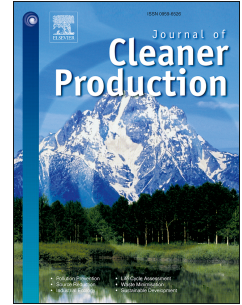# Accepted Manuscript

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Multi-scale input-output analysis of consumption-based water resources: method and application

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ABSTRACT

This work develops a method of multi-scale input-output analysis for the embodied water accounting of an economy. This method can distinguish between the different virtual water contents of imported and local products and is therefore capable of accurately estimating the virtual water that is embodied in trade. As a simplified model rather than a multi-regional input-output analysis, this method substantially

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23 minimizes the data requirements. With the support of averaged Eora global embodied

24 water intensity databases for the world and Chinese economies, a three-scale

25 embodied water input-output analysis of the Beijing economy in 2007 has been

26 conducted. Dozens of virtual water flows that relate to the Beijing economy have been

27 identified and analyzed. Only 15% of the total water resources embodied in Beijing's

28 local final demand were from local water withdrawal; 85% were from domestically

29 and internationally imported products. The virtual water import is revealed to play a

30 more important role than physical water transfer in easing Beijing's water shortage.

31 Since the average water use efficiency of the Beijing economy is much higher than

32 that of the Chinese economy but somewhat lower that of the rest of the world, Beijing

33 is suggested to shifting its imports to foreign countries to optimize global water use.

34 The method developed can be useful for water saving strategies for multiple

35 responsible entities holding different opinions, and it can be easily applied to the

36 embodied water accounting of a sub-national or even smaller economic community.

37

38 **Keywords**

39 Multi-scale input-output analysis; Consumption-based water resources; Water

40 resources embodied in trade; Virtual water strategy

41

42 **1. Introduction**

43   With the acceleration of globalization, cooperation, and specialization in the world

44 economy, ever-increasing international and interregional trade have brought more

2

45   trade imbalance issues concerning water resources. The water resources that are

46   embodied in export, import, and bilateral trade have therefore attracted a significant

47   amount of attention (Dalin et al., 2014; Hoekstra and Mekonnen, 2012). Among these

48   studies, input-output analysis (IOA), and increasingly multi-region input–output

49   (MRIO) analysis, plays an important role in tracing consumption-based water

50   resource usage and in determining responsibility (Deng et al., 2015; Guan et al., 2014).

51   Some water indicators, for example, the Water Stress Index (WSI) and the Water

52   Exploitation Index (WEI) (Lenzen et al., 2013a; Pfister et al., 2009; Zhao et al., 2015)

53   have also been attached to IOA to assist in the policy making.

54   Because the data support on a national level is relatively complete, the

55   consumption-based water resources of countries around the world and the virtual

56   water that is embodied in international trade have been successfully analyzed and

57   estimated by MRIO analyses (Chen and Chen, 2013; Lenzen et al., 2013a). Based on

58   available statistic trade data, some studies have made great contribution by connecting

59   a national MRIO model to a global MRIO model with limited number of country

60   groups to analyze regional virtual water flows (Cazcarro et al., 2016; Feng et al., 2011;

61   Yu et al., 2010). However, for other sub-national or ever smaller regional economies

62   where the detailed input-output data are not available, a complete water resource

63   MRIO still presents difficulties. For example, the virtual water MRIO studies of

64   Chinese regions either ignored international imported virtual water (Jiang et al., 2015;

65   Zhao et al., 2015) or assumed that imported products and the locally produced

66   products are homogenous (Deng et al., 2016).

67   Because of the lack of available data, some IOA based studies used the

68   single-region input-output (SRIO) model to estimate the virtual water flow of an

69   economy. The SRIO-based studies have either ignored imported virtual water (Zhao

70   et al., 2016) or have made the water intensity for imports equal to that of local product

71   (Guo et al., 2016; Renault, 2003; Zhao et al., 2009). Therefore, the SRIO can only

72   estimate how much water is saved by importing a product instead of producing

73   domestically, i.e., the water resources use that is avoided by imports (WAI). And it

74   prevents estimation of the real virtual water transfer and the design of oriented virtual

75   water strategies.

76   First presented by Chen and his colleagues, the method of multi-scale input-output

77   (MSIO) was proposed to construct carbon emission intensity database and to support

78   carbon emission accounting of a building (Chen et al., 2011). The present work

79   contributes a universal multi-scale input-output (MSIO) method to analyze embodied

80   water flows of an economy. It can distinguish between the different virtual water

81   contents of the same products from different economies, which is superior to SRIO. In

82   addition, because the averaged embodied water intensity databases for the world and

83   for national economies have been used to estimate the virtual water that is embodied

84   in trade, this method requires much less data than a complete MRIO analysis does.

85   The MSIO can be easily applied to account the resource use of a sub-national or even

86   a smaller economy according to individual need.

87   Beijing, as a megacity and the capital of China, has long suffered from water

88   shortage because of a series of both natural and social economic factors, such as an

89   unbalanced spatial distribution, heavy water pollution, a large population and rapid

90   economic growth. It is reported that the groundwater reserves of Beijing (1.74 billion

91   m^3 in 2015) has been declining over the past a few decades, the amount of which has

92   been reduced by 9.48 billion m^3 since 1980 (BWA, 2015). The rivers with relative

93   heavy water pollution (lower than V class water standard defined by Ministry of

94   Environmental Protection of China) account for 39.7% of the total river length in

95   2015 (BWA, 2015). Aiming to demonstrate the MSIO method of water resources and

96   assist water saving strategy design of Beijing, a case study has been conducted for a

97   three-scale embodied water input-output analysis of the Beijing economy. The rest of

98   the paper is organized as follows: Methodology and data sources are elaborated in

99   Section 2. Section 3 presents the results of embodied water accounting of the Beijing

100   economy. Section 4 discusses the advantages of the MSIO and contributes some

101   virtual water strategies for Beijing to save water resources withdrawal. Finally,

102   conclusions are drawn in Section 5.

103

104   **2. Methods and materials**

105   **2.1 Multi-scale input-output (MSIO) analysis**

106   **2.1.1 Multi-scale ecological input-output table of an economy**

107   To distinguish between the virtual water contents of local and imported products, a

108   non-competitive ecological extended input-output table is considered as the basis of

109   the MSIO analysis. Table 1 shows the general form of a multi-scale ecological

110   input-output table of an economic system.

111   The illustrated system is divided into n_0 industrial sectors, which are

112   simultaneously sustained by local and imported products. The imports are assumed to

113   be from m external economic systems, and the economic system in the S_h scale is

114   divided into n_h industrial sectors. $z_{i,j}^{L}$ and $z_{i,j}^{S_h}$ represent local products and

115   imported product of the S_h scale from Sector i that are used as intermediate inputs for

116   local Sector j. y_i^{L} and $y_i^{S_h}$ represent local products and imported products of the S_h

117   scale from Sector i to satisfy the local final use. The local products from local Sector i

118   that satisfy external use in the external economic system are represented as exports,

119   e_i^{L}. Imported products are also re-exported to the external economic systems (see

120    $e_i^{S_h}$). Finally, x_i represents the total output of the i-th local sector, and $F_{k,j}$ represents

121   the k-th water resources flow that is consumed by the j-th local sector.

122

123   Table 1

124   Multi-scale ecological input-output table of an economic system[1]

Input \ Output		Intermediate use			Final use		Output
		Sector 1	…	Sector n_0	Local final consumption	Export	
Local inputs	Sector 1	$z_{1,1}^{L}$	…	z_{1,n_0}^{L}	y_1^{L}	e_1^{L}	x_1
	⋮	⋮	…	⋮	⋮	⋮	⋮
	Sector n_0	$z_{n_0,1}^{L}$	…	z_{n_0,n_0}^{L}	$y_{n_0}^{L}$	$e_{n_0}^{L}$	x_{n_0}
Imported inputs from S_1	Sector 1	$z_{1,1}^{S_1}$	…	$z_{1,n_0}^{S_1}$	$y_1^{S_1}$	$e_1^{S_1}$	
	⋮	⋮	…	⋮	⋮	⋮	
	Sector n_1	$z_{n_1,1}^{S_1}$	…	$z_{n_1,n_0}^{S_1}$	$y_{n_1}^{S_1}$	$e_{n_1}^{S_1}$	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	

Imported inputs from S_m	Sector 1	$z_{1,1}^{S_m}$	…	$z_{1,n_0}^{S_m}$	$y_1^{S_m}$	$e_1^{S_m}$
	⋮	⋮	…	⋮	⋮	⋮
	Sector n_m	$z_{n_m,1}^{S_m}$	…	$z_{n_m,n_0}^{S_m}$	$y_{n_m}^{S_m}$	$e_{n_m}^{S_m}$
Direct water resources withdrawal	Water type 1	$F_{1,1}$	…	F_{1,n_0}		
	⋮	⋮	…	⋮		
	Water type p	$F_{p,1}$	…	F_{p,n_0}		

[1] The added value part is omitted as it is not involved in the basic formulation.

2.1.2 The basis formulas of multi-scale input-output analysis

Figure 1 shows the water resources input and output flows of a typical industrial sector i in an economic system (only the k-th water flow is considered). $\varepsilon_{k,j}^{L}$ and $\varepsilon_{k,j}^{S_h}$ represent the k-th embodied water resource intensities of local products from Sector j and imported products from Sector j of the economic system in the S_h scale. Here, the embodied water intensity is principally defined as the marginal water cost when the total amount of a product changes by an incremental unit.
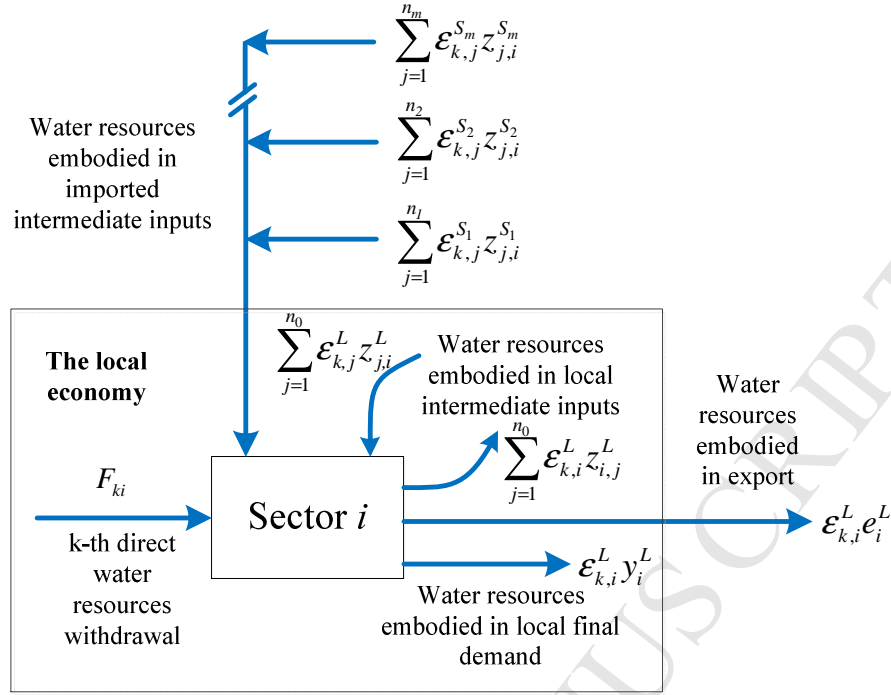
Figure 1. The virtual water balance of an industrial sector in an economic system

According to conservation law, the physical embodied water balance equation for local Sector i can be written as

$$F_{k,i} + \sum_{j=1}^{n_0}(\varepsilon_{k,j}^L z_{j,i}^L) + \sum_{h=1}^{m}\sum_{j=1}^{n_h}(\varepsilon_{k,j}^{S_h} z_{j,i}^{S_h}) = \varepsilon_{k,i}^L\left(\sum_{j=1}^{n_0} z_{i,j}^L + y_i^L + e_i^L\right). \tag{1}$$

Based on the basic economic balance of an input-output table (see Table 1), it is understood that

$$x_i = \sum_{j=1}^{n_0} z_{i,j}^L + y_i^L + e_i^L. \tag{2}$$

For the entire economic system that is complemented by water resource flows of p types as an economic-ecological integration, an aggregate matrix equation can be induced as

$$\mathbf{F} + \boldsymbol{\varepsilon}^{\mathbf{L}}\mathbf{Z}^{\mathbf{L}} + \sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h}) = \boldsymbol{\varepsilon}^{\mathbf{L}}\mathbf{X}, \tag{3}$$

in which

149
$$\mathbf{F} = \left[F_{k,i} \right]_{p \times n_0},$$

150
$$\boldsymbol{\varepsilon}^{\mathbf{L}} = \left[\varepsilon_{k,i}^{L} \right]_{p \times n_0}, \quad \mathbf{Z}^{\mathbf{L}} = \left[z_{i,j}^{L} \right]_{n_0 \times n_0}, \quad \boldsymbol{\varepsilon}^{S_h} = \left[\varepsilon_{k,i}^{S_h} \right]_{p \times n_h}, \quad \mathbf{Z}^{S_h} = \left[z_{i,j}^{S_h} \right]_{n_h \times n_0},$$

151
$$\mathbf{X} = \left[x_{i,j} \right]_{n_0 \times n_0}, \text{ where } x_{i,j} = x_i \text{ when } i = j, \text{ and } x_{i,j} = 0 \text{ when } i \neq j.$$

152

2.1.3 The embodied water intensity database based on the MSIO analysis

154 The embodied water intensity matrix for local products, as the basis for estimating

155 the virtual water resource flows, can be given based on Eq. (3) as

156
$$\boldsymbol{\varepsilon}^{\mathbf{L}} = (\mathbf{F} + \sum_{h=1}^{m} (\boldsymbol{\varepsilon}^{S_h} \mathbf{Z}^{S_h}))(\mathbf{X} - \mathbf{Z}^{\mathbf{L}})^{-1}. \qquad (4)$$

157 It can be seen that the direct water withdrawal data, non-competitive economic

158 input-output data and the embodied water intensity matrixes for imported products are

159 the preconditions for obtaining the embodied water intensity database of local

160 products. As long as the embodied water intensity database of local products is

161 obtained, the water resources that are embodied in the final demand and the exports

162 can be calculated accordingly. After several deformations, Eq. (4) can also be

163 rewritten as the following to make it easier to understand:

164
$$\boldsymbol{\varepsilon}^{\mathbf{L}} = (\mathbf{F} + \sum_{h=1}^{m} (\boldsymbol{\varepsilon}^{S_h} \mathbf{Z}^{S_h}))\mathbf{X}^{-1}(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}, \qquad (5)$$

165 where $\mathbf{A}^{\mathbf{L}} = \mathbf{Z}^{\mathbf{L}} \mathbf{X}^{-1}$ is a coefficient matrix that describes the inputs in the production

166 of these sectors, and $(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}$ is the so-called Leontief inverse (Miller and Blair,

167 2009). The equation is formally the same as the basis formula in universal

168 environmental input-output analysis (EIOA). In EIOA, only $\mathbf{F}\mathbf{X}^{-1}$ as direct water use

169 coefficients is applied to calculate the water resources embodied in final demand.

170 However, besides the local water withdrawal, some of the water resources that are

171 embodied in local products have originated from external economies by means of

172 imported intermediate input. Therefore, in Eq. (5), the "direct" water use coefficients

173 include not only the coefficients that originate from direct local water withdrawal

174 ($\mathbf{FX}^{-1}$) but also the coefficients that originate from external water imports

175 ($\sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h})\mathbf{X}^{-1}$). They together constitute the total water coefficients (internal and

176 external) of local products. $\varepsilon^{L,L}$ ($\mathbf{FX}^{-1}(\mathbf{I}-\mathbf{A^L})^{-1}$) and ε^{L,S_h}

177 ($\sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h})\mathbf{X}^{-1}(\mathbf{I}-\mathbf{A^L})^{-1}$) are used to denote local (with direct water withdrawal)

178 and external (with imported intermediate input in S_h scale) embodied water intensities

179 of local products.

180 **2.2 Data source**

181   Based on the MSIO method illustrated in Section 2.1, the three-scale embodied

182 water input-output analysis of the Beijing economy in 2007 is performed as a case

183 study. There are three types of essential databases for MSIO analysis. The first

184 database is a direct water use matrix for the Beijing economy in 2007. The ecological

185 input-output analysis assumes that the water transfer in an economic system has been

186 approximately covered by the input-output data among different industrial sectors.

187 For example, the tap water fee indicating the water transfer from the water supply

188 industry to other industries has been itemized as the intermediate output of the water

189 supply industry in the statistics data. As the physical entry of water resources to

190 human society, the direct water withdrawal data – rather than direct water

191 consumption – are therefore concerned in this work. The statistical data that was

192   contributed by the Second National Economic Census of China has been referred to

193   (see SI, Table S4) (CECY, 2010). Total water resource consumption has been divided

194   into three types of water usage according to different withdrawal purposes.

195   Agricultural water is for agricultural water requirements, mainly irrigation. Industrial

196   water is for industrial production processes, for example, washing coal or cooling

197   generator systems. Domestic water refers to daily water use by residents.

198   The second database is the economic input-out table. The official economic

199   input-output table for the Beijing economy in 2007 has been adopted (BSB, 2009).

200   This monetary input-output table is in units of Chinese Yuan (referred to as Yuan

201   hereafter). There are 42 industrial sectors in the table, which can be found in Support

202   Information (SI), Section S1.1. It is a competitive input-output table that does not

203   distinguish between local and imported products. By assuming that the imported

204   products have been distributed to intermediate input and final use with the same ratio

205   of local products (Guan et al., 2014; Shao et al., 2016; Weber et al., 2008), it is

206   transformed into a non-competitive input-output table. The intermediate input-output

207   matrix and final use matrix of local products, domestic imported products, and foreign

208   imported products can be obtained accordingly. For example, the foreign-imported

209   intermediate input-output matrix, $\mathbf{Z^M}$, can be calculated as

210    $$z_{i,j}^M = z_{i,j}\left(\frac{x_i^M}{x_i + x_i^D + x_i^M}\right) \qquad (6)$$

211   where $z_{i,j}$ is the total intermediate input from Sector i to Sector j, x_i is the total output

212   of Sector i, x_i^D is the domestically imported economic flow of Sector i, and x_i^M is

213   the foreign-imported economic flow of Sector i. Meanwhile, the final demand of

214   Sector i from foreign imports, $\mathbf{F^M}$, is expressed as

215
$$f_{i,k}^M = f_{i,k}\left(\frac{x_i^M}{x_i + x_i^D + x_i^M}\right) \tag{7}$$

216   where $f_{i,k}$ is the k-th final consumption of Sector i.

217   The last data source concerns the embodied water intensity databases for the

218   domestic and foreign imported products of the Beijing economy. The results from an

219   MRIO analysis to estimate the embodied water intensity database for 26 sectors of

220   186 countries all over the world in 2007 on the basis of the Eora global MRIO

221   database have been referred to (Lenzen et al., 2012; Lenzen et al., 2013b; Shao, 2014).

222   According to the multi-scale input-output scheme, in principle, the databases should

223   represent the rest of the world excluding the Chinese economy (because the products

224   from the Chinese economy are considered to be domestic imported products) and the

225   rest of China excluding the Beijing economy to estimate the virtual water that is

226   embodied in foreign and domestic imports. With respect to the former, the average

227   embodied water intensity for the 26 sectors in the other 185 nations of the world

228   economy has been applied to estimate water resources embodied in foreign imported

229   products (see SI, Table S2). However, regarding the latter, excluding the Beijing

230   economy from the Chinese database is difficult. Therefore, the embodied water

231   intensity for 26 sectors of the Chinese economy, as part of the results of the global

232   MRIO analysis, has been applied to estimate to estimate water resources embodied in

233   domestic imported products (see SI, Table S3). Because the share of the Beijing

234   economy is a small part of the Chinese economy (the GDP ratio is approximately 3%),

235   the deviation that the assumption presents can be ignored.

236

237   **3. Results**

238   **3.1 The embodied water intensity of the Beijing economy**

239   In 2007, Beijing has withdrawn 3.21 billion m^3 water. Meanwhile, the

240   consumption-based water resources of Beijing is estimated as 11.28 billion m^3 water,

241   approximately 3.51 times higher than the production-based water resources

242   withdrawal. The embodied water intensities of all economic sectors in the Beijing

243   economy in 2007 in the form of water resource withdrawal initiated by the final

244   consumption of one unit product (this work uses the monetary unit) are shown in

245   Figure 2 (the values can be found in SI, Table S5).

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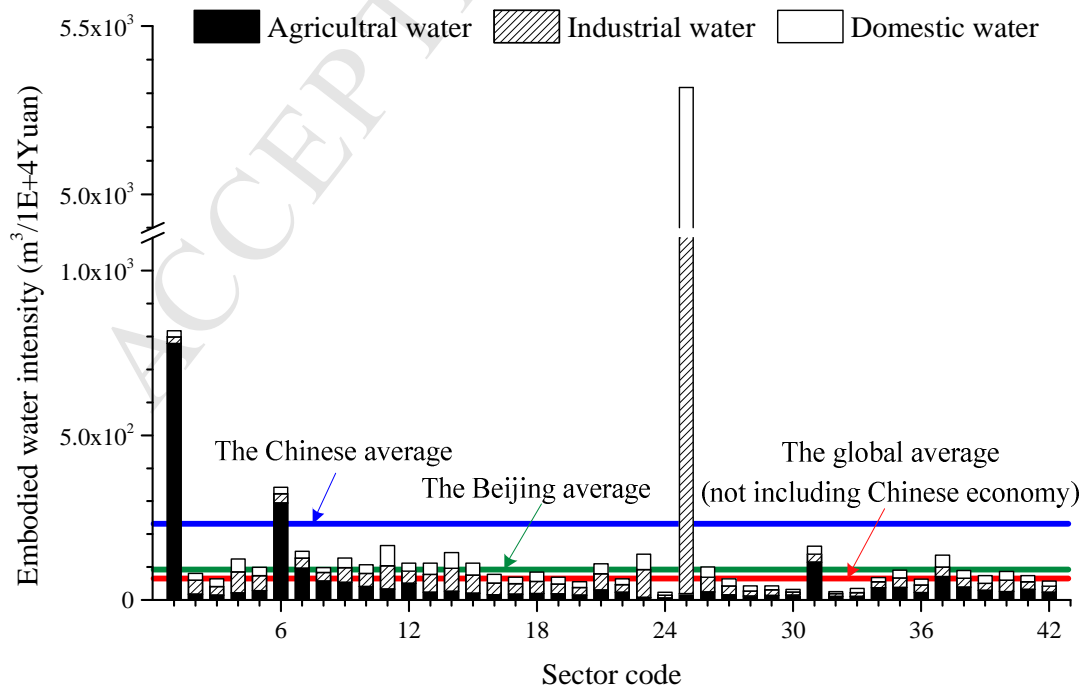
247

248   Figure 2. The embodied water intensity of the Beijing economy in 2007

249

250   Among the 42 industrial sectors, Sector 25 (Production and Distribution of Water)

251   has the highest embodied water intensity, and Sector 1 (Agriculture, Forestry, Animal

252   Husbandry and Fishery) ranks second. It is because these two industries have

253   withdrawn abundant raw water resources, accounting for more than 85% of the total

254   freshwater withdrawal. The final products that are supplied by these sectors, such as

255   tap water, foods, and tobacco, are water-intensive products. Beijing can increase

256   imports of these products to save local water resources. Although many industries

257   seem irrelevant to agriculture, every sector has embodied agricultural water intensity.

258   The advantage of input-output analysis is that it can reveal the complex technical and

259   economic interactions of different industries.

260   A key theoretical premise of this study is that, because of the variation in

261   technological efficiency and the diversity of economic structure, the same type of

262   products that are produced in different communities have different embodied water

263   intensities, i.e., virtual water contents. The obtained results agree with this premise

264   (see the comparisons of Tables S2, S3, and S4 in SI). The average output-valued

265   embodied water intensity for the entire global economy (not including the Chinese

266   economy), the Chinese economy, and the Beijing economy in 2007 have been

267   estimated as 71.69 m^3/1E+04 Yuan, 235.72 m^3/1E+04 Yuan, and 91.97 m^3/1E+04

268   Yuan (the former two are calculated from the embodied water intensity database of

269   the Chinese economy and the rest of the global economy in 2007; see Figure 2). It can

270 be observed that the average water use efficiency of the Beijing economy is much

271 higher than that of the Chinese economy but somewhat lower that of the rest of the

272 world. Thus, on average, China needs more than twice as many water resources as

273 Beijing to have the same economic output value.

274   The significant gap between the Chinese and Beijing economies is mainly a

275 reflection of the embodied agricultural water intensity, where China's average value is

276 161.59 m^3/1E+04 Yuan and Beijing's average value is only 41.04 m^3/1E+04 Yuan

277 (which is even lower than the average value of the rest of the world). In 2012, over 88%

278 of the total agricultural area in Beijing had adopted water-efficient irrigation, and the

279 coefficient of irrigation agricultural water was as high as 0.70 in 2013 (Geng, 2014).

280 At the same time, agricultural water use in Beijing has continually dropped since 2001

281 (CSY, 2015). With regard to China, the coefficient was only 0.52 in 2013 (Geng,

282 2014). The Chinese government plans to increase this coefficient to over 0.60 in 2030

283 according to the national policy referred to as "the Strictest Water Resources

284 Management System" (SCC, 2012); the implementation of this policy was also

285 emphasized in a recently launched draft of the five-year-plan for China. Smooth

286 implementation of the plan will contribute to a lower embodied water intensity of

287 China.

288 **3.2 Water resources embodied in the final demand of the Beijing economy**

289   One of the most important core issues in ecological economics is that the use of

290 resources, such as water resource withdrawal, and environmental emissions, such as

291 greenhouse gas emissions, are driven by human final demand or final consumption.

292   All embodied water flows related to the Beijing economy have been calculated and

293   are illustrated in Figure 3 (the definitions and values of the embodied flows are shown

294   in SI, Table S6). Essentially, the final consumption of Beijing is simultaneously met

295   by foreign imported, domestic imported and local products. However, local products,

296   which were emphasized in Section 2.1, involve local, domestic, and global embodied

297   water intensities through direct water withdrawal, domestic, and foreign imported

298   intermediate inputs, respectively. Therefore, part of the embodied water of the local

299   products has also originated from domestic and foreign imported embodied water.

300   This is often ignored in previous studies, and the MSIO has made it possible to

301   identify and calculate it in the present work.

302

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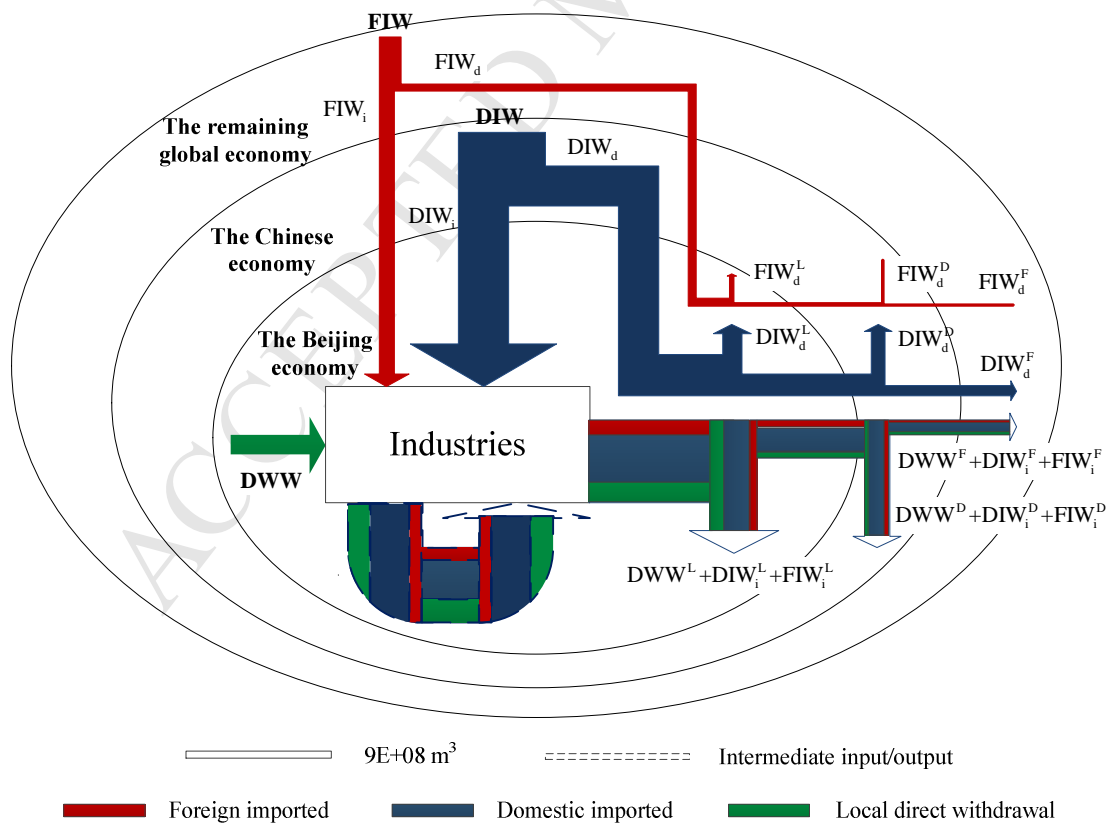
304 Figure 3. The embodied water flows of the Beijing economy in 2007 (DWW: direct water

305 withdrawal; FIW: foreign imported water resources; DIW: domestically imported water

306 resources; Superscript L/D/F: water resources embodied in local final demand/domestic

307 export/foreign export; subscript d: direct imported water resources; Subscript i: indirect

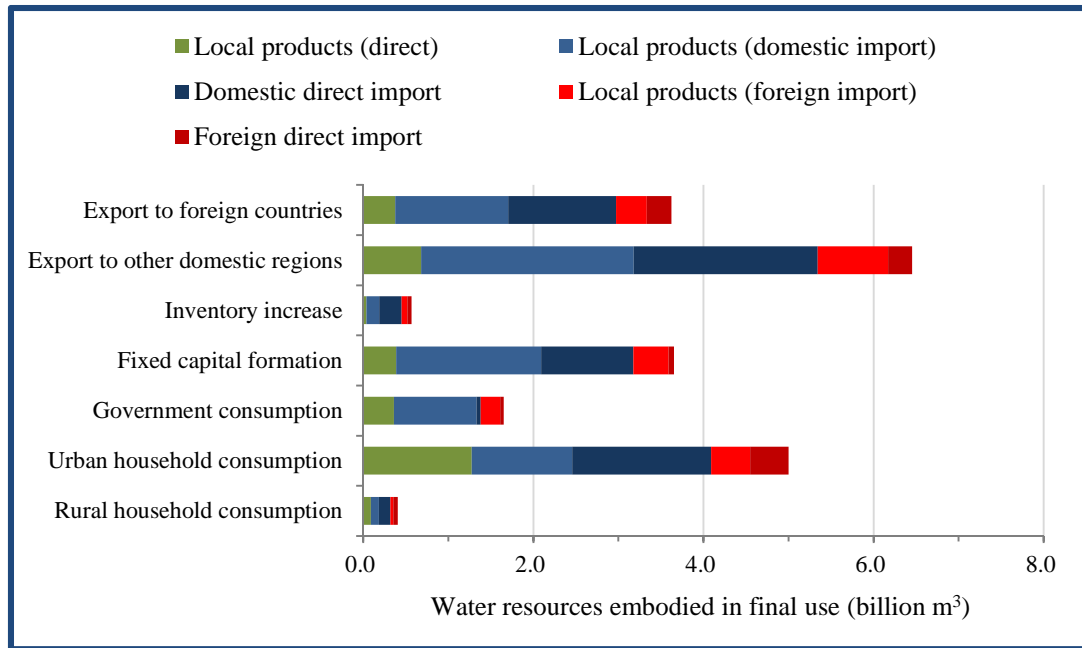308 imported water resources through imported intermediate inputs)

309

310 According to the results, less than 1/5 of the total water resources that are embodied

311 in Beijing's local final demand have been met by direct local water withdrawal

312 (DWW^L). Concerning domestic imported water (DIW^L), in addition to the 3.17 billion

313 m^3 of ostensible embodied water that is supplied by direct domestic import (DIW_d^L),

314 another 4.10 billion m^3 of water resources have also been supplied through

315 intermediate industrial processes (DIW_i^L). The invisible or indirect embodied water of

316 local products that originated from domestic import is even larger than the obvious or

317 direct embodied water. Together, they supply more than approximately 3/5 of the total

318 embodied water of Beijing's local final consumption. The situation for foreign

319 imported water that is embodied in local final consumption is similar (FIW^L); the

320 ostensible (FIW_d^L) and unapparent embodied water resources (FIW_i^L) are 0.65 billion

321 m^3 and 1.20 billion m^3, accounting for approximately 16% of the total embodied

322 water of local final consumption.

323 Beijing's local final demand includes rural household consumption, urban

324 household consumption, government consumption, fixed capital formation, and

325 inventory increase. In addition, local products have also been exported to other

326 Chinese regions and foreign countries, and together, they form the final use of local

327 products (see Figure 4). The water resources that are embodied in urban household

328 consumption are approximately 12 times higher than the water resources of rural

329 household consumption. The ratio of the urban population to rural population is only

330 approximately 5.45, which reveals the significant gap between the standards of

331 resource use of urban and rural people.

332   Like local final consumption, the water resources that are embodied in total

333 domestic and foreign exports each constitute five components. Except for the

334 embodied water that is directly supplied by direct local water withdrawal (DWW^D

335 and DWW^F) and domestic (DIW_d^D and DIW_d^F) and foreign imported products (FIW_d^D

336 and FIW_d^F), a significant portion of the domestic and foreign exports' embodied water

337 that is supplied by local products also originates from domestic (DIW_i^D and DIW_i^F)

338 and foreign imported intermediate inputs (FIW_i^D and FIW_i^F). Local freshwater

339 withdrawal and domestic and foreign imports' embodied water account for 10.56%,

340 72.26%, and 17.18% of the total domestic export water. With respect to foreign

341 export water, the ratios are essentially the same. Nearly half (47%) of the 21.35

342 billion m^3 of virtual water resources related to Beijing (direct water withdrawal plus

343 domestic imported water plus domestic imported water, DWW+DIW+FIW) has been

344 re-exported or re-located to external economies.

345

18

Figure 4. Water resources embodied in the final use of the Beijing economy in 2007

3.3 Embodied water trade balance of the Beijing economy

Beijing has 14.53 billion m^3 of domestic imported water from other Chinese

regions, which is approximately 2.25 times greater than domestic exported embodied

water. Regarding foreign trade, foreign exported embodied water is slightly higher

(0.18%) than foreign imported embodied water. Domestic imported water is also 4

times greater than foreign imported water. Concerning domestic and foreign exported

water, the ratio is only approximately 1.78. Overall, total water resources embodied in

domestic trade is 2.90 times greater than the total water resources of foreign trade.

Figure 5 shows the water balance of each industry in the Beijing economy in 2007.

Overall, the primary industry and most secondary industries are embodied water net

importers, and most tertiary industries are embodied water net exporters. Sector 1

(Agriculture, Forestry, Animal Husbandry and Fishery) involves the largest embodied

water trade and is also the largest embodied water importer. It may because

362 agriculture is a water-intensive industry, and its embodied water intensity is the

363 second largest after the water industry. This result also indicates that Beijing, as a

364 megacity, is highly dependent on imported agricultural products.

365   Sector 19 (Manufacture of Communication Equipment, Computer and Other

366 Electronic Equipment) is the second largest embodied water trader and also exports

367 the most embodied water among all industries. Unlike the agriculture industry, Sector

368 19's embodied water import and export are both very large, although the former is

369 approximately 20% larger than the latter. The industry involves many high-tech

370 products, whose trade deals have led to the massive embodied water flows.

371
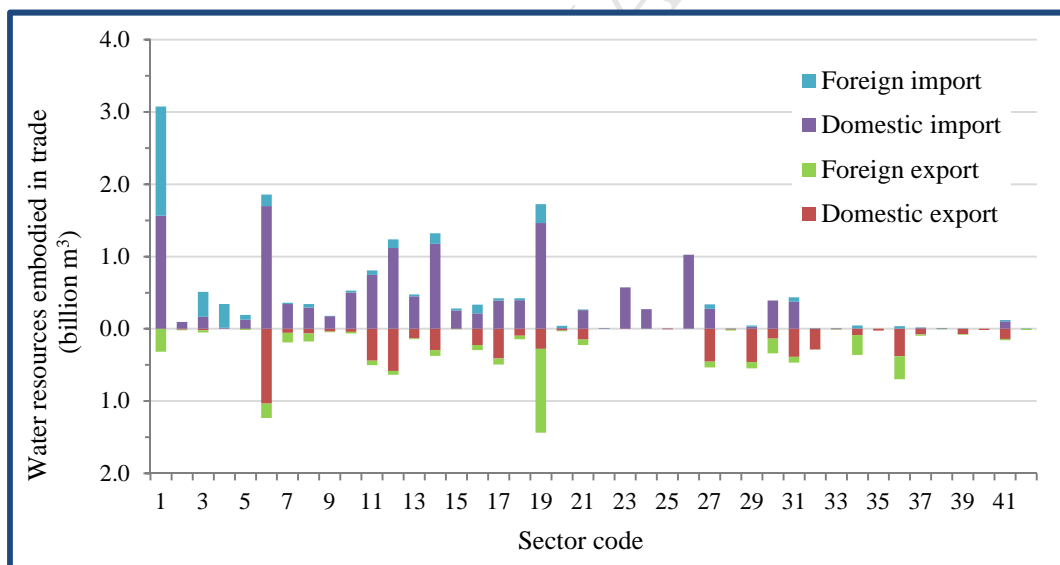
373 Figure 5. The water trade balance of the Beijing economy in 2007

374

375   Sector 6 (Manufacture of Foods and Tobacco) ranks third and is also the second

376 largest embodied water importer and exporter after Sectors 1 and 19, respectively. For

377 most industries, the water that is embodied in domestic trade is greater than the water

378   that is embodied in foreign trade. Because there are typically more barriers in

379   international trade than in domestic trade, this result is reasonable. However, Sector

380   19 is the opposite. This contrast may be because the production advantage of sector

381   19 is sufficiently distinct to offset tariffs and the different preferences of domestic and

382   foreign customers.

383

384   **4. Discussion**

385   **4.1 Comparing this study to other related studies**

386   According to different measures to estimate the virtual water resources that are

387   embodied in imports, there are four IOA methods that can be applied to analyze the

388   consumption-based water resources use of an economy:

389   (1) SRIO (Single Regional Input-Output Analysis)

390   The water resources that are embodied in imports are ignored. Only the local water

391   resources are concerned.

392   (2) SRIO-r (Single Regional Input-Output Analysis-revised)

393   The water intensities for imports are assumed equal to that of local products. The

394   water resources use that is avoided by imports (WAI) rather than that is embodied in

395   imports is calculated.

396   (3) MRIO (Multi-Region Input-Output Analysis)

397   The same products from different countries are treated as completely different

398   types of products. The water resources that are embodied in imported products for

399   meeting local final demand are calculated.

400   (4) MSIO (Multi-Scale Input-Output Analysis)

401   The output-averaged embodied water intensity databases for the external

402   economies are applied to estimate the water resources that are embodied in imports.

403   In order to illustrate the differences between these IOA methods, they have been

404   applied separately to analyze the consumption-based water resources of the Beijing

405   economy in 2007. The results are compared in Table 2 (since a complete MRIO

406   analysis needs massive data to perform, here this paper only compares the results of

407   the former three methods; the differences between MSIO and MRIO are discussed

408   later in theory).

409   Table 2

410   Water resources accounting results based on different IOA methods

IOA method	Embodied water intensity (m^3/1E+04 Yuan)	Water resources embodied in local final demand (billion m^3)	Water resources embodied in total final use (billion m^3)	Water resources embodied in domestic imports (billion m^3)	Water resources embodied in foreign imports (billion m^3)
SRIO	21.39	2.15	3.21	-	-
SRIO-r	21.39	2.15	3.21	1.06 (WAI)	2.26 (WAI)
MSIO	91.97	11.28	21.35	14.53	3.62

411

412   It can be seen that in general the results of SRIO and SRIO-r are much lower than

413   that of MSIO. It is because the SRIO and the SRIO-r have ignored and

414   underestimated the water resources that are embodied in imports. As indicated in Eq.

415   (5) and the related descriptions in Section 2.1, the embodied water intensity of Beijing

416   local products consists of local (with direct water withdrawal), domestic (with

417   domestic imported intermediate input), and global (with foreign imported

418   intermediate input) embodied water intensities (see SI, Section S2 and Figure S1).

419   The intensities obtained from SRIO and SRIO-r are equal, which is indeed the local

420   embodied water intensity of MSIO. Therefore the results of SRIO and SRIO-r are

421   only part of the results of MSIO, and the MSIO can provide us with additional

422   information on imported water resources that is embodied in local products.

423   Although in theory the MRIO is more accurate than the MSIO with respect to

424   regional resolution, the size of their basis data differs by orders of magnitude. For

425   example, in this study, on the basis of the existing world and Chinese embodied water

426   intensity datasets (which are typically drawn from previous MRIO analysis), 6,174

427   embodied water flows have been analyzed to obtain the final results. However, an

428   MRIO analysis that connects all Chinese provinces to all countries may involve over

429   70 million economic flows (assuming that each Chinese region has 30 sectors and 5

430   types of final demand and each country has 57 sectors and 3 types of final demand).

431   Nearly half of the data required, i.e., economic trade flows between Chinese region

432   and foreign countries, cannot be found in the existing databases or studies, and many

433   assumptions must be made.

434   Since the MSIO can distinguish between the different embodied water resources of

435   imported products and local products, it was proved to be superior to the SRIO.

436   However, MSIO is not a perfect method. And the present study also involves a few

437   uncertainties. For example, the aggregation error in connecting 26 sectors-based Eora

438   intensity database to 42 sectors-based Beijing input-output data. When the MRIO data

439   are not available or reliable, the MSIO can be served as a compromised but efficient

440 way to address consumption-based environmental issues. The advantage of MSIO

441 will be even more prominent when it needs to conduct an embodied water analysis for

442 a sub- national or even a small economy. The obtained embodied water intensity

443 database would be very useful for water footprint analysis of an engineering system,

444 e.g., a wastewater treatment plant, a building, too (Meng et al., 2014; Shao and Chen,

445 2013, 2016).

446   Some previous studies have analyzed the carbon emissions and embodied water of

447 the Beijing economy by MSIO (Chen et al., 2013; Guo et al., 2012; Han et al., 2015).

448 However, these studies have certain limitations. First, China's economy was not

449 excluded from the averaged database of the world economy. Second, the database for

450 the Chinese economy that was applied was derived from a single-region analysis that

451 did not distinguish between import products and local products. These limitations

452 created deviations in the final results.

453 **4.2 Virtual water strategy of the Beijing economy**

454   Beijing and other northern Chinese regions have long suffered from water shortage.

455 Given that the southern regions have more than enough water resources, the Chinese

456 government launched the nationwide "South-to-North Water Transfer Project"

457 (SNWTP) in 2002 after over fifty years of discussion and planning (Li, 2016). The

458 middle route of the SNWTP officially began operations in December 2014 after

459 twelve years of construction (Li, 2016). Approximately 1.9 billion m^3 of freshwater

460 has been distributed to Beijing during the past two year, which has alleviated the local

461 water shortage and groundwater overdraft (Li, 2016). Over 70% of Beijing's tap water

462   is currently from the SNWTP (Li, 2016), and a rise in the groundwater level has been

463   observed for the first time in 16 years (STD, 2015).

464   According to the results, in 2007, Beijing domestically and internationally imported

465   14.53 and 3.62 billion m^3 of embodied or virtual water. The net import is

466   approximately 8 billion m^3 of virtual water (all from domestic imports). It can be seen

467   that virtual water transfer plays a more important role than physical water transfer in

468   easing Beijing's water shortage. This conclusion is consistent with that of Zhao et al.

469   (Zhao et al., 2015). Improving local water use efficiency can be considered the most

470   fundamental and sustainable measure to reduce direct water withdrawal of Beijing.

471   Since Beijing relies heavily on domestic imported water resources and the Chinese

472   average embodied water intensity is much higher that the Beijing average and the

473   global average, Beijing would also benefit a lot from the improvement of water use

474   efficiency on the domestic level. Beijing can invest in or spread water-saving

475   technology in other Chinese regions to reduce the Chinese average embodied water

476   intensity.

477   The concept of virtual water was first proposed by Allan in 1998 and has been

478   considered essential to a strategic solution for water-scarce regions (Allan, 1998).

479   Because all products (mainly agricultural products in early research) consume water

480   resources during production in the form of virtual water or embodied water, the

481   water-scarce problem can be settled through the commercial trade of water-intensive

482   products. Since the cost of physical transport of water resources is very high, virtual

483   water strategy can be considered as an alternative and better way to alleviate Beijing's

484 water shortage problem. The MSIO-based results can be very helpful in the design of

485 water saving strategies for multiple responsible entities holding different opinions.

486 Concerning reducing Beijing's local water resource withdrawal only, Beijing should

487 enlarge its imports of Sector 1 (agricultural products), 6 (foods and tobacco), 4 (metal

488 ores), and 7 (textile products). It is because these products have the largest local

489 embodied water intensities, and they can be easily substituted by imported like

490 products.

491   However, for the entirely different matter of global water saving, the production of

492 high-intensity products should be allocated to economies with high water production

493 efficiency or low water intensity. Whether Beijing should import or where it should

494 import from should also depend on water use efficiency. Since the average water use

495 efficiency of the Beijing economy is much higher than that of the Chinese economy

496 but somewhat lower that of the rest of the world, Beijing should enlarge its

497 international imports and reduce its domestic imports.

498

499 **5. Conclusions**

500   Virtual water accounting has been a research hotspot in water resource

501 management field. This work contributed a multi-scale input-output (MSIO) analysis

502 method to account the consumption-based water resources of an economy. It can

503 distinguish the different virtual water contents of imported products and local

504 products. Compared with the single region input-output analysis (SRIO) method, the

505   MSIO can improve the accounting accuracy. Meanwhile, it requires much less data

506   than a complete MRIO analysis does.

507   The framework and algorithm of the MSIO method for water resources accounting

508   of an economy were presented in detail in Section 2.1. In order to illustrate the MSIO

509   method, a three-scale embodied water input-output analysis of the Beijing economy in

510   2007 was performed as a case study. On the basis of an Eora global MRIO analysis,

511   the output-weighting averaged embodied water resources intensity database for the 26

512   sectors in the other 185 nations (excluding China) of the world economy was applied

513   to estimate the water resources embodied in the foreign imports of Beijing.

514   Meanwhile, the database for the Chinese economy as a part of the MRIO analysis

515   results was applied to estimate the embodied water resources of Beijing's domestic

516   imports.

517   The consumption-based water resources consumption of Beijing was estimated as

518   11.28 billion m^3, which was 3.51 times higher than the production-based water

519   resources withdrawal in 2007 (3.21 billion m^3). It is revealed that the average water

520   use efficiency of the Beijing economy (109 Yuan/m^3) is much higher than that of the

521   Chinese economy (42 Yuan/m^3) but somewhat lower that of the rest of the world (139

522   Yuan/m^3). Among the total amount of 21.35 billion m^3 water resources that were

523   related to Beijing, 15% were from direct water withdrawal, 68% were from

524   domestically imported virtual water resources, and 17% were from international

525   imported virtual water resources. Over 1/2 of these water resources have been

526 embodied in Beijing's local final demand, only 30% have been exported to other

527 regions in China, and 17% have been exported to other countries.

528 In 2007, Beijing imported 14.53 billion m^3 water resources from other Chinese

529 regions, which was approximately 2.25 times greater than domestic exported

530 embodied water (6.45 billion m^3). Meanwhile, the foreign imported embodied water

531 (3.62 billion m^3) was more or less the same as foreign exported embodied water (3.62

532 billion m^3). It is revealed that the primary industry and most secondary industries

533 were embodied water net importers, and most tertiary industries were embodied water

534 net exporters.

535 The differences between different IOA methods are discussed in the last section.

536 According to the results of this paper, the net virtual water import of Beijing was

537 approximately 8 billion m^3 (all from domestic imports) in 2007. It is much larger than

538 the physical water transfer of Beijing during 2015-2016 (approximately 1.9 billion m^3)

539 from the nationwide "South-to-North Water Transfer Project". The virtual water

540 transfer is revealed to play an important role in easing Beijing's water shortage.

541 According to the results, in order to save local water resources withdrawal, Beijing

542 should enlarge its imports of Sector 1 (agricultural products), 6 (foods and tobacco), 4

543 (metal ores), and 7 (textile products). On the other hand, in order to improve the water

544 use efficiency worldwide and maximize water conservation, Beijing should enlarge its

545 international imports and reduce its domestic imports.

546

554

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656

- A multi-scale input-output analysis method (MSIO) has been contributed.

- The MSIO can greatly minimizes the data requirements compared to the MRIO method.

- Water resources embodied in final demand and trade of Beijing have been analyzed.

- Averaged embodied water databases for the world and Chinese economies were applied.

- More than 3/5 of local final demand's embodied water were domestically imported.