

Decomposition analysis of water footprint changes in a water-limited river basin: A case study of the Haihe River Basin, China

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Abstract

Decomposition analysis of water footprint (WF) changes, or assessing the changes in WF and identifying the contributions of factors leading to the changes, is important to water resource management. Instead of focusing on WF from the perspective of administrative region, we built a framework in which the input-output (IO) model, the Structural Decomposition Analysis (SDA) model and the Generating Regional IO Tables (GRIT) method are combined to implement decomposition analysis for WF in a river basin. This framework is illustrated in the WF in Haihe River Basin (HRB) during 2002 to 2007, which is a typical water-limited river basin. It shows that the total WF in the HRB increased from $4.3 \times 10^{10} \text{ m}^3$ in 2002 to $5.6 \times 10^{10} \text{ m}^3$ in 2007, and the agriculture sector makes the dominant contribution to the increase. Both the WF of domestic products (internal) and the WF of imported products (external) increased, and the proportion of external WF rose from 29.1% to 34.4%. The technological effect was the dominant contributor to offsetting the increase of WF. However, the growth of WF caused by the economic structural effect and the scale effect was greater, so the total WF increased. This study provides insights about water challenges in the HRB and proposes possible strategies for the future, and serves as a reference for WF management and policy making in other

1 water-limited river basins.

2

3 **1 Introduction**

4 A water footprint (WF) concept quantifies water resource consumption of human
5 beings (Yang and Zehnder, 2007). The WF of a region is the volume of fresh
6 water consumed during the production of goods and services consumed by the
7 inhabitants in that region (Hoekstra et al., 2011; Hoekstra, 2013) and is a useful
8 guide for virtual water (VW) trade and water management (Allan, 1998, 1999;
9 Zhao et al., 2005; Hoekstra and Chapagain, 2007; Wheida and Verhoeven, 2007;
10 Verma et al., 2009; Hoekstra et al., 2011; Mekonnen and Hoekstra, 2012; Zeng
11 et al., 2012; Wang et al., 2013). Furthermore, the WF of a product or service is
12 mathematically equal to its VW content, which means the water resources
13 consumed in its production process (Allan, 1998; Hoekstra and Hung, 2002,
14 2005; Zhao and Samson, 2012; Chen and Chen, 2013; Vanham et al., 2013). The WF
15 of an economic sector identifies total water resource consumption in the
16 production process (Hoekstra and Chapagain, 2007).

17 It is important to assess yearly changes in the WF of a region, identify the key
18 economic sectors and factors leading to the changes, and quantitatively evaluate the
19 contributions of those sectors and factors to the changes so that policy-makers and
20 management can take water-saving actions for the economic sector or factor with the
21 largest contribution; this is called the decomposition analysis of WF changes
22 (Hoekstra et al., 2011; Zhang et al., 2012).

23 The decomposition analysis of WF changes contains two key parts. First, the
24 intersectoral connections and the material-product networks among different
25 economic sectors should be analyzed (Leontief, 1941). For example, if sector A uses
26 intermediate products of sector B as its raw material, then the water used by sector B
27 to produce these intermediate product should be considered the indirect WF of sector
28 A (Leontief, 1941). Leontief (1941) found that the input-output (IO) model

1 could represent the monetary trade of intermediate products between different
2 sectors in an economic system. A series of studies have since implemented the
3 IO model in regional WF accounting and proved that the IO model can identify the
4 direct and indirect WF contained in the final products of each sector (Chen, 2000;
5 Dietzenbacher and Velázquez, 2007; Lenzen, 2009; Zhao et al., 2009, 2010;
6 Zhang et al., 2011a, 2011b; Wang et al., 2013). Second, it is necessary to assess
7 quantitatively the yearly changes in WF and the contributions of key factors
8 (Hoekstra and van den Bergh, 2003; Kondo, 2005; Zhang et al., 2012).

9 On the basis of the IO model, the Structural Decomposition Analysis (SDA)
10 model has been developed to analyze quantitatively the contribution of each
11 factor to the total change (Hoekstra and van den Bergh, 2003; Guo, 2010). The IO
12 model and the SDA model are widely used in decomposition analysis of WF changes:
13 several previous studies have proved that these methods can decompose the WF
14 changes and quantitatively show the contribution of each sector and factor
15 (Kondo, 2005; Zhang et al., 2012).

16 Previous studies only focused on decomposition analysis of WF changes from the
17 perspective of administrative regions, however, river basins are more important to
18 water resource management. A river basin is a natural geographic unit and an
19 important carrier of human activities with a relatively complete eco-hydrological
20 pattern (Haihe River Water Conservancy Commission, 2008; Zhao et al., 2010; Mao
21 and Yang, 2012). Studying water resources at the scale of a river basin could better
22 reflect the water resources situation, and managing water resources from the
23 perspective of a river basin is more reasonable (Chen et al., 2005; Schendel et al.,
24 2007; Verma et al., 2009; Zhao et al., 2010; Feng et al., 2012). Decomposition
25 analysis of WF changes from the perspective of a river basin is important to water
26 resource management and policy making, especially in a water-limited river basin.

27 The lack of homologous IO data is a barrier to implementing decomposition analysis
28 of WF changes from the perspective of a river basin. Decomposition analysis is based
29 on the IO model, which requires an IO table (Hoekstra and van den Bergh, 2002;

1 Zhao et al., 2010; Zhang et al., 2012); but the IO table for a river basin is usually
2 unavailable because official statistics are provided based on administrative unit.
3 Moreover, the IO data for a river basin cannot be obtained by simply adding the data
4 for administrative regions together because there are economic exchanges between
5 regions, which could be identified difficultly and may lead to double counting.

6 This study bridges the gap in quantitative knowledge and implements the
7 decomposition analysis of WF changes from the perspective of a river basin. A
8 Generating Regional IO Tables (GRIT) method is introduced to compute the IO
9 data for a river basin from the administrative units located in that basin. A branch of
10 the SDA model called the weighted average decomposition (WAD) method is
11 used in this analysis because it is more accurate than other kinds of SDA
12 models (Dietzenbacher and Los, 1998; Li, 2004; Kondo, 2005; Zhang et al., 2012).
13 To test its effectiveness, this GRIT-IO-WAD framework is illustrated with the
14 example of the Haihe River Basin (HRB), which is a water-limited river basin in
15 north China. The computation is made for the period 2002 to 2007, when the
16 HRB experienced rapid industrial transformation and economic growth and the
17 official data in this period is the latest available. This study analyzes WF
18 changes in the HRB, and serves as a reference for water resource management
19 and policy-making in this and other water-limited river basins.

20

21 **2 Methodology and material**

22 **2.1 Study area**

23 The HRB is a political, economic and cultural center of China. It is a typical
24 water-limited river basin (see Fig. 1). Beijing, Tianjin and 25 other large and
25 medium-sized cities lie in this basin. The HRB is an important industrial and
26 high-tech base, and also one of the largest agricultural production bases (Haihe River
27 Water Conservancy Commission, 2011). However, the HRB is one of the most

1 water-scarce regions in China and holds nearly 10% of the total population of the
2 country. The region has been transferring water from external regions through various
3 water diversion projects. The South-North Water Transfer Project (the first phase)
4 transfers nearly 7.0×10^9 m³ of water yearly from the Changjiang River Basin to HRB;
5 even with this large scale water transfer, there is still a yearly gap of about 6.7×10^9 m³
6 of water necessary for agriculture, industry, domestic, and environmental uses in the
7 basin (Haihe River Water Conservancy Commission, 2011). Therefore, the study of
8 WF and decomposition analysis of WF changes in the HRB is a particularly
9 meaningful example to guide water resource management in water-limited water
10 basins.

11 **2.2 GRIT-IO-WAD framework for WF**

12 **2.2.1 Computing the IO data by GRIT method**

13 The GRIT method, developed by Jensen et al. (1979), assesses the IO table for a
14 region according to the IO tables of its sub-regions. Using the GRIT method, the IO
15 table for a river basin can be obtained from the IO tables of the administrative units
16 located in the basin (Jensen et al., 1979; Zhao et al., 2010; Feng et al., 2012); thus
17 the IO model and the WAD model could be used to quantify the WF from a river
18 basin perspective.

19 To analyze the WF in the HRB in 2002 and 2007 by the IO method, the IO
20 data for 2002 and 2007 on the river basin scale are necessary. Because official
21 statistics are only provided based on administrative unit, in this study, the IO data
22 from 2002 and 2007 are derived from the official IO tables of Beijing, Tianjin, and
23 Hebei using the GRIT method. The GRIT method assumes the proportion of
24 intermediate products of economic sectors in a river basin is similar to that at the
25 national level, and the proportion of the economic contributions of each
26 administrative unit in the river basin equals the proportion of their land in the scope of
27 the river basin (Jensen et al., 1979; Zhao et al., 2010; Feng et al., 2012). Even with

1 these assumptions, the model has enough accuracy to be treated as a reflection of the
 2 real world (Jensen et al., 1979; Zhao et al., 2010; Feng et al., 2012). We use a series
 3 of mechanical steps to modify the national and administrative IO data to their
 4 equivalents in the HRB as follows:

5 First, the total output of each sector in the HRB is calculated:

$$6 \quad \mathbf{TO} = [p_i] = [\eta^B p_i^B + \eta^T p_i^T + \eta^H p_i^H] \quad (1)$$

7 where \mathbf{TO} (RMB) is the vector of monetary total output in the HRB ($n \times 1$
 8 dimensional vector. n is the number of sectors), whose element, p_i , (RMB) is the
 9 output of sector i in the HRB; η^B , η^T , and η^H are the proportion of the land of
 10 Beijing, Tianjin, and Hebei in the scope of the HRB, which equates to 100% in this
 11 study. p_i^B , p_i^T , and p_i^H are the total outputs of sector i for Beijing, Tianjin, and
 12 Hebei, respectively.

13 Second, the matrix of intersectoral transactions of each sector in the HRB is
 14 calculated:

$$15 \quad \mathbf{A} = [a_{ij}] = [a_{ij}^N \times L_{ij}] \quad (2)$$

$$16 \quad b_{ij} = a_{ij}^N \times (1 - L_{ij}) \quad (3)$$

$$17 \quad L_{ij} = \frac{p_i / \sum_i p_i}{p_i^N / \sum_i p_i^N} \quad (4)$$

18 where \mathbf{A} is the direct consumption coefficient matrix ($n \times n$ dimensional matrix) in
 19 the IO table, whose element, a_{ij} , is the direct consumption coefficient; which means
 20 the monetary volume of products of sector i consumed by sector j when sector j
 21 produces one unit product. a_{ij}^N is the input coefficient in the national IO table. b_{ij} is
 22 the import coefficient, which means the monetary volume of products imported from
 23 sector i outside of the HRB when sector j in the HRB is producing one unit product.
 24 L_{ij} is the location quotient of sector i , which reflects the difference between its

1 importance in the regional and national economic systems (Jensen et al., 1979; Zhao
 2 et al., 2010). p_i is the output of sector i in the HRB, while p_i^N is the national
 3 output of sector i .

4 Finally, the total consumption of each sector in the HRB could be assessed using Eqs
 5 (5) to (8), and all the IO data needed by the IO model is obtained:

$$6 \quad \mathbf{FIN} = [f_i] = \left[p_i + \delta \times q_i^N + \sum_j b_{ij} \times p_j - \sum_j a_{ij} \times p_j \right] \quad (5)$$

$$7 \quad \delta = \frac{\sum_i p_i}{\sum_i p_i^N} \quad (6)$$

$$8 \quad \mathbf{g} = [g_i] = [f_i \times \lambda_i] \quad (7)$$

$$9 \quad \mathbf{h} = [h_i] = [f_i \times \mu_i] \quad (8)$$

10 where \mathbf{FIN} (RMB) is the vector of final consumption volume ($n \times 1$ dimensional
 11 vector), whose element, f_i (RMB), is the final consumption volume of sector i ; q_i^N is
 12 the national import volume of sector i ; and δ is the proportion of total output in the
 13 HRB to national output. \mathbf{g} (RMB) is the vector of internal consumption volume,
 14 which is the products produced and consumed in the HRB ($n \times 1$ dimensional vector),
 15 whose element, g_i (RMB), is the internal consumption volume of sector i ; λ_i is the
 16 proportion of internal consumption in final consumption from the national IO table. \mathbf{h}
 17 (RMB) is the vector of import volume, which is the products produced in other
 18 regions and finally consumed in the HRB ($n \times 1$ dimensional vector), whose element, h_i ,
 19 (RMB) is the import volume of sector i ; and μ_i is the proportion of import volume in
 20 final consumption from the national IO table.

21 **2.2.2 WF calculation based on the IO model**

22 The IO model represents the monetary trade of products and services among
 23 different industries of an economic system (Leontief, 1941). The calculation

1 of the WF for each sector follows the procedure used by Chen (2000), Kanada
2 (2001), Zhao et al. (2009) and Zhang et al. (2011a).

3 To calculate WF, it is necessary to compute the water use coefficient of
4 different sectors, which is defined as the water needed for producing one
5 monetary unit (RMB) in a region. The equation to compute the water use
6 coefficient vector is as follows:

$$7 \quad \mathbf{DWC} = [w_i/m_i] \quad (9)$$

8 where \mathbf{DWC} ($\text{m}^3\text{RMB}^{-1}$) is the direct water coefficient vector ($n \times 1$ dimensional
9 vector), which is the amount of direct water intake to produce one monetary unit of
10 production. w_i is the direct water consumption of sector i (m^3).

11 The total WF consists of internal and external WFs (Hoekstra and Chapagain,
12 2007). The internal WF (IWF) is the domestic water resources used to produce
13 goods and services consumed in the studied region. The external WF (EWF) is
14 the VW contained in imported goods and services. To compute the IWF and
15 EWF in the studied region, we have:

$$16 \quad \mathbf{IWF} = \mathbf{t}[\mathbf{I}-\mathbf{A}]^{-1}\mathbf{g} \quad (10)$$

$$17 \quad \mathbf{EWF} = \mathbf{t}[\mathbf{I}-\mathbf{A}]^{-1}\mathbf{h} \quad (11)$$

18 where \mathbf{IWF} is the vector of IWF ($n \times 1$ dimensional vector), and \mathbf{EWF} is the vector of
19 EWF ($n \times 1$ dimensional vector). \mathbf{t} indicates the diagonal matrix of \mathbf{DWC} ($n \times n$
20 dimensional matrix). \mathbf{I} is a unit diagonal matrix ($n \times n$ dimensional matrix) and
21 $[\mathbf{I}-\mathbf{A}]^{-1}$ is the Leontief inverse matrix.

22 **2.2.3 Factor decomposition analysis for WF changes**

23 The contribution factors of the WF changes in the HRB from 2002 to 2007 are
24 resolved into technological, economic structural, and scale effects. The technological
25 effect shows the influence of changes in direct water use efficiency, which represents
26 the effect of technological change on water consumption for one monetary unit of

1 output. Normally, technology improvements reduce the water footprint of a product
 2 (Hubacek and Sun, 2005). The economic structural effect is the change in the supply
 3 and demand relationship between different sectors in the economic system, which is
 4 mathematically reflected by changes in the Leontief inverse matrix. The scale effect
 5 denotes the influence of changes in the total amount of final products (Kanada, 2001;
 6 Kondo, 2005; Zhang et al., 2012).

7 The SDA method is conducted based on start period data and end period data.
 8 In this study, the start period is the year 2002 and the end period is the year
 9 2007. The contributions of the above three factors are determined by the
 10 following equations (Kanada, 2001; Kondo, 2005; Li, 2004).

$$11 \quad \Delta T = T_1 - T_0 = \mathbf{t}_1[\mathbf{I} - \mathbf{A}_1]^{-1} \mathbf{m}_1 - \mathbf{t}_0[\mathbf{I} - \mathbf{A}_0]^{-1} \mathbf{m}_0 = \mathbf{t}_1 \mathbf{B}_1 \mathbf{m}_1 - \mathbf{t}_0 \mathbf{B}_0 \mathbf{m}_0$$

$$12 \quad = E(\Delta \mathbf{t}) + E(\Delta \mathbf{B}) + E(\Delta \mathbf{m}) \quad (12)$$

$$13 \quad E(\Delta \mathbf{t}) = \frac{1}{3} \Delta \mathbf{t} \mathbf{B}_0 \mathbf{m}_0 + \frac{1}{6} \Delta \mathbf{t} \mathbf{B}_1 \mathbf{m}_0 + \frac{1}{6} \Delta \mathbf{t} \mathbf{B}_0 \mathbf{m}_1 + \frac{1}{3} \Delta \mathbf{t} \mathbf{B}_1 \mathbf{m}_1 \quad (13)$$

$$14 \quad E(\Delta \mathbf{B}) = \frac{1}{3} \mathbf{t}_0 \Delta \mathbf{B} \mathbf{m}_0 + \frac{1}{6} \mathbf{t}_1 \Delta \mathbf{B} \mathbf{m}_0 + \frac{1}{6} \mathbf{t}_0 \Delta \mathbf{B} \mathbf{m}_1 + \frac{1}{3} \mathbf{t}_1 \Delta \mathbf{B} \mathbf{m}_1 \quad (14)$$

$$15 \quad E(\Delta \mathbf{m}) = \frac{1}{3} \mathbf{t}_0 \mathbf{B}_0 \Delta \mathbf{m} + \frac{1}{6} \mathbf{t}_1 \mathbf{B}_0 \Delta \mathbf{m} + \frac{1}{6} \mathbf{t}_0 \mathbf{B}_1 \Delta \mathbf{m} + \frac{1}{3} \mathbf{t}_1 \mathbf{B}_1 \Delta \mathbf{m} \quad (15)$$

16 where T_1 (m^3) is the vector of the total WF for the end period, T_0 (m^3) is the
 17 vector of the total WF for the start period, and ΔT is the vector of the difference
 18 between them. \mathbf{t}_1 and \mathbf{t}_0 ($\text{m}^3 \text{RMB}^{-1}$) are the diagonal matrices of the direct water
 19 coefficient vectors during the end and start periods, respectively; $\Delta \mathbf{t}$ is the difference
 20 between \mathbf{t}_1 and \mathbf{t}_0 . \mathbf{A}_1 and \mathbf{A}_0 are the direct consumption coefficient matrices during
 21 the end and start periods, respectively; \mathbf{m}_1 and \mathbf{m}_0 (RMB) are the final demand
 22 vectors during the end and start periods, respectively; and $\Delta \mathbf{m}$ is the difference
 23 between \mathbf{m}_1 and \mathbf{m}_0 . To make the calculation clearer, \mathbf{B}_1 represents $[\mathbf{I} - \mathbf{A}_1]^{-1}$ and \mathbf{B}_0
 24 represents $[\mathbf{I} - \mathbf{A}_0]^{-1}$. $\Delta \mathbf{B}$ is the difference between \mathbf{B}_1 and \mathbf{B}_0 . $E(\Delta \mathbf{t})$ (unit: m^3) is
 25 the contribution of the technological effect; $E(\Delta \mathbf{B})$ (unit: m^3) is the contribution of
 26 the economic structural effect; and $E(\Delta \mathbf{m})$ (unit: m^3) is the contribution of the
 27 scale effect (Kondo, 2005).

1 **2.3 Data**

2 In this study, water consumption is calculated as the fresh water input needed
3 for production in 17 main sectors (see Table 1). For direct water consumption,
4 VW and WF only concern blue water, which means surface water and
5 groundwater. Green water, which contains precipitation and soil moisture, is
6 not considered because many sectors and services exclusively use blue water,
7 except agriculture and the sectors that depend on agricultural raw materials
8 (Renault, 2003; Zhang et al., 2012). Including green water would greatly increase
9 the share of agricultural water use and lead to biased conclusions in estimating
10 the value of water use across different sectors (Zhao et al., 2010). As a result of
11 the lack of information about the situation of pollutants and pollution intensity
12 for each sector, the consumption of gray water, which means water used to
13 dilute wastewater, is ignored as some literatures did (Zhao et al., 2010;
14 Hoekstra et al., 2011; Zhang et al., 2012).

15 The IO data for Beijing, Tianjin, Hebei, and the national data, which contain the 17
16 main sectors (see Table 1), come from the latest available official publication
17 of China (Beijing Statistics Bureau, 2003, 2008; Tianjin Statistics Bureau,
18 2003, 2008; Hebei Statistics Bureau, 2003, 2008; National Bureau of Statistics,
19 2003, 2008). Chinese national and regional statistics bureaus make IO tables
20 each five years, and the latest IO table was published for the year of 2007. The
21 direct and indirect water coefficients are computed based on the data in
22 official bulletins and yearbooks (Haihe River Water Conservancy Commission,
23 2003, 2008; Ministry of Water Resources, 2003, 2008).

24

25 **3 Results**

26 **3.1 Changes in WF**

27 The WFs in the HRB in 2002 and 2007 are shown in Fig. 2, and the corresponding

1 sector names in Fig. 2 can be found in Table 1. The total WF of the HRB surged from
2 $4.3 \times 10^{10} \text{ m}^3$ (70.9% of which is IWF) in 2002 to $5.6 \times 10^{10} \text{ m}^3$ (65.6% of which is IWF)
3 in 2007, increasing about 30%. In fact, the total available water resources (including
4 water transferred from other regions) in the HRB was $4.0 \times 10^{10} \text{ m}^3$ in 2002 and
5 $3.8 \times 10^{10} \text{ m}^3$ in 2007 (Haihe River Water Conservancy Commission, 2003, 2008), and
6 this gap between WF and available water resources conforms to the water resources
7 tension in the HRB. The surge in WF is attributable to soaring agricultural demand
8 ($1.0 \times 10^{10} \text{ m}^3$), and the steady increase of WFs for service-related sectors. In the total
9 WF increase of $1.3 \times 10^{10} \text{ m}^3$ from 2002 to 2007, $6.1 \times 10^9 \text{ m}^3$ was from internal sources
10 and $6.6 \times 10^9 \text{ m}^3$ was from external sources, which correlated with water use volume in
11 previous studies and the official statistics for the HRB (Haihe River Water
12 Conservancy Commission 2003, 2008; Zhao et al. 2010). In 11 sectors (No.1, No.4,
13 No.6 to No.8, and No.12 to No.17), the IWF and EWF both increased (Table 1). In 4
14 sectors (No.2, No.3, No.10, and No. 11), the IWF and EWF both decreased (Table 1),
15 which might be due to the government's limits (Beijing Government, 2010). For the
16 sectors of non-metallic mineral products and wood, paper and others, the IWF
17 decreased while the EWF increased, indicating they began to depend more on external
18 water resources. Agriculture; electricity, heat, and water; chemical industry; and wood,
19 paper and others had the largest total WFs in both 2002 and 2007. These four WFs
20 account for over 80% of the total.

21 As explained above, IWF relates to the use of local water resources in the HRB, and
22 EWF represents the VW in products imported from outside and consumed in the HRB.
23 The two kinds of WFs have different effects on water scarcity in a river basin: the
24 IWF consumes local water resources in the river basin, while the EWF is a
25 supplement to save the local water resource, match the demand of products and
26 relieve the pressure on local water resources (Zhang et al., 2012).

27 From 2002 to 2007, the proportion of EWF in the HRB rose from 29.1% to 34.4%. Of
28 the 13 sectors with incremental total WFs, the increases in EWFs in 7 sectors are
29 much larger than their increases in IWFs. This probably relates to government policy

1 orientation. Since the 2000s, governments in the Haihe River Basin have strengthened
2 restrictions on water use in industries. Many water-intensive factories, especially
3 those with large WFs, were forced to improve their water-use efficiency or move out
4 of the basin. In the meantime, high-tech industries with low water intensity and high
5 added value were strongly encouraged.

6 The agriculture sector experienced the largest expansions in IWF and EWF. As the
7 most water-intensive sector, agriculture is always the core of Chinese strategies with
8 respect to water scarcity. From 2002 to 2007, the agricultural IWF in the HRB grew
9 22.5%, while the EWF grew 79.1%, which shows a shift to greater dependence on
10 external water resources.

11 In most other sectors, the WFs increased slightly. Of the 13 sectors whose WF
12 increased, 10 sectors' EWFs had higher growth rates than their IWF; but, in electricity,
13 heat and water; construction; transportation, postal services, information transmission,
14 computer services, and software; wholesale, retail trade, accommodation, and catering;
15 and real estate and renting, the IWF growth rate was close to that of the EWF growth
16 rate. In the financial sector and in other services, the IWF growth was higher than that
17 of the EWF. This is mainly due to the population explosion and development of
18 tertiary industries. As the Chinese political, economic and cultural center, the HRB
19 has advantages in attracting capital and talent that lead to the expansion of the
20 economy and population. Although electricity, heat and water; construction; and the
21 service sectors (No. 13 to No. 17 in Table 1) have relatively low direct and total water
22 coefficients, the huge demands for energy, housing, and services make very large total
23 WFs. Not only the EWFs but also the IWFs in these sectors increased, because some
24 fresh water must be consumed on site rather than be replaced by external VW.

25 Overall, the WF in the HRB has increased about 30% and begun to depend more on
26 the EWF while the IWF has begun to be controlled. The sectors with high direct water
27 coefficient and large WF have been the major focus of the basin's water resources
28 management (Haihe River Water Conservancy Commission, 2011). Under the
29 government's green development strategy, industrial restructuring will continue to

1 play a significant role in water resources conservation in the HRB in the future
2 (Beijing Government, 2010).

3 **3.2 Factors in WF changes**

4 The contributions of the technological effect $E(\Delta t)$, economic structural effect
5 $E(\Delta B)$, and scale effect $E(\Delta m)$ to changes in WF in the HRB are shown in Table 1.
6 Positive values indicate an increase in WF, while negative values indicate a decrease.

7 The technological effect ($E(\Delta t)$, $-4.2 \times 10^{10} \text{ m}^3$) was the main factor in offsetting the
8 WF increase, which equals -330.0% of the final change in WF (Table 1). $E(\Delta t)$ in all
9 sectors had significant decreases. In terms of volume changes, the $E(\Delta t)$ for
10 agriculture ($-2.1 \times 10^{10} \text{ m}^3$); electricity, heat, and water ($-6.6 \times 10^9 \text{ m}^3$); and
11 metal products ($-3.2 \times 10^9 \text{ m}^3$) decreased most, equaling 49.6% , 15.7% , and
12 7.6% of the total $E(\Delta t)$. $E(\Delta t)$ made different contributions to the changes in
13 WF in different sectors. $E(\Delta t)$ in the sector of wood, paper, and others had the
14 greatest proportional contribution to water conservation (27697.8%), while
15 $E(\Delta t)$ in the sector of wholesale, retail trade, accommodation, and catering had
16 the least proportional contribution (36.3%). For agriculture, irrigation techniques
17 have improved to reduce water losses and increase water use efficiency. Moreover,
18 water-saving agronomic technologies, for instance, deep plowing, water and soil
19 conservation, and planting drought-resistant varieties, have been widely popularized
20 by the government and enterprises (Beijing Government, 2010). For manufacturing
21 industries, a set of water-saving mechanisms has been built, characterized by water
22 recycling, reuse, and control (Haihe River Water Conservancy Commission, 2011).
23 The volume of industrial water use per value added plummeted from 9.8×10^{-5}
24 $\text{m}^3\text{RMB}^{-1}$ to $1.9 \times 10^{-5} \text{ m}^3\text{RMB}^{-1}$ from 2002 to 2007, which is now much less than that
25 in other regions of China (Beijing Government, 2010).

26 The scale effect ($E(\Delta m)$, $4.8 \times 10^{10} \text{ m}^3$) was the main contributor to the WF increase,
27 equaling 380.1% of the final ΔT . $E(\Delta m)$ in all 17 sectors grew; the top three were
28 agriculture ($2.8 \times 10^{10} \text{ m}^3$); electricity, heat, and water ($4.5 \times 10^9 \text{ m}^3$); and the

1 chemical industry ($2.5 \times 10^9 \text{ m}^3$), equaling 57.7%, 9.3%, and 5.1% of the total
2 change in $E(\Delta \mathbf{m})$. $E(\Delta \mathbf{m})$ made different proportional contributions to the WF
3 changes in different sectors. The increases in $E(\Delta \mathbf{m})$ make up more than 100%
4 of the total changes, especially in the sectors of wood, paper, and others
5 (27072.6%); non-metallic mineral products (1007.5%); and textile, clothing,
6 and leather products (935.5%). The increased contribution of $E(\Delta \mathbf{m})$ was mainly
7 related to population growth and drastic demand expansion. From 2002 to 2007, the
8 population of the HRB increased at the rate of 9.2‰ per year, much higher than the
9 national average rate of 4.8‰ per year, and the scale of final demand soared from
10 $2.4 \times 10^{12} \text{ RMByr}^{-1}$ to $6.7 \times 10^{12} \text{ RMByr}^{-1}$ (Beijing Statistics Bureau, 2003, 2008;
11 Tianjin Statistics Bureau, 2003, 2008; Hebei Statistics Bureau, 2003, 2008;
12 National Bureau of Statistics, 2003, 2008), which made the contribution of scale
13 effect to the total WF increase. Because population and living standards keep
14 increasing (National Bureau of Statistics, 2008; Haihe River Water Conservancy
15 Commission, 2011), the scale effect may put more pressure on water resources in the
16 future.

17 The impact of the economic structural effect $E(\Delta \mathbf{B})$ is less than that of the
18 technological effect and scale effect (49.9% of the final change), but the absolute
19 amount of $E(\Delta \mathbf{B})$ is still considerable ($6.4 \times 10^9 \text{ m}^3$). There were increases in the
20 $E(\Delta \mathbf{B})$ in 10 sectors. The top three were agriculture ($3.2 \times 10^9 \text{ m}^3$); electricity,
21 heat, and water ($2.6 \times 10^9 \text{ m}^3$); and the mining industry ($4.3 \times 10^8 \text{ m}^3$), equaling
22 48.8%, 41.4%, and 6.7% of the total change in $E(\Delta \mathbf{B})$. The $E(\Delta \mathbf{B})$ of the other 7
23 sectors declined; the biggest declines were in real estate and renting (-1.6×10^8
24 m^3), the financial sector ($-6.4 \times 10^7 \text{ m}^3$), and food and tobacco ($-6.1 \times 10^7 \text{ m}^3$),
25 equaling -2.6%, -1.0%, and -1.0% of the total change in $E(\Delta \mathbf{B})$. $E(\Delta \mathbf{B})$ made
26 different contributions to the WF changes in different sectors. $E(\Delta \mathbf{B})$ in the
27 sectors of wood, paper, and others (725.2%); electricity, heat, and water
28 (479.9%); and non-metallic mineral products (82.9%) made greater
29 proportional contributions to the WF increase than $E(\Delta \mathbf{B})$ in other sectors; and

1 $E(\Delta\mathbf{B})$ in textile, clothing, and leather products (-96.0%); the financial sector
2 (-73.2%); and real estate and renting (-34.7%) made greater proportional
3 contributions to decreasing their WFs. The economic structural effect, which
4 includes the proportion of sectors, demand pattern change, price leverage, change of
5 intermediate products, and economized material input caused by management
6 improvement, reflects the impact of industrial restructuring (Chen and Yang, 2011).
7 From 2002 to 2007, the proportion of the agriculture WF in the total WF grew slightly
8 from 64.5% to 68.0%, while that of services increased from 6.9% to 10.2%, and that
9 of the manufacturing industry declined from 28.6% to 21.8%. This may relate to the
10 Beijing Olympic Games in 2008, for which the government made a series of industrial
11 restructurings in the HRB. To decrease the WF, industrial restructuring to create more
12 efficient water savings should be undertaken by the government and companies.

13 We do not analyze the above factors' contributions to IWF and EWF
14 independently, because they are equivalent to their contributions to the total
15 WF. This is according to the demand-driven view of VW developed by
16 Renault (2003), who noted that the value of VW imported by a region (i.e.,
17 EWF) is the volume that the region would have consumed if it had to produce
18 the product itself. Therefore, the EWF could be seen as a replacement that
19 saves IWF and should be treated the same as IWF (Renault, 2003); and thus the
20 factors have the same proportion of effects on them.

21

22 **4 Discussion**

23 **4.1 Implications for water management**

24 The changes in the IWF and EWF of the HRB and the decomposition of the
25 contribution of each factor could be useful for evaluating the achievements of past
26 management and policies and for supporting future work on solving the water
27 problems in the HRB.

1 The industrial restructuring promoted by the government has started to change the
2 water use patterns in the HRB. Methods for controlling or lessening the size of high
3 water intensity sectors or relocating them out of the HRB has achieved some
4 remarkable results in sectors such as food and tobacco, textiles, and some service
5 sectors. In the future, industrial restructuring should play a more important role in
6 reducing the pressure on water resources in the HRB or shifting the pressure to the
7 EWF. The agricultural sector remains one of the focal areas. However, shifting to
8 rainfed farming and/or reducing the size of the agricultural sector may have painful
9 repercussions with respect to profits and ecosystems (Zhang et al., 2012). The
10 government should consider protecting the profits of farmers or ensuring proper
11 compensation.

12 The technological effect is the major factor in offsetting the increase in WF and there
13 are still possibilities for further improvement, which deserve more attention of the
14 government and enterprises. The marked contribution of the scale effect to the WF
15 increase is mainly attributable to the expansion of population and per-capita demand,
16 which indicates that basin planners should consider the capacity of water resources in
17 future planning. Importing VW can be a water supplement to mitigate water pressures
18 in the HRB, but controlling the growth of the internal water footprint might be more
19 necessary to sustainability in the long term.

20 The expansion of the EWF shifts the pressure of water demand in the HRB to other
21 regions. However, a detailed investigation of the trade-offs of this shift and the VW
22 situation in other regions should be made to evaluate whether this shift makes new
23 water problems in other regions or basins. For example, the increased agricultural
24 scale in southern China seems to have made less increase in its WF than that in
25 western China, which is likely because the former area has much greater precipitation
26 than the latter. Therefore, the former region may be more suitable for exporting VW
27 contained in agricultural products to the HRB.

1 **4.2 Method improvements in the future**

2 The GRIT method introduced in this study is a highly flexible method of processing
3 IO tables that focuses on describing the IO status in a region accurately at the macro
4 level rather than the micro level (Jensen et al., 1979). It has better applicability and
5 accuracy than other methods, such as the biproportional scaling method (Stone, 1961)
6 and Kuroda's method (1988), when data are lacking. If detailed data on the
7 economic exchanges between administrative regions are available, the accuracy of
8 these other methods will be near to or better than that of GRIT method, and
9 researchers could choose other methods or combine the GRIT method with them to
10 achieve better accuracy.

11 The IO method assumes that imports are produced under the same conditions as
12 domestic products (Leontief, 1941; Zhao et al., 2009). This is in accordance
13 with the demand-driven vision of VW, which notes that the value of VW
14 imported by a region is the volume that the region would have consumed if it
15 had to produce the product itself (Renault, 2003). In fact, different regions
16 usually have different production situations and the water coefficient vectors
17 are different. If it is necessary to get the real WF of imported products, the
18 EWFs should be assessed from the perspective of the producing area, which
19 requires a VW and IO analysis for those areas, or even building a
20 multi-regional VW statistics system to evaluate the WF of the products in
21 regional trade.

22 The GRIT-IO-WAD framework for WF could be implemented in other river basins.
23 Although the computation of this framework for WF is straightforward, it has similar
24 drawbacks to the IO method. The data requirements are enormous because the input
25 and output of each production process and economic activity circulation process have
26 to be accounted for, so the IO table is necessary (Leontief, 1941; Zhao et al., 2010).
27 In this study, because of the lack of more detailed data, we used the available IO data
28 for 2002 and 2007 and aggregated the economic sectors into 17 main sectors; some

1 aggregation errors are inevitable. A separate analysis of different branches (planting,
2 livestock farming, aquaculture, and forestry) in agriculture, which makes up more
3 than half of the total EWF in the HRB, could not be implemented. A detailed analysis
4 of WF changes in agriculture and other sectors might be a target for future studies.

5

6 **5 Conclusions**

7 The input-output (IO) and Structural Decomposition Analysis (SDA) models
8 are often used to assess quantitatively the WF changes between different years and
9 the contributions of key economic sectors and factors leading to those changes, called
10 the decomposition analysis of WF changes. However, conventional studies only focus
11 on WF from the perspective of administrative regions rather than from the perspective
12 of river basins. In this study, to make a decomposition analysis of WF changes at the
13 river basin scale, we used a framework that combines the Generating Regional IO
14 Tables (GRIT) method, IO, and weighted average decomposition (WAD) method
15 of the SDA model. This GRIT-IO-WAD framework is tested with the example
16 of the Haihe River Basin (HRB). Three major factors caused the WF changes,
17 including the technological effect that reflects the contribution of technological
18 changes, the economic structural effect that reflects the contribution of structural
19 relationship changes between sectors, and the scale effect that reflects the contribution
20 of the change in the total amount of final products. The following conclusions are
21 reached:

22 (1) The total WF of the HRB surged from $4.3 \times 10^{10} \text{ m}^3$ in 2002 to 5.6×10^{10} in 2007,
23 increasing about 30%. The agriculture sector made the dominant contribution
24 ($1.0 \times 10^{10} \text{ m}^3$) to the increase of total WF, which is much larger than that of
25 any other sector. The proportion of external WF (the WF of imported products) rose
26 from 29.1% to 34.4%, which shows that the dependence of the HRB on external water
27 resources is increasing.

1 (2) The technological effect was the main contributor to counteracting the rise of WF,
2 and it has the potential to reduce the WF by $4.2 \times 10^{10} \text{ m}^3$. The contribution of the
3 scale effect played a dominant role in the WF increase, which led to an increase of
4 WF of $4.8 \times 10^{10} \text{ m}^3$. The contribution of the economic structural effect to the WF is
5 relatively less, but led to an increase in WF of $6.4 \times 10^9 \text{ m}^3$. Therefore, the government
6 and enterprises should keep developing technologies, adjusting the industrial structure
7 to encourage water-saving methods, and controlling the growth of production.

8

9 **Appendix A: List of abbreviations**

10 EWF: external water footprint

11 GRIT: Generating Regional IO Tables

12 HRB: Haihe River Basin

13 IO: input-output

14 IWF: internal water footprint

15 SDA: Structural Decomposition Analysis

16 VW: virtual water

17 WAD: weighted average decomposition

18 WF: water footprint

19

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25

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Table 1. Contribution of factors to the changes in total WF

Sector	$E(\Delta t)$			$E(\Delta B)$			$E(\Delta m)$			ΔT	
	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRF (%)
1-Agriculture	-20845.4	-204.9	49.6	3100.9	30.5	48.8	27918.2	274.4	57.7	10173.8	79.9
2-Mining industry	-2339.4	923.8	5.6	427.3	-168.8	6.7	1658.8	-655.0	3.4	-253.2	-2.0
3-Food and tobacco	-636.0	421.7	1.5	-61.2	40.6	-1.0	546.4	-362.2	1.1	-150.8	-1.2
4-Textile, clothing, and leather products	-324.8	-739.4	0.8	-42.2	-96.0	-0.7	410.8	935.5	0.8	43.9	0.3
5-Wood, paper and others	-1773.0	-27697.8	4.2	46.4	725.2	0.7	1733.0	27072.6	3.6	6.4	0.1
6-Electricity, heat and water	-6594.1	-1202.8	15.7	2630.9	479.9	41.4	4511.4	822.9	9.3	548.2	4.3
7-Coke, gas and oil processing	-1060.3	-753.4	2.5	49.6	35.2	0.8	1151.5	818.2	2.4	140.7	1.1
8-Chemical industry	-2361.4	-566.4	5.6	289.3	69.4	4.5	2489.1	597.0	5.1	417.0	3.3
9-Non-metallic mineral products	-271.7	-990.4	0.6	22.7	82.9	0.4	276.4	1007.5	0.6	27.4	0.2
10-Metal products	-3173.8	436.2	7.6	192.8	-26.5	3.0	2253.5	-309.7	4.7	-727.5	-5.7
11-Machinery and equipment manufacturing	-819.7	387.5	2.0	6.7	-3.2	0.1	601.4	-284.4	1.2	-211.5	-1.7
12-Construction	-221.4	-41.1	0.5	-27.4	-5.1	-0.4	787.8	146.1	1.6	539.1	4.2
13-Transportation, postal services, information transmission, computer services and software	-660.6	-145.9	1.6	53.3	11.8	0.8	1060.0	234.1	2.2	452.8	3.6
14-Wholesale, retail trade, accommodation and catering	-263.7	-36.3	0.6	-50.3	-6.9	-0.8	1040.4	143.2	2.1	726.5	5.7
15-Real estate and renting	-232.5	-49.1	0.6	-164.4	-34.7	-2.6	870.5	183.8	1.8	473.5	3.7
16-Financial sector	-42.4	-48.0	0.1	-64.7	-73.2	-1.0	195.4	221.2	0.4	88.3	0.7
17-Other services	-402.0	-91.6	1.0	-50.6	-11.5	-0.8	891.3	203.2	1.8	438.7	3.4
Total	-42022.1	-330.0	100.0	6359.1	49.9	100.0	48396.1	380.1	100.0	12733.1	100.0

Note: The Total is the sum for each column. The columns for Volume show the volume (10^6 m^3) of $E(\Delta t)$, $E(\Delta B)$, $E(\Delta m)$, and ΔT in each sector.

Volumes are computed from Eqs. (13), (14), and (15). The columns of CRS (contribution rate to sector) show the proportion of $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, and $E(\Delta\mathbf{m})$ in $\Delta\mathbf{T}$ in each sector. $\text{CRS} = \text{Volume}/(\Delta\mathbf{T}) \times 100\%$. The columns of CRF (contribution rate in factor) show the proportion of each sector's $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, $E(\Delta\mathbf{m})$, and $\Delta\mathbf{T}$ in the total $E(\Delta\mathbf{t})$, total $E(\Delta\mathbf{B})$, total $E(\Delta\mathbf{m})$, and total $\Delta\mathbf{T}$. $\text{CRF} = (\text{Volume}/\text{Total Volume}) \times 100\%$. For example, in the sector of agriculture, the volume of $E(\Delta\mathbf{t})$ is $-2.1 \times 10^{10} \text{ m}^3$; the proportion of this $E(\Delta\mathbf{t})$ in the $\Delta\mathbf{T}$ in agriculture ($1.0 \times 10^{10} \text{ m}^3$) is -204.9% ; the proportion of this $E(\Delta\mathbf{t})$ in the total $E(\Delta\mathbf{t})$ ($-4.2 \times 10^{10} \text{ m}^3$) is 49.6% .

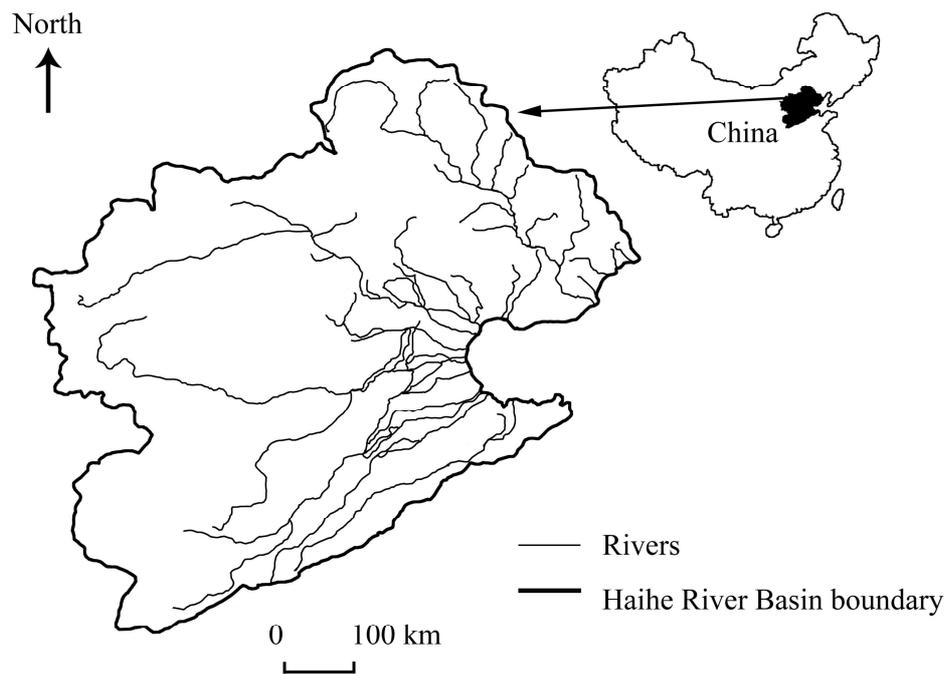
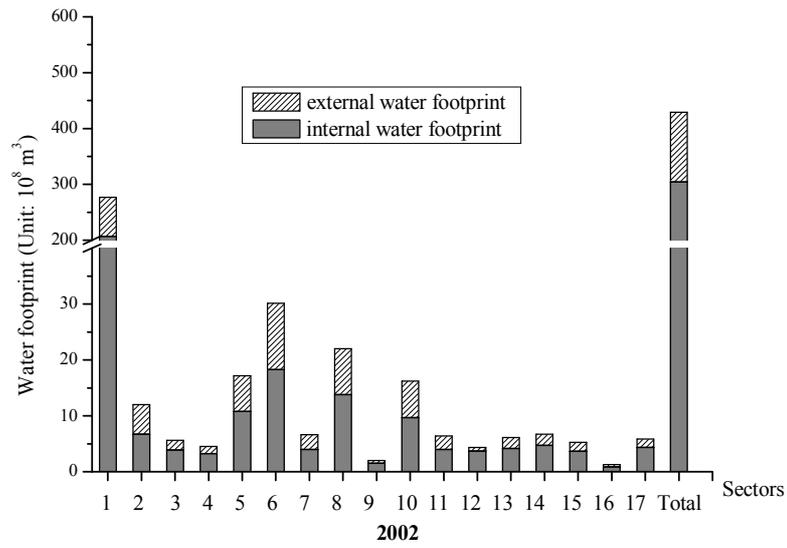
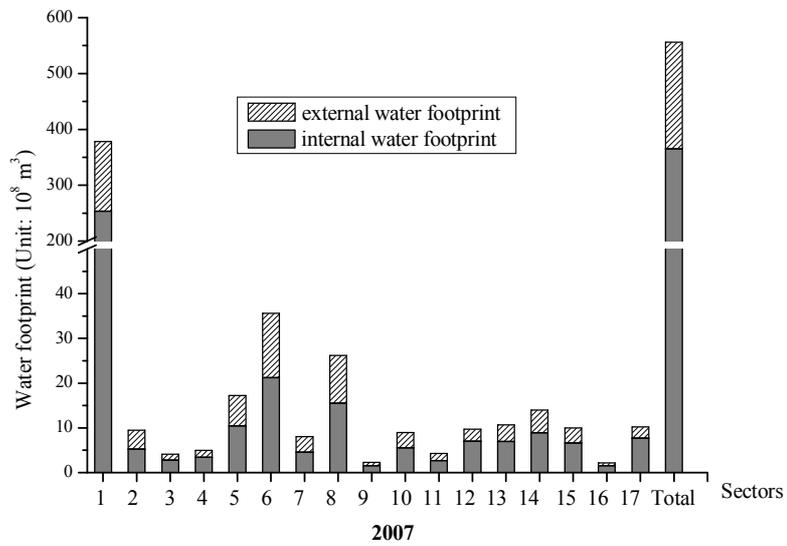


Figure 1. Location of study area (adapted from website of Haihe River Water Conservancy Commission
<http://www.hwcc.gov.cn/pub/hwcc/static/szygb/gongbao2011/>)



(a)



(b)

Figure 2. WFs in the HRB in 2002 (a) and 2007 (b)