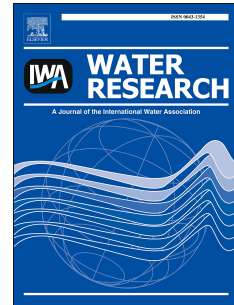


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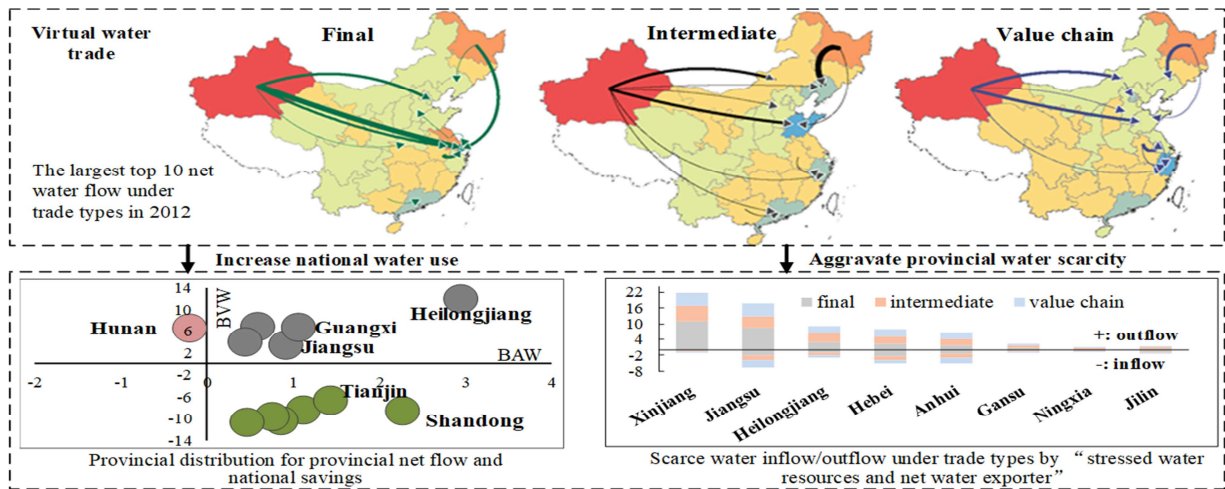
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Graphic abstract

Can virtual water trade save water resources?

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23 **Abstract**

24 At times, certain areas of China suffering from water shortages. While China's
25 government is spurring innovation and infrastructure to help head off such problems,
26 it may be that some water conservation could help as well. It is well-known that water
27 is embodied in traded goods—so called “virtual water trade” (VWT). In China, it
28 seems that many water-poor areas are perversely engaged in VWT. Further, China is
29 engaging in the global trend of fragmentation in production, even as an interregional
30 phenomenon. Perhaps something could be learned about conserving or reducing
31 VWT, if we knew where and how it is practiced. Given some proximate causes,
32 perhaps viable policies could be formulated. To this end, we employ China's
33 multiregional input-output tables straddling two periods to trace the trade of a given
34 region's three types of goods: local final goods, local intermediate goods, and goods
35 that shipped to other regions and countries. We find that goods traded interregionally
36 in China in 2012 embodied 30.4% of all water used nationwide. Nationwide, water
37 use increased substantially over 2007-2012 due to greater shipment volumes of water-
38 intensive products. In fact, as suspected, the rise in value chain-related trade became a
39 major contributing factor. Coastal areas tended to be net receivers of VWT from
40 interior provinces, although reasons differed, e.g. Shanghai received more to fulfill
41 final demand (67.8% of net inflow) and Zhejiang for value-chain related trade (40.2%
42 of net inflow). In sum, the variety of our findings reveals an urgent need to consider
43 trade types and water scarcity when developing water resource allocation and
44 conservation policies.

45 **Keywords:** multiregional input-output analysis; value chain; virtual water trade;

46 national water savings; embodied water

Nomenclature

| | |
|------------------------|---|
| MRIO | multiregional input-output |
| VWT | virtual water trade |
| TF | trade of final goods |
| TI | trade of intermediate goods for the final stage of production |
| TVC | trade in value chain/value chain-related trade |
| BVW | balance of virtual water embodied in trade |
| VW | virtual water embodied in trade |
| WAI | virtual water uses avoided by imports |
| BAW | balance of avoided water uses |
| BVWs | balance of virtual scarce water embodied in trade |
| BAWs | balance of avoided scarce water use |
| \mathbf{T}^{sr} | total outflows from region s to r |
| \mathbf{Y}^{sr} | final demand of region r for products from region s |
| \mathbf{Z}^{sr} | intermediate use of products in region r from region s |
| \mathbf{A}^{sr} | input coefficient matrix for region r 's intermediate use that are produced in region s |
| \mathbf{B}^{sr} | Leontief inverse matrix |
| \mathbf{X}^t | exports to foreign countries from region t |
| \mathbf{T}_d^{sr} | domestic value chain-related trade in region r from region s |
| \mathbf{T}_g^{sr} | global value chain-related trade in region r from region s |
| s, r, t | region s, r, t |
| m^3/yr | m^3/year |

47 **1. Introduction**

48 Due to the nature of watersheds, China's water resources are unevenly
49 distributed; About 66% of water resources are located in South China (Ministry of
50 Water Resources of the People's Republic of China, 2015). It is perhaps no wonder
51 that many parts of China are suffering from severe water shortages as a result since it
52 uses about 14% of the world's fresh water (The World Bank, 2014). Moreover, the
53 nation's demand for water is growing, exacerbating water scarcity issues (Distefano
54 and Kelly, 2017; Sowers et al., 2010). Clearly, better management measures are
55 needed to ensure a more sustainable China.

56 So, how can China make water resources more sustainable? Technological
57 innovation is one approach toward making more efficient use of water, And

58 infrastructure such as the “South to North Water Diversion” should mitigate some
59 water scarcity (Zhang et al., 2011). An alternative way to generate sustainable water
60 use practices is to consider virtual trade of water. Oki and Kanae (2004) coined the
61 term “virtual water trade” (VWT) to discuss water that is used as an input into the
62 production of goods and services that are traded.

63 Water resources used in international trade more than doubled from 1986 to 2007
64 (Dalin et al., 2012). Chapagain et al. (2006) identified global water savings in
65 international agricultural products trade. Chouchane et al. (2018); Duarte et al. (2019)
66 identified some proximate causes of VWT; Lenzen et al. (2013) examine water
67 scarcity. All of the above plus Hoekstra and Hung (2005) addressed effective water
68 management policies. In summary, VWT is influenced by many factors--economy,
69 population size, cultivated area, water endowments, etc. But it does not always benefit
70 water-scarce regions (Kumar and Singh, 2005).

71 The scale and structure of VWT has received some attention at the municipal
72 level in China, e.g. Beijing (Han et al., 2015; Zhang et al., 2011); provincial and
73 multi-provincial level, e.g., Hebei (Liu et al., 2018; Liu et al., 2017b), Liaoning (Dong
74 et al., 2013) and 30 provinces (Chen et al., 2017; Dong et al., 2014; Zhang and
75 Anadon, 2014; Zhao et al., 2015); watershed, e.g., Haihe River Basin (White et al.,
76 2015; Zhao et al., 2010); and eight hydro-economic regions (Guan and Hubacek,
77 2007). Zhao et al. (2019) note that VWT runs from China’s water-scarce north to its
78 south (from less-developed to more-developed areas); so VWT runs against water
79 availability. So Feng et al. (2014) suggest incorporating a measure of water scarcity
80 into subnational VWT analysis. Nonetheless, Zhao et al. (2019) note that the relative
81 productivity of land between agriculture and non-agriculture uses is a better indicator
82 than is water availability.

83 We note from a multi-provincial table of China for 2007 that 31% of
84 interregional trade is due to the exchange of final goods and 69% is due to
85 intermediate inputs, where the latter relates to value chains. This suggests that the
86 fragmentation of production is strong within China. That is, there is an abundance of
87 industrial activity in China that focuses on producing goods across multiple borders,
88 from the production of individual unfinished parts to assemblage of final products
89 (Athukorala and Yamashita, 2007). The fragmentation of production is increasing
90 interregionally in China as well as internationally (Meng et al., 2014).

91 Due to the global financial crisis (2008-2009), international trade's share of total
92 global production declined by three percentage points from 2007 to 2010 according to
93 the 30 multi-provincial table of China. Meanwhile, the value of final goods and
94 intermediate input trade increased substantially, by 67% and 22%, respectively. And
95 trade increased further through 2012, by another 28%. This implies that trade in
96 intermediate inputs is accelerating and that provinces are intensifying their
97 specialization of production. Meanwhile this means that firms are getting more
98 specific in targeting locations from which they buy intermediate products to support
99 their domestic supply chains. These trade trends in intermediate inputs affect the
100 locations in which water is used. In this vein, it is necessary for us to analyze how
101 production fragmentation shapes trade types and, thereby, water use across provinces
102 and nations. The effects of production fragmentation on VWT have been largely
103 ignored.

104 We decompose interregional trade to learn how the fragmentation of domestic
105 production is affecting the apparent availability of provincial and national water
106 resources. To date, literature on the effects of production fragmentation have mostly
107 focused on the virtual trade of carbon and particularly at an international scale, testing

108 the pollution haven hypothesis (Zhang et al., 2017). A few studies point out that
109 China's west incurs higher environmental costs but provides lower value-added gains
110 via its position in the domestic supply chains as well as industry mix compared to
111 other regions (Liu et al., 2015; Meng et al., 2013).

112 Herein we evaluate VWT from 2007 to 2012. This enables an examination into
113 how the economic crisis of 2008–2009 has altered interregional trade and its impact
114 on the environment. Moreover, our distinction between the trade for goods in final
115 versus intermediate uses is useful in testing the importance of VWT, e.g.,
116 environmental policy concentrating on the responsibility of water usage. Our
117 approach helps identify the responsibility for virtual water use by incorporating
118 multiple stakeholders. Another policy is related to alleviating water scarcity, Zhao et
119 al. (2015) and Feng et al. (2014) discuss the necessity of improving the supply-side
120 perspective of efficiency and considering water scarcity into policy framework.
121 Instead, our analysis yields insight into the full supply-chain context. Further, for
122 national water use, the effects (savings or losses) of existing VWT and production
123 fragmentation is unclear. The broader vision of VWT impacts on water resources in
124 China, which our approach yields, can be important in this vein.

125 To depict the production fragmentation, we distinguish different purposes of the
126 inflows of virtual water based on production stages: final consumption, processing for
127 final consumption, and processing for re-export. Accordingly, three different trade
128 types emerge. The first two focus upon the trade of final goods and of intermediate
129 goods in a final stage of production. The goods traded interregionally are “used” by
130 receivers of inflows. The third trade type is associated with the production of
131 intermediate goods that are shipped to be used as inputs for further production in
132 another region or nation. We call this “value chain-related trade”. This type of trade

133 determines whether a region or a nation receives intermediate products for processing
134 and ships the intermediates for processing or final consumption to a different region
135 or country (Borin and Mancini, 2015; Dean and Lovely, 2010; Wang et al., 2017b).

136 In prior studies, various methods have been employed. Some use a bottom-up,
137 crop-by-crop accounting framework to trace VWT in agriculture products (Dalin et
138 al., 2014; Ma et al., 2006; Zeng et al., 2012). Others use environmental extended
139 input-output (IO) analysis of various spatial resolutions, e.g. single region or
140 multiregional (Deng et al., 2016; Duarte et al., 2002; Lenzen, 2009; Liu et al., 2018;
141 Llop, 2013). The IO method expands the scope beyond agriculture products by
142 involving industrial products and services. This enables a study of VWT by
143 considering water-intensive products, like electric power, chemical manufacturing,
144 paper products and food processing.

145 We employ a multiregional input-output (MRIO) approach to evaluate VWT
146 along with water savings in interprovincial trade over two periods, 2007-2010 and
147 2010-2012. We focus on the role of three different trade types: (i) the trade of final
148 goods (TF), (ii) the trade of intermediate goods for the final stage of production (TI)
149 and (iii) trade in value chain (TVC) (*Appendix S1 Equation (2)*). Our analyses focuses
150 on freshwater *use* (quantify of water distributed to users, part of which returns to the
151 environment) instead of freshwater *consumption* (includes only water lost via
152 evaporation, absorption by products, and/or any other losses). The former seems to
153 better represent the broader impact of humans on local water resources and
154 ecosystems and data accuracy, so we employed freshwater use to assess the resource
155 losses in the goods production in specific provinces.

156 Researchers have considered how changes in the balance of VWT affects

157 provincial water use given provincial water scarcity (Feng et al., 2014; White et al.,
 158 2015). The water stress index is a key indicator of water scarcity and is defined as the
 159 ratio of water demanded to total local water resources available (Liu et al., 2017a;
 160 Pfister et al., 2009). Such studies enable an understanding of the causes of water
 161 scarcity and of the region suffering from them. Instead, we distinguish how water
 162 scarcity varies across provinces to reveal its influence on VWT under different trade
 163 types. Thus, our study identifies the impacts of both trade types and water scarcity and
 164 suggests how to improve water management policies.

165 2. Materials and Methods

166 2.1 Multiregional input-output analysis (MRIO)

167 Provincial virtual water trade under different trade types is calculated by using a
 168 MRIO analysis. In this framework, the total commodity outflows from region s to r (s ,
 169 $r=1, \dots, G$), can be written as, $\mathbf{T}^{sr} = \mathbf{Y}^{sr} + \mathbf{Z}^{sr}$, where \mathbf{Y}^{sr} is region r 's final demand for
 170 products from region s , \mathbf{Z}^{sr} is region r 's intermediate use of products from region s .
 171 Like Zhang et al. (2017), we classify trade between each pair of provinces s and r ,
 172 \mathbf{T}^{sr} , into three types as follows:

$$173 \quad \mathbf{T}^{sr} = \underbrace{\mathbf{Y}^{sr}}_{TF^{sr}} + \underbrace{\mathbf{A}^{sr} \mathbf{B}^{rr} \mathbf{Y}^{rr}}_{TF^{sr}} + \underbrace{\mathbf{A}^{sr} \mathbf{B}^{rr} \sum_{t \neq r}^G \mathbf{A}^{rt} \mathbf{B}^{tr} \mathbf{Y}^{tr}}_{T_d^{sr}} + \underbrace{\mathbf{A}^{sr} \sum_{t \neq r}^G \mathbf{B}^{rt} \mathbf{Y}^{tr}}_{T_d^{sr}} + \underbrace{\mathbf{A}^{sr} \sum_t^G \mathbf{B}^{rt} \sum_{u \neq r}^G \mathbf{Y}^{tu}}_{TVC^{sr}} + \underbrace{\mathbf{A}^{sr} \sum_t^G \mathbf{B}^{rt} \mathbf{X}^t}_{T_g^{sr}} \quad (1)$$

174

175 where $\mathbf{B}^{rr} = (\mathbf{I} - \mathbf{A}^{rr})^{-1}$, \mathbf{A}^{sr} is the input coefficient matrix for region r 's intermediate
 176 uses that are produced in region s . \mathbf{B}^{tr} is the Leontief inverse matrix, representing the
 177 gross output of region t required to produce a unit increase in the final demand of
 178 region r . \mathbf{X}^t is the array of exports to foreign countries from region t . TF^{sr} defines the
 179 trade in final products, in which the trade partner region directly uses the shipped

180 products located in the shipping region. TF^r defines the trade in intermediate products
 181 for the final stage of production, in which those products are further processed by a
 182 trade partner before that trade partner uses them as a final good. TVC^{sr} defines value-
 183 chain-related trade, both domestic value chain-related trade (T_d^{sr}) and global value
 184 chain-related trade (T_g^{sr}). For TVC^{sr} , traded products cross provincial borders more
 185 than once. The products may be finally absorbed by a province (T_d^{sr}) or further
 186 processed to become exported (T_g^{sr}). Then, based on the balance of gross output of a
 187 province, total outputs can be decomposed into five parts: use in local economic
 188 activities, export to foreign countries, and outflow to other regions as a final product,
 189 outflow for use in the final stage of production, and outflow as value chain-related
 190 trade. Similarly, each province's water uses as embodied in these five output
 191 components can be derived. This is done by pre-multiplying output by a
 192 multiregional vector of sectoral water-use intensities (*Appendix S1*).

193 A province's net virtual inflow of water (or *balance of virtual water use*
 194 embodied in trade between regions, BVW) is the difference between its total virtual
 195 water inflows and outflows from and to all other provinces. The virtual water inflows
 196 or outflows can be further disaggregated into virtual water embodied in trade in final
 197 products, trade in intermediate products for the final stage of production and the value
 198 chain-related trade as follows:

$$199 \quad BVW^{sr} = VW^{sr} - VW^{rs} = (\mathbf{F}^s \mathbf{B}^{ss} TF^{sr} - \mathbf{F}^r \mathbf{B}^{rr} TF^{rs}) + (\mathbf{F}^s \mathbf{B}^{ss} TVC^{sr} - \mathbf{F}^r \mathbf{B}^{rr} TVC^{rs})$$

200 (2)

201 where, the BVW^{sr} represents the net virtual water inflow into region r from region s
 202 and VW^{sr} (VW^{rs}) indicates the virtual water outflows from region s (r) to region r (s).
 203 A positive net virtual water outflow (*VWT exporter*) indicates that interprovincial

204 trade causes a province's water use to be higher than might otherwise be thought.

205 We also evaluated effects of interprovincial trade on national water savings via
 206 *balance of avoided water uses, BAW*. The BAW induced by the trade between two
 207 provinces is obtained as the difference between virtual water uses embodied in
 208 commodity outflows (VW) and virtual water uses avoided by the inflow of
 209 commodities (WAI):

$$\begin{aligned}
 BAW^{sr} &= (VW^{sr} - WAI^{sr}) + (VW^{rs} - WAI^{rs}) \\
 &= (F^s B^{ss} - F^r B^{rr})TF^{sr} + (F^s B^{ss} - F^r B^{rr})TI^{sr} + (F^s B^{ss} - F^r B^{rr})TVC^{sr} \\
 &\quad + (F^r B^{rr} - F^s B^{ss})TF^{rs} + (F^r B^{rr} - F^s B^{ss})TI^{rs} + (F^r B^{rr} - F^s B^{ss})TVC^{rs}
 \end{aligned}$$

210
 211 (3)

212 The first three terms in Equation (3) identify national water savings from the
 213 perspective of the production structure and amount of water saved via outflows of
 214 commodities from region s to r . These can be further divided into the three trade
 215 types. The last three terms explain national water savings associated with the inflows
 216 of commodities to region s from r . We calculated each province's national water
 217 savings as the average of its water savings via commodity inflows and outflows,
 218 $BAW^s = (\sum_{r \neq s}^G BAW^{sr})/2$. Subsequently we obtained a new measure of national water
 219 savings by summing across provincial average national water savings,
 220 $BAW = \sum_s^G BAW^s$. A positive value of this quantity indicates that interprovincial trade
 221 induces higher-than-expected national water use (when no interprovincial trade). The
 222 same goes for its components for the three trade types. Clearly, national water uses
 223 are "saved" when virtual water is shipped from a relatively more water-efficient
 224 province to one that is less water-efficient (Dalín et al., 2014).

225 2.2 Incorporating water scarcity into MRIO

226 We also consider water scarcity. For this, we weight *provincial water use* by a
227 *water stress index* (the ratio of water demanded to total local water resources
228 available) and obtain an indicator that we call *scarce water use*. Higher values of
229 scarce water use indicate that a province consumes more water than it “should”, given
230 its resource base. Subsequently, we also derived a measure scarcity-weighted VWT
231 (virtual scarce water trade). A “*scarce water exporter*” is a province with little
232 available water that, in net, outwardly ships water-intensive products. Further,
233 scarcity-weighted national water savings (“*national scarce water savings*”) identifies
234 the impact of VWT on the scarce water use nationwide. When water resources flow
235 from a less water-stressed, more water-efficient province to a province that is more
236 water-stressed, but less-efficient water user, national scarce water resources are
237 “saved” through trade. (*Appendix S1*).

238 **2.3 Data sources**

239 MRIO tables allows us to trace water embodied in goods so that the water uses
240 can allocated to ultimate consumers. MRIO tables of China quantify economic
241 transactions amongst 30 sectors across 30 provinces for 2007, 2010 and 2012. They
242 all were retrieved from School of International Development, University of East
243 Anglia.

244 Our analysis focuses on the blue water impacts of the interprovincial trade on
245 provincial and national water uses, aligning with Zhao et al. (2015); Zhao et al.
246 (2010). We linked the MRIO table of China to data on freshwater use. For this, first,
247 we extracted the volume of water used by primary, secondary and tertiary industries
248 from the *Chinese Statistical Yearbook 2008, 2011 and 2013* (China National Bureau
249 of Statistics, 2011) and the *China Urban-Rural Construction Statistical Yearbook*

250 2007, 2010 and 2012 (Ministry of Housing and Urban-Rural Development, 2011).
251 Water used by primary industry is mostly agricultural—crops, grassland, forestry,
252 orchards and fishing. Secondary industry’s water use is concentrated in mining,
253 manufacturing, electricity and construction. Tertiary industries used water to produce
254 services, e.g. commerce, restaurants, posts, cargo transportation and
255 telecommunications (China National Bureau of Statistics, 2011).

256 Second, more details on water use data by secondary industries is available from
257 the *Chinese Economic Census Yearbook 2008* (The State Council 's second national
258 economic census leading group office, 2010); so we used them to estimate water-use
259 shares (see Zhao et al. (2015)), which we applied to 2007, 2010 and 2012. Third, we
260 base subsectoral tertiary water use on each subsector’s share of intermediate inputs
261 from the “water production as suggested by (Zhang and Anadon, 2014) (see *Appendix*
262 *S2*).

263 **3. Results**

264 **3.1 Water uses by trade type.** National water use increased continuously from 580.4
265 billion m³/yr in 2007 to 613.8 billion m³/yr in 2012, in which 30.4% (186.9 billion
266 m³/yr) was embodied in interprovincial trade within China. For 2012, we show that of
267 this traded aspect, TI, TF and TVC composed relatively equal shares (*Appendix Table*
268 *S1*). Water embodied in international exports showed up as a negative impact brought
269 by the financial crisis since it decreased by 13% over 2007-2010 and by 9% further
270 over 2010-2012. Of course, global value chain-related trade decreased too, by 23%
271 over 2007-2010 and by 19% more over 2010-2012. Structural changes in interregional
272 trade arose too. As a result, they shifted from an orientation toward TVC (2007)

273 toward TF (2010), then toward TI (2012). This suggests that the VWT has gained
274 more of an interregional trade tilt over time.

275 In 2012, the share of total provincial water use embodied in interregional trade
276 ranged widely across China's 30 provinces—from 8.1% in Guangdong to 56.5% in
277 Anhui. The main provinces involved in upstream processes were generally less-
278 developed central, west and northeast parts of China, e.g. Anhui, Heilongjiang,
279 Xinjiang, Inner Mongolia. These provinces have a dominant TI trade type that ranges
280 from 14.3% to 20.1%; this indicates that they ship intermediate goods for further
281 processing elsewhere domestically. Provinces with large amounts of water embodied
282 in trade in the 2007-2010 period tended to display a similar tendency in 2012, but
283 with a slight difference in the dominant trade type (TVC in 2007, TF in 2010). The
284 dominant trade type was particular to provinces. For example, Heilongjiang (TVC in
285 2007, TI in 2012) shifted its mix of commodity outflows after the financial crisis,
286 reducing international exports while increasing the domestically destined outflows of
287 intermediate goods (*Appendix Fig. S1, Table S2-S4*).

288 **3.2 Interprovincial water flows by trade type.** We identify critical virtual importers
289 and exporters of water for the three trade types (see Fig. 1, *Tables S5-S8*). Results
290 show that the developed coastal provinces tend to rely on virtual imports of water
291 from less-developed agricultural provinces. Major sectors and regions that virtually
292 export or import water remain largely unchanged over the study period. Nonetheless,
293 water flows strengthen among the central provinces by 2012. Provinces located in the
294 northwest, southwest, northeast, and Yangtze River regions, which feature agriculture

295 as a major industry, were top virtual exporters of water. The virtual outflows of water
296 declined in the west and northeast regions between 2007 and 2012. For example,
297 Xinjiang's total water outflows ranked it first among all flows for each trade type over
298 the three years. But the outflows from Xinjiang declined by 1.2 billion m³/yr from
299 2007 to 2012. In contrast, the Yangtze River regions intensified their virtual outflows
300 of water. For example, Anhui's water outflows rose by 2.1 billion m³/yr between 2007
301 and 2012, and its total virtual outflows of water ranked it among the top four flows in
302 2012. Top importers provinces consist were either populous, coastal, or both. Virtual
303 inflows of water into coastal provinces declined from 2007 to 2012. For example, the
304 east coast, particularly Shanghai, decreased its virtual imports of water via final goods
305 by 3.1 billion m³/yr from 2007 to 2012, although the inflows to Shanghai have always
306 been among the largest TF flows. In contrast, the Yellow River region increased its
307 virtual imports of water, e.g. Inner Mongolia shifted from being a virtual water
308 exporter via value chain-related goods to one for final goods.

309 Further, our results highlight the disparities among Chinese provinces via the
310 different trade types of net virtual inflows/outflows of water. For example, as a virtual
311 water importer, Shanghai mainly receives an inflow of goods for final consumption,
312 indicating its downstream position in domestic production chains. Shandong and
313 Guangdong, meanwhile, mainly receive virtual inflows of water via goods they
314 further process before consuming the goods themselves as a final use; Zhejiang also
315 obtains virtual inflows of water for further processing but it mostly re-exports those
316 processed goods. As a virtual exporter of water, for example, Xinjiang mainly ships

317 goods elsewhere for final consumption; Heilongjiang, Guangxi and Anhui ship such
318 goods, which are processed and eventually consumed as final goods by the regions
319 that receive them. Hubei, Guizhou, and Gansu virtually ship water for value chain-
320 related trade. Water-intensive goods are largely agriculture commodities and
321 electricity; the difference is that a province either directly consumes them as an
322 imported good (direct trade) or as a good for further processing (indirect trade) and
323 does so differently given its position within the domestic supply chain. (for analysis
324 about regional VWT, refer to *Appendix S3*).

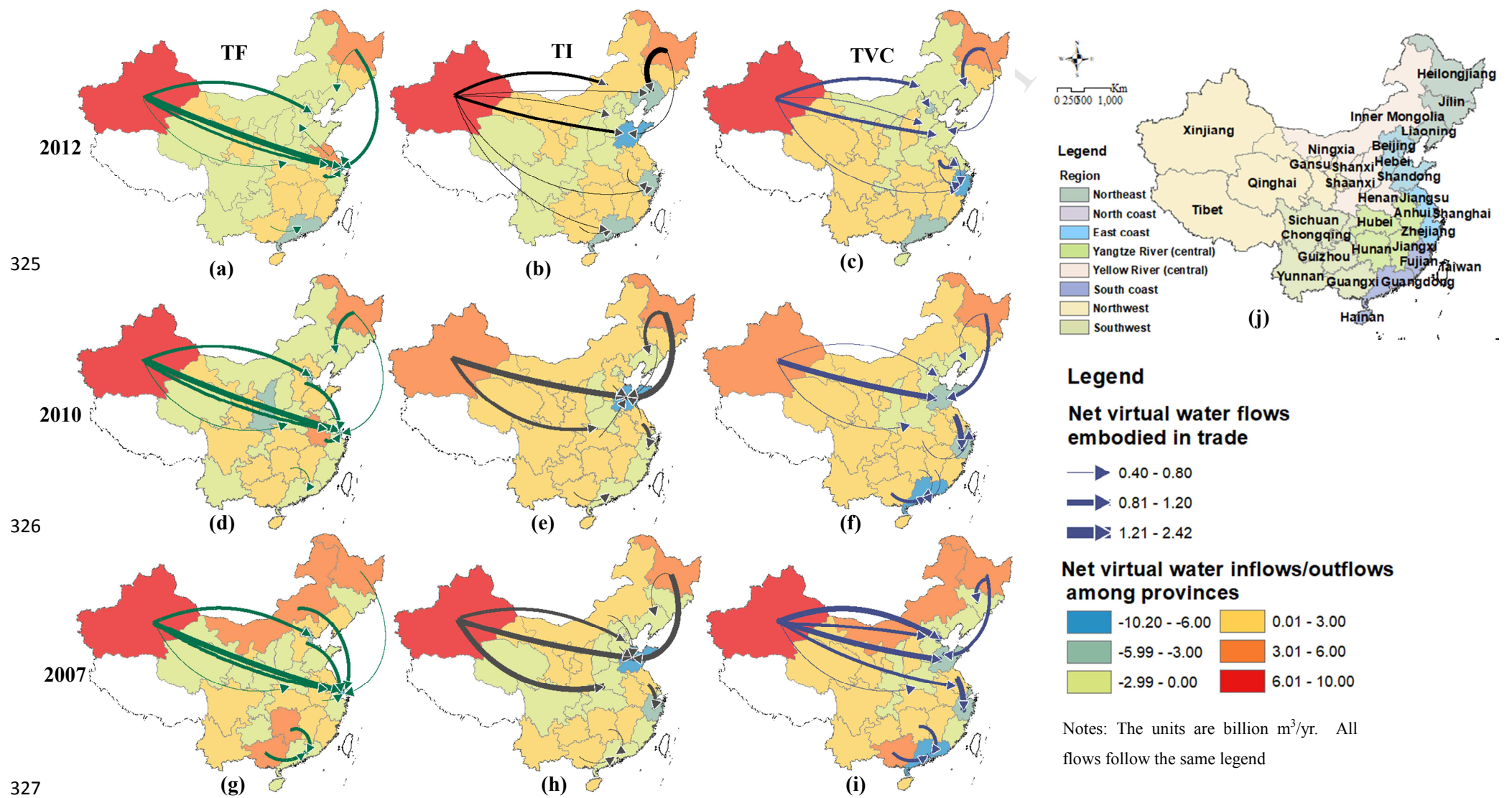


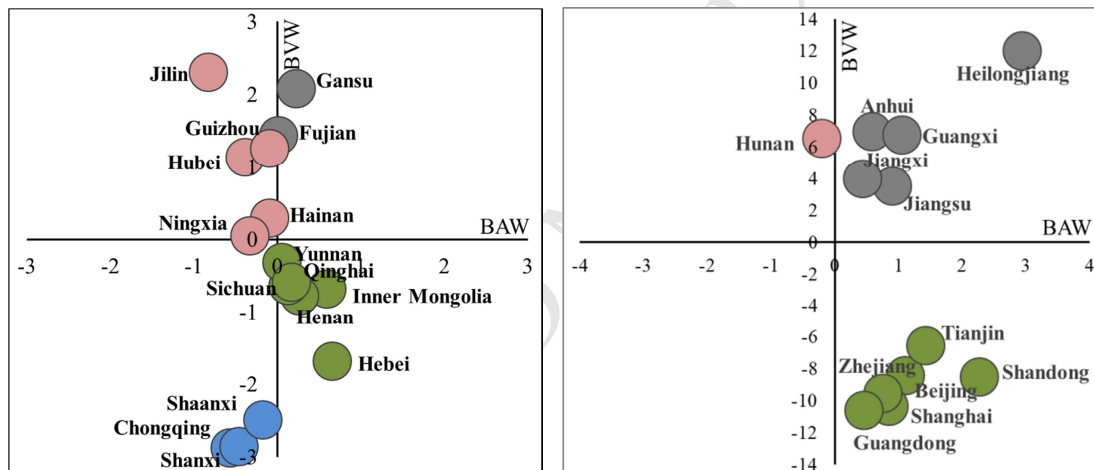
Fig. 1. The 10 largest net water flows in interprovincial trade for three trade types in 2007-2012.

328 **3.3 Water savings.** We find interprovincial trade activities consistently lead to a rise
329 in national water use—by 28.0, 13.6 and 20.3 billion m³/yr for 2007, 2010 and 2012,
330 respectively. We find the proximate cause to be the rising fragmentation of
331 production, with value chain-related trade being the biggest contributor (*Appendix*
332 *Table S5*). Over the study period, TVC dominates the rise of national water use with
333 more than 37% of the total increase. Although TI also generates a modest increase.

334 Trade activities enhanced apparent national water use in about two thirds of
335 the provinces. Further, provinces performed differently in terms of BAW and BVW,
336 which we classify into four categories (Fig. 2, *Appendix Table S5*). The most desirable
337 scenario for a province is to be located in the third quadrant. There both water is
338 saved from provincial and national perspective. Shanxi, Chongqing and Shaanxi, are
339 located here with provincial and national water savings of 8.2 and 1.2 billion m³/yr,
340 respectively.

341 Provinces identified within the first quadrant experienced higher-than-expected
342 provincial and national water use. Spending an extra 62.6 and 13.2 billion m³/yr in
343 provincial and national water, respectively. Provinces in this quadrant are natural
344 targets for water conservation efforts. Key trade type and sectors varied by province.
345 For example, Xinjiang should pay attention to TF and TI outflows, since they are
346 major contributors its provincial and national water uses increase (37.9% of BVW,
347 30.5% of BAW; 33.5% of BVW, 36.7% of BAW). For Heilongjiang and Guangxi, TI
348 outflows should be scrutinized (38.3% of BVW, 42.6% of BAW; 36.0% of BVW,
349 35.1% of BAW). As might be expected, agriculture sector is an apt target for water

350 savings since it accounts for more than 50% of virtually traded water in most
 351 provinces, and is especially key in Guangxi (89.0% in TF), Heilongjiang (89.4% in
 352 TF) and Xinjiang (95.9% in TF). Still, electric power producers account for about 20%
 353 of the water embodied in trade for several provinces (e.g. Jiangsu, Anhui, Fujian).
 354 Similarly, attention to water conservation efforts should be paid to chemical
 355 processing in Sichuan and textile production in Fujian (*Appendix Fig. S2*). Note that
 356 Xinjiang, Heilongjiang and Guangxi appear to be especially ripe for efforts aimed at
 357 reducing national and provincial water use.



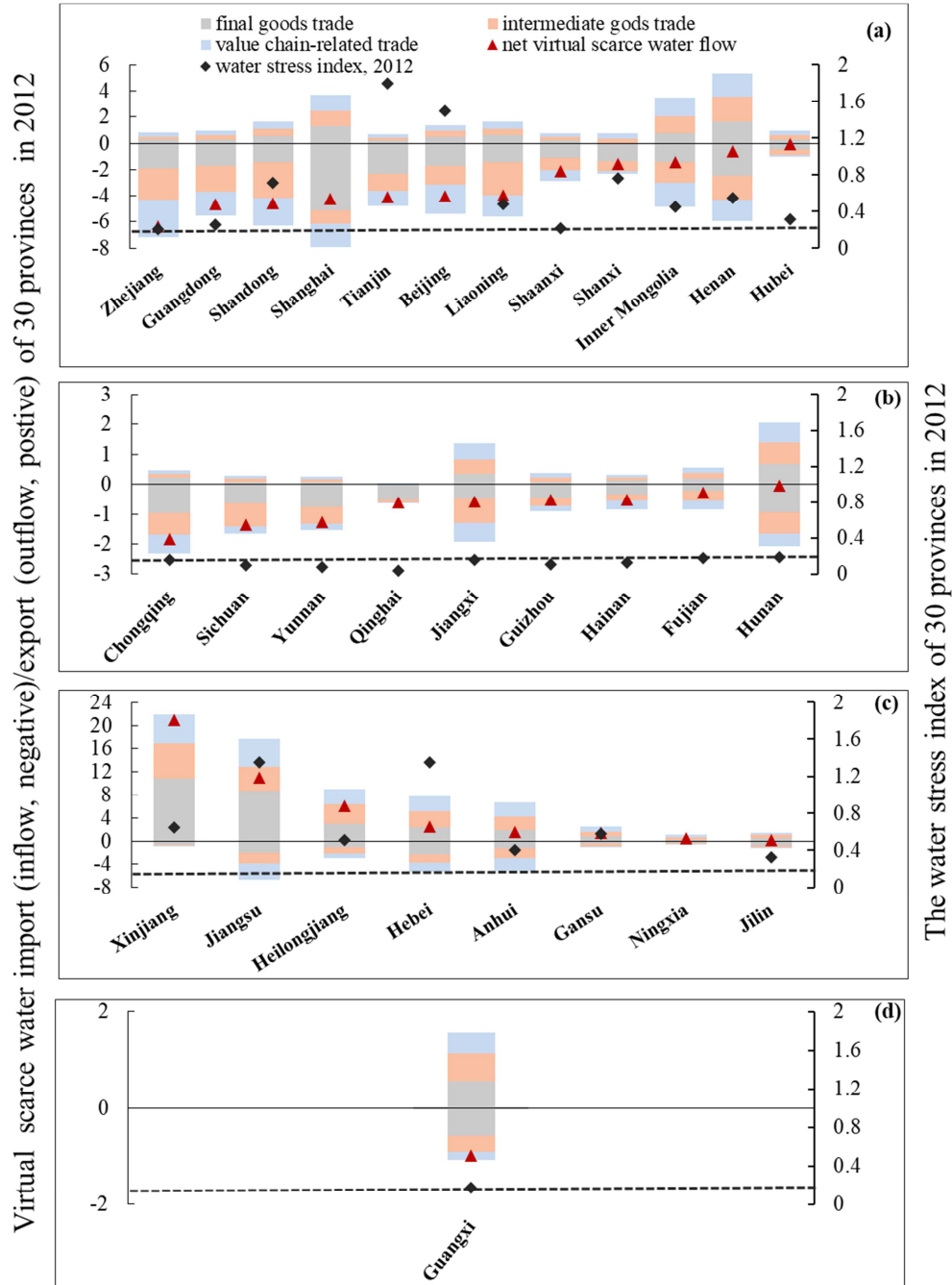
358

359 Fig. 2. The distribution of total BVW and BAW in 30 provinces in China in 2012

360 Note: The units are billion m³/yr. The left figure identifies provinces with BVW and BAW less than 3
 361 m³/yr. That on the right contains provinces with BVW and BAW more than 3 m³/yr. Xinjiang is
 362 omitted for high value (7, 26).

363 **3.4 Re-mapping VWT with consideration of water scarcity.** We find there was
364 281.5 billion m³/yr scarce water in 2012—45.9% of the nationwide water use.
365 Provinces with higher water-stress and, hence, major users of scarce water, are
366 mainly in northern regions (*Appendix Table S12*). For example, Hebei, Shandong and
367 Henan rank 3rd, 5th and 6th in terms total scarce water use, but rank 15th, 12th, and 11th
368 in total water use. Jiangsu, Xinjiang and Heilongjiang have high scarce water use.

369 In 2012, 92.0 billion m³/yr of scarce water was associated with interprovincial
370 trade, and were fairly evenly distributed across trade types. Provinces of greatest
371 concern are those that have stressed water resources and net water outflow—Xinjiang,
372 Jiangsu, Heilongjiang, Hebei, Anhui, Gansu, Ningxia, and Jilin. (See Fig. 3, *Appendix*
373 *Table S13*.)

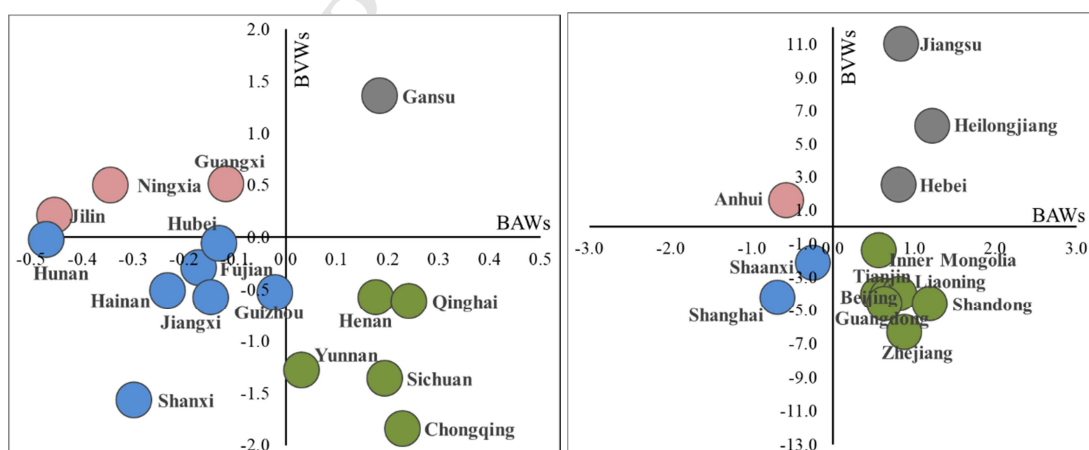


374

375 Fig. 3: China's provinces by net scarce water transfer and water scarcity, i.e. (a) stressed water resources and net
 376 water importer, (b) abundant water resources and net water importer, (c) stressed water resources and net water
 377 exporter, and (d) abundant water resources and net water exporter.

378 Note: The left vertical axis is scarce water inflow (negative)/outflow (positive) under trade types. The right vertical
 379 axis is the water stress index. Water scarcity is classified into four categories: a value below 20% is regarded as
 380 "no or low stress", a value between 20% and 40% is "moderate stress", a value between 40% and 100% is "serve
 381 stress", and a value above 100% is regarded as "extreme stress". The dotted line indicates a water stress index of
 382 20% in (a), (b), (c) and (d). The water stress index values for Shanghai (3.7) and Ningxia (7.1) are omitted.

383 Limiting VWT could be a more efficient way to save scarce water than might
 384 saving national water use. The VWT led to the heightened national scarce water by
 385 11.9 billion m^3/yr , substantially lower than its enhancements to national water use
 386 (20.2 billion m^3/yr) in 2012. About half of the provinces reduced national water
 387 scarcity through VWT (Fig. 4). As a result, some national scarce water use was saved
 388 (3.9 billion m^3/yr); just a bit more than was saved when ignoring water scarcity (3.5
 389 billion m^3/yr) (*Appendix Table S14*). Provinces in third quadrant are doing quite well,
 390 resulting in both provincial and national scarce water savings (9.9 and 2.4 billion
 391 m^3/yr). Provinces in the first quadrant pose a problem, since their economies increase
 392 scarce water uses at both provincial and national levels (41.9 and 9.5 billion m^3/yr).
 393 On the other hand, these same provinces (Xinjiang, Heilongjiang, Jiangsu, Gansu and
 394 Hebei) may have the greatest potential to improve scarce water savings. In particular,
 395 Xinjiang and Heilongjiang should be targets of enhanced scrutiny in this regard since
 396 critical trade types remain whether water scarcity is considered or not.



397
 398 Fig. 4. The distribution of total BVWs and BAWs by Chinese province in 2012 considering water
 399 scarcity

400 Note: The units are billion m^3/yr . The left figure shows provinces with BVWs and BAWs less than 0.5 and 2.0
 401 m^3/yr , respectively; that to the right shows provinces with values that larger than 0.5 and 2.0 m^3/yr , respectively;

402 for the sake of display, Xinjiang is omitted for high value (6, 21).

403 **4. Discussion**

404 **4.1 Virtually trade of water shaped by production fragmentation**

405 Our results suggest that China's present domestic production network results in
406 virtual water flows from western to coastal regions, from less developed to more
407 developed economies via different trade types. Thus, the environmental externalities
408 of virtual water transfer should be considered when designing water conservation
409 policies. A virtual water compensation scheme may be a practical solution to
410 distributing the ecological burdens equally among provinces. Wang et al. (2017a)
411 propose a compensation mechanism for virtual water trade in crops that follows the
412 "whoever benefits will compensate" principle. Their proposal only considered direct
413 bilateral trade partners.

414 Our study revealed that VWT is related to economic structure, production
415 technology, trade policies and the position in domestic supply chain (Wichelns, 2004;
416 Zhang and Anadon, 2014). We distinguish trade types, i.e. direct and indirect trade to
417 see how it affects VWT, and observe provincial disparity. Results show that the value
418 chain-related trade accounts for 32.7% of VWT. For example, Zhejiang is heavily
419 involved value chain-related trade with other provinces (e.g. Jiangsu, Anhui), which
420 accounts for 40.2% of the total water inflows, followed by final goods trade (24.4%)
421 and intermediate goods trade for final stages of production (35.5%). Insofar as water
422 use responsibility is concerned then, 40.2% of Zhejiang's virtual water inflows should
423 not be fully assigned to Zhejiang. Rather, Zhejiang's third-party receivers are

424 responsible for that aspect of water usage. Following prior research advocating for
425 consumption-based allocation for water-use responsibility, we propose that those
426 provinces involved in interprovincial trade indirect trade (value chain-related trade)—
427 exporters, importers, and a third player, the final consumer—should compensate for
428 their indirect use of water. Specifically, the percentage of indirect trade of water for
429 each province could be used to inform policymakers about the amount of water that
430 should be involved in such a multi-stakeholder compensation framework. This
431 parallels a popular, but somewhat less elaborate, theory of responsibility principle
432 applied in the field of climate change. Here the value gains in the domestic supply
433 chain, the environmental impacts, **and** *water resource utilization* are considered.

434 **4.2 Alleviating water scarcity under the rising fragmentation of production**

435 Although VWT helps coastal provinces meet their total water demand, it has
436 negative impacts: it is potentially increasing the scarcity of water in provinces in
437 which water is already especially scarce. For example, Heilongjiang, had virtual
438 outflows of water to Liaoning, Shandong and other provinces, mainly via intermediate
439 goods trade. While such a strategy relieves water shortages in Shandong, it aggravates
440 water stress in Heilongjiang. Our analysis further informs results in Zhao et al. (2015)
441 by identifying the effects of different trade types.

442 By focusing on trade types, we may be able to devise other ways to reduce water
443 scarcity, e.g. by conserving water related to the trade in intermediate goods. It could
444 be critical to monitor and attempt to control water use within each supply chain. Key

445 initiatives might be to prefer adoption of processes that display greater water
446 efficiency, the more efficient use of inputs, or a higher recycling rate of intermediate
447 products. *A good example* is green supply chains, those that aims to minimize
448 lifecycle environmental impacts of a product via greener design, resource savings,
449 production recycling, etc. (Ahi and Searcy, 2015). It is still at the initial stage in
450 China. With rising fragment production, it is more necessary for all participants in
451 supply chains to make commitment to doing business with environmentally
452 responsible suppliers who produce with less natural resource and pollution. Including
453 the water resource use in the metrics when evaluating the relative green supply-chain
454 performance would focus on water savings as embodied in direct and indirect trades.

455 *Another option*, a market-based instrument, would be to let water prices vary to
456 reflect water scarcity. This could be especially valid in arid regions, where it gives an
457 incentive to reduce water scarcity. The distinction between final and intermediate
458 goods may help the proper identification of commodity exporter, importer, third
459 player who would be more affected by the resulting price increases. The affected
460 agents would share the costs of the price increase with production fragmentation in
461 trade. It has been argued that water prices are too low for major water uses like
462 irrigation; raising them substantially would give farmers more reason to conserve
463 water (Yang et al., 2003). In essence, a major reform to China's system of water
464 prices, at least in certain regions, could stiffly alter water use by agriculture, industry
465 and household. To better address water conservation, reform of water pricing seems
466 appropriate but with it is equally clear that the allocation of water rights will be

467 essential (Webber et al., 2008).

468 **4.3 Saving national and provincial water under production fragmentation**

469 The existing VWT network did not benefit national water use since it enabled
470 water-intensive products to be produced in regions that are less water efficient. Due to
471 VWT, national water use was effectively 20.3 billion m³/yr higher in 2012. An
472 example is Xinjiang's virtual outflows of water to Shandong and Inner Mongolia.
473 Further, as we stated before, the virtual water embodied in the trade of intermediate
474 goods (value chain-related trade) is a main contributor. That is, production
475 fragmentation exacerbates national water use via national water stress. This should be
476 a major concern for China, as blue water resources are becoming increasingly
477 polluted or scarce (Liu et al., 2013). But if production fragmentation continues its rise
478 within China without accompanying efficiency improvements and shifts in
479 interregional trade network, national water resources will become more constrained.
480 So new measures should be considered. The first is to reorganize trade (especially for
481 crops) so that water is used more effectively and efficiently, i.e. trade flows from more
482 water-efficient to less water-efficient provinces (Dalin et al., 2014). A second is to
483 promote better water conservation and industry productivity locally by all parties.
484 This should help decrease national water use and enhance local commodity supplies
485 (e.g. food).

486 Ideally, targets for water conservation policy would develop at a provincial scale
487 since our results show some particularly large interregional and intersectoral flows.

488 We identify provinces (i.e. Xinjiang and Heilongjiang) that have *net* virtual outflows
489 of water due to *gross* outflows of relatively large volumes of water-intensive products.
490 We also identify different trade flows types to be targeted to reduce water use. For
491 example, attention should be paid to the intermediate goods shipped from
492 Heilongjiang and used by other regions in a final stage of production. Further, the
493 awareness of water conservation need should focus on both final goods and
494 intermediate goods traded from Xinjiang in preparation for a final stage of production.

495 Sectorally, our findings support those found elsewhere: agriculture is a main
496 water user, followed by the electric power and chemical industries (*Appendix Fig. S3*).
497 For improving the agricultural water use efficiency, direct potential measures include
498 technological innovation, enhanced awareness of water-saving practices, and the
499 production of crop hybrids that demand less water. Of course, simply improving crop
500 yields alone would prove useful (Foley et al., 2011). In the electric power sector,
501 shifts toward air cooling systems for steam and the use of renewables, especially wind
502 and solar generation, would help (Zhang and Anadon, 2013). Still, production
503 processes may lack the incentive to improve water use efficiency due, for example, to
504 its cost increment. So demand-side management could lead to the water savings. The
505 employment of an eco-labelling scheme that provides final consumers and the
506 industries with new information regarding environmental responsibility (Banerjee and
507 Solomon, 2003). This could be particularly helpful in populated coastal regions.

508 **4.4 Limitations**

509 As with other studies using the MRIO approach, this study has potential
510 limitations, resulting in uncertainties in the analysis: First, our results are aggregated
511 sectorally, so some variation in processes across regions are neglected. Second, we
512 ignore heterogeneity of industrial processes within regions as well, but we
513 heterogeneity exists and can influence estimates of VWT embodied in various trade
514 sectors. Adding product differentiation of industrial processes should be a future
515 research goal.

516 While unavoidable, water use data also results in analytical uncertainty,
517 especially that for secondary industrial sectoral water uses. Use of a 2008 water use
518 ratio is unable to represent the efficiency improvement in each sector properly.
519 Incorporating technological change by sector would be a challenge too, and this is a
520 future research direction.

521 Apart from the water use, water consumption is also used by others to evaluate
522 the impacts of virtual water transfers (Hollanda et al., 2015). The latter represents
523 evaporation and water loss. Future research could be conducted to consider both
524 indicators to gain a better understanding of the virtual water transfers under various
525 trade types.

526 **5. Conclusions**

527 When it comes to water resources, China is at a crossroads of sorts. Water shortages
528 are on the horizon, and both vertical specialization and the fragmentation of

529 production appear to be making the situation worse through the virtual trade of water.
530 This is so since China's developed coastal region is demanding virtual water from its
531 less developed inland regions. In this paper, we apply a framework that traces the
532 water embodied in different trade types across 30 provinces. It tracks how production
533 and trade shape water use. Through it we find different provinces gain or lose water
534 resources via production fragmentation by dominate trade type. For example, the
535 largest source of water inflows into Shanghai and Zhejiang are those for final goods
536 (67.8%) and value chain-related (40.2%). We further find that national water use was
537 more than believed due to interprovincial trade activities; which flow from less water-
538 efficient provinces to more efficient ones. Value chain-related trade was the main
539 contributor.

540 To address China's large, untapped water saving potential, some provinces (e.g.
541 Xinjiang, Heilongjiang), trade types (e.g. intermediate goods trade for the final stage
542 of production), and sectors (e.g. agriculture, electricity) should be a priority when
543 water saving actions are undertaken. Accounting for relative water scarcity in a virtual
544 water trade network can highlight risks of aggravating water stress regions. Still we
545 find that interregional trade would not increase national water scarcity as much as it
546 would national water use. Our findings underline the need to consider trade types and
547 water scarcity when it comes to developing water resource allocation policies.

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556 **Supporting Information.** Additional details on approaches, data sources, additional
557 results analysis, figures and tables.

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Highlights:

- (1) Effects of production fragmentation on virtual water trade was examined.
- (2) Provincial disparity was observed for net virtual water trade in trade types.
- (3) Value chain-related trade contributes to national water use increase the most.
- (4) High water saving potential was revealed in provinces, trade type and sectors.
- (5) We re-map the virtual water trade considering provincial water scarcity.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: