literature has been inspired on dealing with water scarcity through virtual water trade. To mitigate water stress, some researchers believe that food trade to increase virtual water in water-scarce regions is an efficient use of water resources. However, others have argued that the virtual water trade strategy as a solution to water scarcity is fallacious for several reasons: (1) no enough trade capital for traditional agricultural regions, (2) considering water as the only production factor while neglecting land, (3) lack of consumption pattern and production allocation in economic system. Furthermore, virtual water flows have varied effects on water stress for the water-receiving regions and the water-exporting regions. The key to mitigate water stress is improving water use efficiency, whereas the efficiency benefits will be highly compensated by the increased water demand caused by developed economy.

This chapter used a firstly compiled county-level input–output table, which was supported by the research project of “National Natural Science Foundation of the Heihe River Basin major research program.” The MRIO model at county level of the Heihe River Basin was applied to analyze virtual water import and export in 2012. In the MRIO table, the Heihe River Basin consists of 11 counties, and the sectors have been aggregated into 48 sectors. The water resource is divided into groundwater and surface water in the IO table. The total amount of virtual water imported into the Heihe River Basin was 1.06 billion m^3, and the total amount of virtual water exported was 2.11 billion m^3. In total, the Heihe River Basin is a net virtual water exporter at a scale of 1.05 billion m^3, accounting for one third of the total amount of water resource. The upstream and downstream of the basin had little virtual water flows with the rest of basin, whereas the midstream exported 96.31% (2.04 billion m^3) of virtual water to outside the basin, and imported 88.84% (0.94 billion m^3) from outside the basin.

For specific counties, regions with grain production had high levels of water consumption; corn or wheat production accounted for the largest proportion (almost 50%) of total water consumption. For example, the water use for corn production in Ganzhou County accounted for 54.53% (449.07 million m^3) of total water consumption, while the proportion of consumption for wheat was 44.58% (66.64 million m^3) in Shandan County. Ganzhou County accounted for the most virtual water import and export with 0.20 billion m^3 and 0.47 billion m^3, respectively. The top three exporters in the interbasin virtual water flows are Ganzhou, Linze, and Gaotai Counties, and the amount of water exporting is 0.91, 0.71, and 0.66 million m^3, respectively. When it comes to the sector-based water consumption, corn or wheat production in agricultural sector alternatively accounts for the biggest proportion (almost 50%) of total water consumption.

For most of the sectors, virtual water content in surface water is greater than that in groundwater by distinguishing between the “surface water” and “groundwater” components of virtual water, and the ratio of surface water to groundwater ranges from 1.20 to 2.91. Specifically, food manufacturing and tobacco processing industry had the highest amount of import and export virtual water, and the amount reached to 119.33 and 73.57 million m^3 separately. On the contrary, textile industry had the lowest amount of import and export virtual water of 1.44 and 0.20 million m^3. The sectors mainly responsible for virtual water import are the chemical industry, accommodation and catering, the food manufacturing and tobacco processing industries, and the metal smelting and rolling processing industries. In contrast, the sectors that mainly export more virtual water than they import are maize production; the textile industry; transportation and warehousing; and textiles, clothing, shoes and hats, leather down and its products.

Importantly, maize production dominated the largest contributor to the regional water stress, simultaneously, the industrial sectors played a vital role in alleviating water stress. Spatially, most counties in the Heihe River Basin experienced water stress, and extremely high water stress presented in Sunan and Jiayuguan and Qilian Counties with water stress index (WSI) values of 3.02, 2.17, and 1.69, respectively. The application of virtual water strategy in arid regions should take into consideration the comprehensive capacity of economic level, social equity, infrastructural construction, and potential eco-environmental effect.

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