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# Assessment of Virtual Water Flows in Iran Using a Multi-Regional Input-Output Analysis

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**Abstract:** The growth of Iran's agricultural sector in the past few decades has exerted enormous pressure on its aquifers. There is a strong disparity between economic development and natural resource endowments, which threatens water and food security. In this paper, we used a multiregional input–output (MRIO) framework to assess the virtual water flows in Iran. We also estimate the internal and external water footprint of regions compared to their water availability. The results show that the northern part of the country, with no water scarcity, imported virtual water through the trade of goods and services, while severely water-scarce regions were net virtual water exporters. Iran had a net export of 1811 $Mm^3$ per annum. While blue water resources (surface and groundwater) accounted for 92.2% of the national water footprint, 89.1% of total exports were related to the agriculture sector, contributing to only 10.5% of the national income. The results suggest that policy-makers should reconsider the current trade policy regarding food production liberalization in order to make Iran's limited water resources available for producing industrial goods, which can contribute more to the economy.

**Keywords:** virtual water trade; multiregional input–output model; water footprint; Iran

## 1. Introduction

Iran, as an arid country with an average precipitation of 250 mm per year [1], is experiencing severe water challenges due to increasing demand resulting from population growth, changes in lifestyles, economic development and climate change. Water scarcity, as one of the greatest challenges, is not necessarily natural (physical scarcity or first-order scarcity) but is usually the result of socioeconomic (or second-order scarcity) and sociopolitical or institutional processes (third-order scarcity) to meet certain ends [2]. Groundwater resources are the primary supply of water in the country for consumption and production activities since almost 70% of precipitation is lost to evaporation [3]. As a result, the overextraction of groundwater resources has led to environmental issues, including drying lakes and natural ponds, land subsidence, desertification, frequent dust storms, water quality degradation and soil erosion [4]. Rapid groundwater depletion is a common issue in countries in the Middle East, as in Jordan [5], Qatar [6] and Lebanon [7]. In these countries, including Iran, groundwater resources are currently overpumped above their safe yield, although most of them are extracted from legal wells [8]. These problems are set to be exacerbated since Iran is projected to have more than 103 million inhabitants by 2050 [9], while the population in 2018 was 81.6 million. The strategy of policy-makers for achieving self-sufficiency in water-intensive agricultural production has resulted in aquifer depletion at a remarkable pace. This strong desire to self-produce all the requirements placed Iran as the second-leading country in the world regarding groundwater depletion [10]. A study conducted in a water-scarce country in the Middle East, Jordan, concluded that this strategy of inefficient use of water in agriculture is linked to the concept of the "shadow state" through which authorities maintain the support of certain actors [11,12]. Furthermore, there is a wide regional disparity in population distribution, economic development, water availability and, thus, water stress across Iran.

The densely populated central, southern and eastern parts of the country are arid, with 50–200 mm of rainfall per annum, covering more than 80% of the total area of the country. In comparison, the northern regions are humid to hyperhumid, with no water deficit, accounting for less than 5% of Iran's territory. The western parts of the country are semiarid to humid. More than 70% of agriculture in Iran (and almost 100% in the arid parts of the country) is irrigated [13]. In addition to water shortages in most parts of the country, mismanagement regarding the development of economic growth has aggravated groundwater depletion. As an example, the development of water-intensive steel industries in the desert [14] is not sustainable, in particular since there are 5440 km of coastline in both the northern (the Caspian Sea) and southern (Persian Gulf and Sea of Oman) parts of the country, which are preferable locations for such industries from a water resource point of view. Such decision-making has led not only to environmental problems in the form of sinkholes that result from overextraction of groundwater [15] but also to socioeconomic repercussions, i.e., forcing residents to evacuate their homes and leaving them unemployed. These mismatches between the natural resource endowments, the water use efficiency of economic sectors and the development patterns in the country are evaluated in this study with the aim of minimizing the environmental issues.

To carefully evaluate the situation in Iran concerning the current water scarcity, it is necessary to take both supply and demand into account. The virtual water concept, first introduced by Allan [16], is the volume of water needed to produce goods along their supply chains [17]. The water footprint, a bottom-up approach developed by Hoekstra and Hung [18], provides a means to determine the freshwater volume needed for producing goods and services. The water footprint is a consumption-based indicator [19,20], allowing for the identification of either key regions or sectors associated with their water consumption pattern. In various studies, the water footprint concept was used to reveal the relationship between consumption and the volume of water used in the production of certain types of products and/or sectors in a specified geographic area [21]. In this study, we distinguish between the internal (or domestic) and external (or foreign) water footprint to identify the sources of water consumed within the country. The internal water footprint refers to the volume of domestic water supplies used in the production of goods and services consumed by the inhabitants of the region [22]. The external water footprint is the volume of water used in other regions to produce goods that are consumed by the inhabitants of the region. The virtual water concept is closely related to the water footprint and refers to the volume of water embodied in products [23].

According to the Heckscher–Ohlin theory, it is natural resource endowments that should determine the specialization of an area in producing specific products and services. Otherwise, it should import its requirements from other regions [24]. However, studies on virtual water trade concluded that virtual water trade is not correlated with water resource availability and that virtual water flows from water-scarce to water-abundant regions [25,26]. The input–output model, as a top-down approach, is widely used as an effective tool to assess the flows of natural resources like water [27], land [28] or energy [29]. This is of particularly high interest in arid regions with high levels of water scarcity. Egypt and Beijing, in China, for example, used this approach to come up with proper policy implications to accomplish economic development with an efficient and sustainable use of their limited water resources [23,30]. Differences between the bottom-up water footprint and the top-down Input-output (IO) model arise from the intersectoral cutoff [31]. That is, while the former does not consider the entire supply chain, the latter covers the whole of it, which is the main reason for its widespread use in environmental impact assessments. The significance of revealing the inextricable linkages between the natural resources transferred through the complex economic network and its social, economic and environmental issues is assessed in many studies [32–34]. All these studies brought forward practical policy implications for achieving sustainable interactions among social, economic and environmental aspects of consumption patterns based on the multiregional input–output (MRIO) framework.

To date, virtual water trade has not been evaluated thoroughly for Iran, primarily due to lack of data. The exception is the study by Faramarzi et al. (2010) [35], who designed five scenarios to assess how virtual water trade may help to improve cereal production in Iran. They concluded that most of the current water transfer projects in Iran, specifically implemented for wheat production, are not efficient. The reason is that in recipient basins, much larger volumes of water are required for producing the same amount of wheat produced in the source basins. Furthermore, Karandish and Hoekstra (2017) [13] estimated the provincial water savings associated with food trade during the 1980–2010 period. These studies used the bottom-up water footprint approach to just consider certain limited types of agricultural goods, not taking the whole supply chain into account. To better and more comprehensively assess the water trade network, which is conspicuously absent in Iran, we develop a multiregional input–output model to track the origin and the destination of water virtually traded within the country, taking the whole supply chain into consideration. The structure of the rest of the paper is as follows: in the Methods and Data sections, a brief overview of the general IO model and the data sources is described. Appendix A, as the last section, contains more descriptions regarding constructing the MRIO model. This supplementary section is essential, particularly for future studies in Iran, since the procedures outlined in this section describe the procedures for constructing the IO table in the state of lacking transaction data. Following this, we present the results, after which we discuss them and present the limitations of the study. Finally, the conclusion section includes a description of suggested policy implications. The results provide additional insight for policy-makers towards sustainable water management decisions.

## 2. Materials and Methods

### 2.1. Multiregional IO (MRIO) Model

The IO model was first introduced by economist Wassily Leontief [36] and is based on monetary transaction data, exploring interindustry linkages and connections of different sectors available in the economy. The MRIO model is an extension of the general IO model, with a set of simplified models when more than one region is taken into consideration. Denoting the number of regions as $n$, each of which includes $m$ sectors, Equation (1) quantifies the contribution of the production of one sector in any region to the intermediate and final consumption:

$$x_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} a_{ij}^{rs} x_j^s + \sum_{s=1}^{m} y_i^{rs} \tag{1}$$

where $x_i^r$, $a_{ij}^{rs}$, $x_j^s$ and $y_i^{rs}$ denote the total output of sector $i$ in region $r$, the amount of monetary input from sector $i$ in region $r$ required to increase one monetary output of sector $j$ in region $s$, the total output of sector $j$ in region $s$ and the final demand of region $s$ supplied by sector $i$ in region $r$, respectively. We can further transform this equation into matrix notation as follows:

$$X^* = A^* X^* + Y^* \tag{2}$$

where $X^* = \left[x^1, x^2, \ldots, x^n\right]^T$, $A^* = \left(a_{ij}^{rs}\right)$ and $Y^* = \left(y_i^{rs}\right)$ are matrices of the total output, technical coefficients (or direct input coefficients) and final demand, respectively. When Equation (2) is solved, we obtain Equation (3):

$$X^* = (I - A^*)^{-1} Y^*, L^* = (I - A^*)^{-1} = \left[l_{ij}^{rs}\right] \tag{3}$$

where $(I - A^*)^{-1}$ is known as the Leontief inverse or total requirement matrix, whereby each element of $(l_{ij}^{rs})$ represents the amount of output of sector $i$ in region $r$ that is needed (either directly or indirectly) to satisfy one monetary unit of sector $j$'s final demand in region $s$. Water is an essential input in all economic activities. This linkage is reflected through the direct water consumption coefficient, which is defined as the volume of water intake needed to produce one monetary unit of output. This coefficient is calculated as follows:

$$W^r = w_j^r / x_j^r,\ D = \dot{W}(I - A^*)^{-1} \tag{4}$$

where $W^r$ is the direct (or first-round) effect of interindustry interdependencies of sectors in the economy (measured in $m^3/\$10^3$ in this study). Accordingly, $W = \left[W^1, W^2, \ldots, W^3\right]$ is a $1 \times (n \times m)$ row vector of the direct water consumption coefficients by sector and region. Since water is also used indirectly throughout the whole supply chain, we can estimate the total water coefficients $(D)$, also known as the total water multipliers, by multiplying the diagonal direct water consumption matrix $\left(\dot{W}\right)$ by the Leontief inverse matrix.

In this study, we used a three-region MRIO model, the structure of which is provided in Table A1 in Appendix A. The detailed procedure is provided in Appendix A.

Following this, the internal (IWF) and external (EWF) water footprint of the country can be derived as follows:

$$IWF = WC_{domestic} - VW_{export} \tag{5}$$

$$EWF = VW_{import} \tag{6}$$

where $WC_{domestic}$ is the volume of domestic water supplies used in production practices. $VW_{export}$ and $VW_{import}$ are the volume of virtual water exported and imported internationally, respectively.

## 2.2. Data

### 2.2.1. Economic Data to Construct the MRIO Table

We constructed the MRIO table using the 2011 Iranian national IO table, which is the most up-to-date IO table in Iran. There are two types of data required for implementing the IO model: the national transaction data and the water consumption statistics. The national IO table was released recently by the Statistical Center of Iran (SCI) and included 99 sectors producing goods or services [37]. Under the current statistical system in Iran, water intake data for each sector are unavailable; therefore, we aggregated them into eight broad sectors (agriculture, aquaculture, industry, construction, business and finance, public administration, education and household) using the International Standard Industrial Classification [38] of All Economic Activities (ISIC) [39]. This justification is used widely in the literature due to a lack of precise information for each individual sector [23,40]. Trade data regarding the internal and external imports/exports in Iran are not available, and nonsurvey-based methods (or mathematical methods) are needed to reach an acceptable estimate of inter-regional trade flows. As such, a hybrid method was employed to compile the multiregional IO table of Iran instead of using a purely nonsurvey-based approach. In this approach, we used many available statistical data points along with mathematical equations to construct a meaningful table in the state of lacking information. Unlike the nonsurvey-based approaches that are long-established in the literature, the survey-based method is unlikely to be used in research due to the fact that only the central government is in charge of the very time-consuming and, therefore, expensive procedures of collecting data on regional accounts and trade activities [41,42].

2.2.2. Water Availability Data

The 31 provinces in Iran were taken into consideration in constructing the MRIO table, with a subcategorization into three regions of water scarcity (WS) based on provincial-level administrative boundaries (Figure 1): severe ($WS \geq 100\%$), significant ($60\% \leq WS < 100\%$) and moderate ($WS < 60\%$) regions. The water scarcity indicator (WS) is defined as the ratio of withdrawn water to the available water [43], which, in some studies, is also called the withdrawal-to-availability (WTA) ratio [44]. The dataset of direct water input for each of these sectors for the study year 2011 was obtained from annual reports released by the Iran Water Resources Management Company [45].

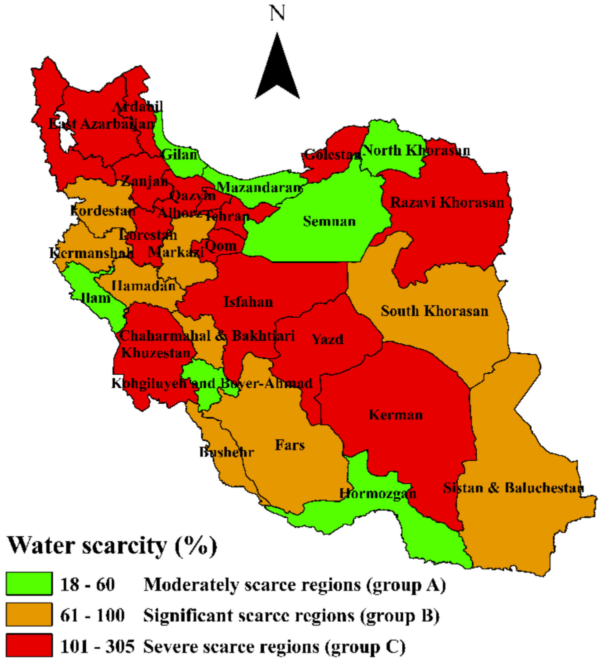


**Figure 1.** Subcategorization of the study area into three regions of moderate, significant and severe water scarcity regions.

The data source for the green and blue water consumption in food production practices within the country was generated using the CROPWAT model [46]. Subsequently, the contribution of green and blue water to total water withdrawals was determined using the agricultural data provided by the Ministry of Agriculture. Green water refers to the soil moisture available for crop production (as a result of rainfall), while blue water denotes the surface and groundwater supplies used for irrigation [47].

## 3. Results

### 3.1. Virtual Water Trade of Regions

Table 1 shows the internal and external virtual water trade of the three classified regions in Iran. The region with severe scarcity, C, was a net virtual water exporter, having a net export of 3583 $Mm^3$. The largest flows were observed in region C, in which 2901 $Mm^3$ of water was imported through internal trade activities (from region C itself and the other two regions, A and B), while 8774 $Mm^3$ of water was exported through the region's external trade activities. The water-rich region A imported 620 $Mm^3$ of water embedded in products and services traded. The moderately exploited region B, similarly, was a net virtual water importer of 1152 $Mm^3$. The economic activities of all the provinces in regions A and B, as classified in Figure 1, were responsible for only 12.2% and 16.4% of the value added in the country, respectively. Nevertheless, provinces in the region C, which produced 71.4%

of the country's value added, were net virtual water exporters, exporting 3584 $Mm^3$ through their trade activities.

As expected, the agriculture sector was responsible for the largest share, with 89.1% of exported and 83.4% of imported virtual water traded internationally. All regions were net virtual water importers in domestic trade but net exporters internationally in food products. Considering the domestic trade, the largest contributions to virtual water imports belonged to the agriculture sector, with 1073, 1765 and 2515 $Mm^3$ in regions A, B and C, respectively, followed by the industry sector, with 123, 226 and 342 $Mm^3$. This net virtual water import of agricultural products is, to a large extent, highlighting the role of consumption-based activities within the country. Distinguishing between blue and green water used in food production reveals that most regions within the country relied on blue water resources. That is, blue water supplies in provinces located in regions A, B and C contributed to 84.4%, 95.0% and 93.9% of total water consumption in food production, respectively. The annual reports released by the Ministry of Energy confirmed that this reliance on aquifers in the middle and eastern parts of the country, in particular, resulted in a groundwater recharge deficit of about 4702 $Mm^3$ per year [48], equal to around 6.9% of irrigation water resources used in food production. From 1990 to 2006, the water table declined by 7.9 m, indicating a mean water table decline of about 0.5 m/year [14].

Despite the high scarcity of region C, this region exported water-intensive agricultural products, making this region a net virtual water exporter. The other two regions also had a net export of water through the transfer of food products associated with foreign trade, with 507 and 795 $Mm^3$ for regions A and B, respectively. Overall, the moderately water-scarce region A, with 620 $Mm^3$, and the significantly water-scarce region B, with 1152 $Mm^3$, were net virtual water importers in the country. These results indicate that the virtual water flows in the highly developed, severely water-scarce region C may be motivated by other factors than water availability, like arable land area, labor, technology, knowledge and capital, local culture or domestic subsidies [49]. There was apparently an inconsistency in trade patterns in Iran. That is, water-abundant regions did not necessarily export virtual water and vice versa. Overall, Iran was a net virtual water exporter, exporting 1811 $Mm^3$ of water abroad.

The results in virtual water flows among different sectors in all regions imply that Iran had an inclination toward the trade of water-intensive, low-value agricultural products, by which it could not generate high revenues for the substantial amounts of exported water. Most evidently, region C, by exporting 3832 $Mm^3$ of water embedded in agricultural products, produced only 5.9% of the value added in the region. Although agricultural practices were much more intensive in region C, the other two regions' agricultural sectors contributed almost twice as much to the value added. This may be caused by the low yields, inefficient water use or producing more water-intensive or low-value products in this region. Another reason is that due to the climatic conditions of regions A and B, these regions have the opportunity to produce certain high-quality agricultural products with much higher market values either internally or externally.

By separating out the volume of water traded by the corresponding transferred monetary value, virtual water traded per unit of exported and/or imported value of the different sectors within the country could be compared (Table 1). The water-intensive agriculture sector had the highest rates of 1830 and 1978 $m^3/\$10^3$ in regions A and B, respectively. In region C, though, the aquaculture sector exported 101,931 $m^3$ per 1000 USD of exported value, almost 45 times that of the value of the agriculture sector. This is primarily due to its geographic location, which is far away from the ocean and the region; therefore, it relies on fish farming (pisciculture) to raise fish commercially in tanks or fish ponds, with higher costs compared to mariculture (fish farming in the ocean). The highly developed, water-stressed region C recorded the highest virtual water imported/exported per unit of monetary value compared to the other two regions. This might be due to its climatic conditions, with less water productivity.

**Table 1.** Internal and external virtual water trade and water footprint of economic sectors and their value added contribution.

| Regions | Sectors | Intermediate Consumption ($Mm^3$) | Internal Virtual Water Trade ($Mm^3$) | | | External Virtual Water Trade ($Mm^3$) | | | Total Net Export ($Mm^3$) | Value of Foreign Virtual Water Traded ($m^3/\$10^3$) | | Value Added Contribution in Region (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Import | Export | Net Export | Import | Export | Net Export | | Imported | Exported | |
| A | Agriculture | 8927 | 1667 | 593 | −1073 | 426 | 933 | 507 | −566 | 1575 | 1830 | 11.48 |
| | Aquaculture | 423 | 14 | 18 | 4 | 4 | 52 | 48 | 53 | 1304 | 1219 | 0.76 |
| | Industry | 465 | 143 | 20 | −123 | 24 | 40 | 16 | −107 | 48 | 32 | 37.36 |
| | Construction | 50 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 176 | 13 | 5.76 |
| | Business and Finance | 51 | 8 | 14 | 7 | 2 | 5 | 3 | 10 | 5 | 6 | 27.70 |
| | Public Administration | 9 | 9 | 1 | −8 | 1 | 0 | 0 | −9 | 18 | 47 | 7.96 |
| | Education | 2 | 1 | 0 | −1 | 0 | 0 | 0 | −1 | 11 | 22 | 3.71 |
| | Household | 7 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 8 | 10 | 5.28 |
| B | Agriculture | 13186 | 2639 | 874 | −1765 | 1179 | 1974 | 795 | −971 | 1759 | 1978 | 11.88 |
| | Aquaculture | 477 | 22 | 20 | −2 | 10 | 60 | 51 | 48 | 1436 | 1371 | 0.59 |
| | Industry | 723 | 271 | 45 | −226 | 78 | 92 | 14 | −212 | 28 | 36 | 33.09 |
| | Construction | 67 | 1 | 0 | −1 | 1 | 1 | 0 | −1 | 138 | 18 | 5.49 |
| | Business and Finance | 63 | 17 | 14 | −3 | 6 | 9 | 2 | −1 | 5 | 9 | 27.98 |
| | Public Administration | 16 | 14 | 1 | −13 | 4 | 1 | −2 | −15 | 12 | 38 | 10.94 |
| | Education | 4 | 1 | 0 | −1 | 0 | 0 | 0 | −1 | 12 | 35 | 4.43 |
| | Household | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 16 | 5.60 |
| C | Agriculture | 34870 | 3986 | 1471 | −2515 | 7157 | 13504 | 6347 | 3832 | 1768 | 2231 | 5.91 |
| | Aquaculture | 406 | 42 | 4 | −38 | 52 | 51 | −2 | −39 | 15937 | 101931 | 0.09 |
| | Industry | 3198 | 407 | 65 | −342 | 1317 | 1308 | −9 | −351 | 49 | 27 | 37.21 |
| | Construction | 277 | 6 | 0 | −6 | 17 | 12 | −5 | −11 | 265 | 13 | 5.09 |
| | Business and Finance | 292 | 30 | 53 | 23 | 65 | 319 | 254 | 277 | 5 | 6 | 33.24 |
| | Public Administration | 77 | 35 | 4 | −31 | 160 | 24 | −136 | −167 | 18 | 18 | 10.23 |
| | Education | 13 | 1 | 0 | −1 | 2 | 0 | −2 | −3 | 19 | 39 | 3.04 |
| | Household | 50 | 1 | 10 | 9 | 2 | 39 | 37 | 46 | 9 | 9 | 5.19 |

### *3.2. Water Footprint of Regions and Sectors*

From a consumption-based point of view, regions have different characteristics regarding their internal and external water footprint. Regions A and B shared almost the same structure, in which their internal water footprint accounted for 95.1% and 90.7% of the total water footprint, respectively. This can primarily be attributed to the fact that these regions do not engage in the global trade network but attempt to produce most of their requirements domestically, in line with the self-sufficiency strategy in the country [50]. This is more evident in water-intensive goods (e.g., agricultural products). Region C, however, had an external water footprint contributing 26.8% to the total water footprint, 15.0% of which was brought about by industrial trade activities (Figure 2). This is due to the fact that residents of regions with stronger economies consume more industrial products and services, which in turn increases the contribution of nonfood products to the total water footprint (WF).

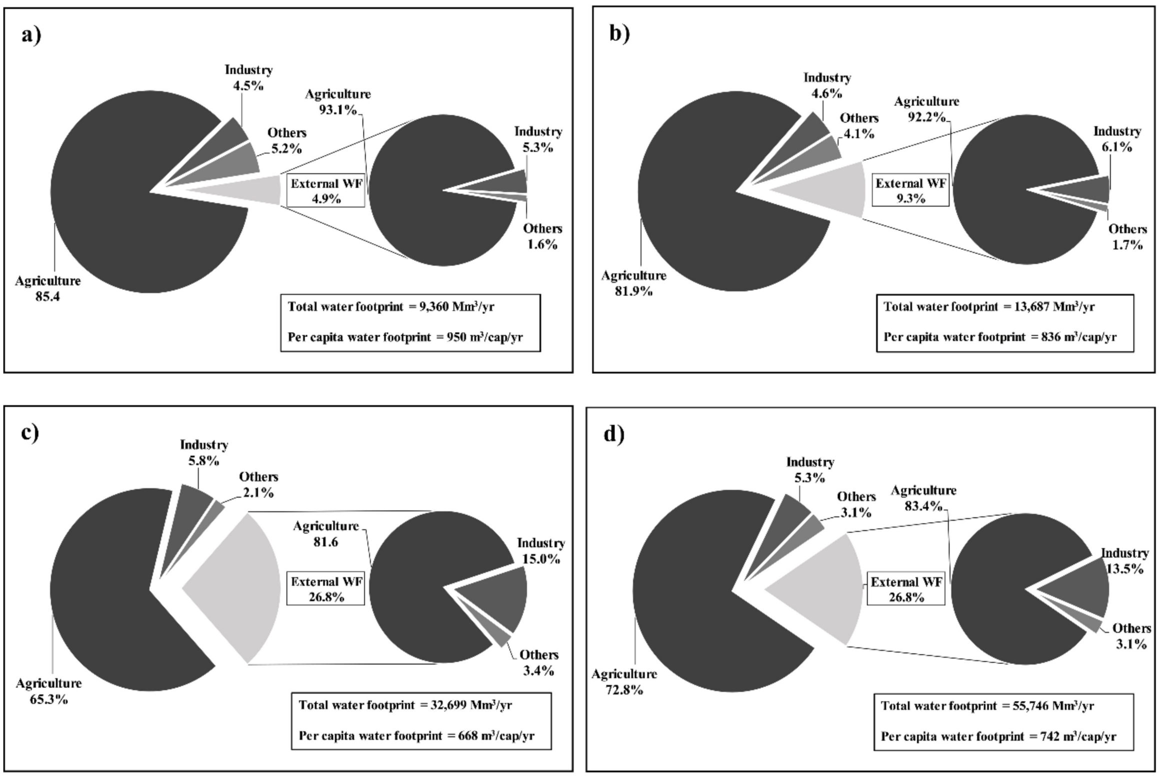


**Figure 2.** Water footprint composition: (**a**) region A, (**b**) region B, (**c**) region C and (**d**) the entire country.

We found that the WF of region C accounted for 58.7% of Iran's WF (32.7 Gm$^3$/year), indicative of its trade activities, particularly its external exports, resulting in 8.8 Gm$^3$/year, which was 586.4% and 94.8% higher than that of regions B and A, respectively. Regions B and A ranked next in the national WF, with 24.6% (13.7 Gm$^3$) and 16.8% (9.4 Gm$^3$), respectively. The per capita WF, however, followed a completely different pattern in these regions, with the highest in region A, with 950 m$^3$/cap/year, followed by regions B and C, with 838 and 668 m$^3$/cap/year, respectively. Overall, Iran had a per capita WF of 742 m$^3$/year.

On average, the agriculture sector was responsible for 88.5% of the national WF, slightly less than the global average of 92.2% [51]. The contribution of the industry sector to the national WF was 7.8%, almost two percent less than the global average, at 9.6% [52]. Considering the fact that most parts of Iran have an arid climate, with an average precipitation of about 250 mm per year, most of which occurs in winter (i.e., little or no precipitation during several months of the year), our results suggest that blue water resources contributed 92.2% to the national WF. This is notable, as the global virtual water trade is dominated by green water resources, making up 74% of the total water footprint globally [51].

## 4. Discussion and Limitations of the Study

### 4.1. Virtual Water Trade and Water Footprint

This is the first study to trace the virtual water flows within and from Iran using the most detailed data available and taking the whole supply chain into account. The water footprint of the country was also estimated. The results, however, carry some extent of uncertainties inherent in the data and the models used in this study. Although about 78% of the water used in food production globally is from green water resources [53,54], we showed that, on average, more than 86.4% of the water used in food production in Iran was provided by limited blue water resources with high opportunity and environmental costs, yet with higher reliability when compared to green water supplies. Even the northern regions of the country with adequate rainfall throughout the year use up their blue water resources to produce only certain types of crops, namely, rice, tea and citrus, largely due to their limited arable land and specific soil characteristics. Moreover, this study reveals that regions with higher water availability seemed to have virtual water deficits, suggesting that virtual water flow is not only driven by water resource endowments but by other factors, such as arable land area, labor, local culture and policies regarding trade activities, as suggested by Guan and Hubacek (2007) [49]. Comparing the trade data of different sectors reveals that, as expected, agriculture played a key role in virtual water exports. That is, all regions in the country were net virtual water exporters through the transfer of food products. For example, about 6% of the UK's water footprint is located in Iran, mostly by importing two types of water-intensive crops cultivated in the southern provinces with severe water scarcity: dates (63%) and pistachios (33%) [55]. Producing and exporting food irrigated using rapidly depleting aquifers made Iran the second-leading country in the world in terms of groundwater depletion [10], threatening not only water and food security but also socioeconomic sustainability in the country.

The region's water footprint is highly correlated with the economic conditions represented by the value added. Provinces with stronger economies located in region C had higher water footprints in comparison with regions A and B. This is attributed to the consumption patterns of residents in those regions along with trade activities. We estimated the total water footprint of Iran as 55.7 Gm$^3$ for the year 2011, which was 742 m$^3$/cap/year. Other studies estimated the water footprint of Iran as 102.6 Gm$^3$/year with 1624 m$^3$/cap/year for the period of 1997–2001 [52] and 75.7 Gm$^3$/year with a per capita blue water footprint of 589 m$^3$/year for the period of 1996–2005 [56]. These studies, however, used very limited climatic information, thereby not capturing the temporal and spatial variability of both climate and water availability across the entire country [57]. Furthermore, none of these global assessments considered the interindustry interdependencies within the whole supply chain.

All regions in the country relied on internal water resources in a way that the internal water footprint was responsible for 95.1%, 90.7% and 73.2% of the total water footprint in regions A, B and C, respectively. While the most considerable share of both the internal and external water footprint belonged to the consumption and trade of agricultural products, this sector does not contribute much to the economy of the country, highlighting the total (direct plus indirect) water used per unit of economic output. There was also an inconsistency between the distribution of water resource endowments and the spatial patterns of trade. That is, the severely water-scarce region C was a net virtual water exporter, while the moderately water-scarce region A imported large volumes of water through its trade activities.

### 4.2. Major Destinations of Exports and Water-Intensive Trade Structure

In this section, we give a general overview of export patterns associated with agricultural and industrial products and provide a comparison between the different products based on their contribution to the national income. Iran exports a much higher volume of industrial products to other countries than it does agricultural crops. That is, in 2011, the exports of the industry sector accounted for 95.8% of the total amount of exports, whereas the figure for the agriculture sector was 3.4% (Figure 3). However, the volume of exported water through food products was more than 11 times larger than for industrial products—largely due to its larger total water multipliers (direct plus indirect water used per unit of economic output)—in comparison with industrial products, as shown in Figure 4. Yet the exported volume of water only contributed to 10.5% of income, while the share of industry was considerably higher, at 95.4%. The use of blue water resources in particular comes at the cost of environmental issues such as declining groundwater tables at an increasing rate, drying lakes and rivers, serious land subsidence, desertification, more frequent dust storms, water quality degradation and soil erosion [13]. Yet national decision-makers aim to achieve complete food self-sufficiency (i.e., cutting the food imports to zero) and, at the same time, strive to increase food exports. It is due to this strategy that exports of agricultural products increased from 2.7 million tons in 2011 to 5.0 million tons in 2017, an 85.4% increase in six years despite the overabstraction of water and its concomitant environmental consequences. This reveals that the resource water is somehow overlooked in policy-making.

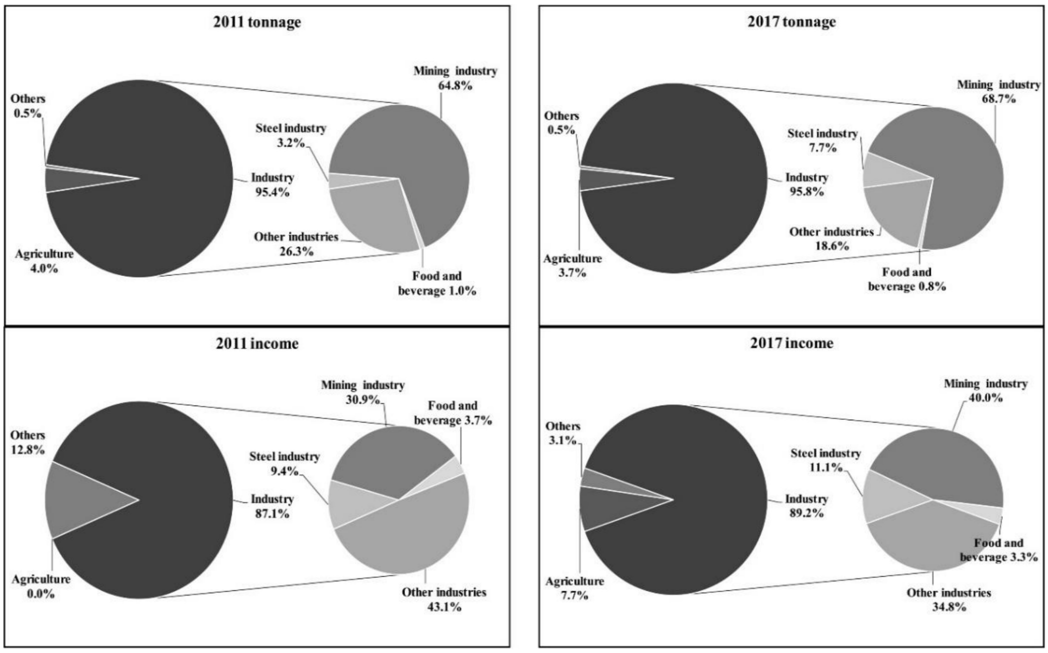


**Figure 3.** Contribution of agricultural and industrial products to exports (tons) and their resulting income ($).

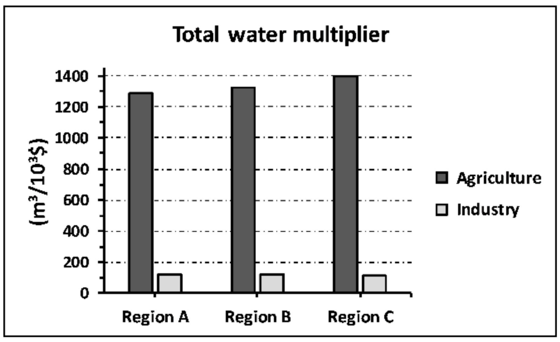


**Figure 4.** Comparison of total water multipliers ($m^3/\$10^3$) between the agriculture and industry sectors.

While economic policies focused on land reforms, water-intensive steel production industries have been developed in the heart of the desert, exacerbating groundwater exploitation as the only source of water available. Figure 3 demonstrates that the steel industry contributed to 3.3% (around 2 million tons) of nonfood exports, making up 9.4% of the national income in 2011. Economic development has increased the demand for such materials, and, accordingly, the exports of steel products increased to more than 10 million tons in 2017, making up 7.7% of nonfood exports, with a share of about 11.1% of the national income.

Overextraction of groundwater through deep wells to fulfill the steel industry's water requirements has caused severe land subsidence within the country, more frequently in hyperarid provinces (Isfahan, Yazd and Kerman), with an increasing number of sinkholes (depressions of up to 80 m in diameter and 50 m deep), forcing local residents to evacuate the endangered towns and villages [3]. It is, therefore, more sensible to produce these types of products in coastal regions, where the opportunity and environmental costs associated with water withdrawal would be lower. Moreover, apart from the fact that groundwater is almost without any charge to all kinds of users (i.e., industry and irrigation), the Iranian government subsidized energy costs, encouraging overextraction beyond the groundwater replenishment capacity.

Additionally, from an economic perspective, increasing trends in exports from 2011 to 2017 were accompanied by decreased efficiency, i.e., generating less revenue per ton of output. The substantial reduction in the value per ton of export sales from 2011 to 2017 illustrates the scale of policy barriers in trade activities, on top of which are the unprecedented recent economic sanctions imposed by the US against Iran.

Figure 5 shows the destinations of agricultural and industrial products exported in 2011. Considering all trade partners, it can be seen that there was a great difference between the economic value of exported products in physical units. This might be driven by the type of products transferred to a certain trade destination and, also, by the value of currency under the treaty. Overall, Iraq is the major destination for food products, with a share of 43.6%. This significant share contributed to only 24.7% of income, i.e., 1.3 tons per 1000 USD. Among other partners, the United Arab Emirates and Russia ranked next, with 13.6% and 7.6% of exports, respectively, sharing the same price of 0.7 tons/$\$10^3$. Germany, the Netherlands and France, as European partners of Iran, recorded prices of 0.15, 0.28 and 0.10 tons/$\$10^3$, respectively, highlighting the higher values of their currency in comparison with the leading partners mentioned earlier. Some of these ratios are presented in Figure 5. The large volumes of water exported virtually through the trade of food products indicate an oversimplification of environmental issues brought about by this water-intensive trade structure. As such, it can be concluded that in Iran, economic output (GDP) is often at higher levels of importance in comparison with environmental problems, mainly due to political prioritizations.

As such, this study investigated virtual water transfer patterns in Iran, which have been proven to have a key role in global water savings [58]. Unlike other studies that concluded that Iran was a net virtual water importer [13,52,59], we showed that Iran exported 1811 $Mm^3$ of water.

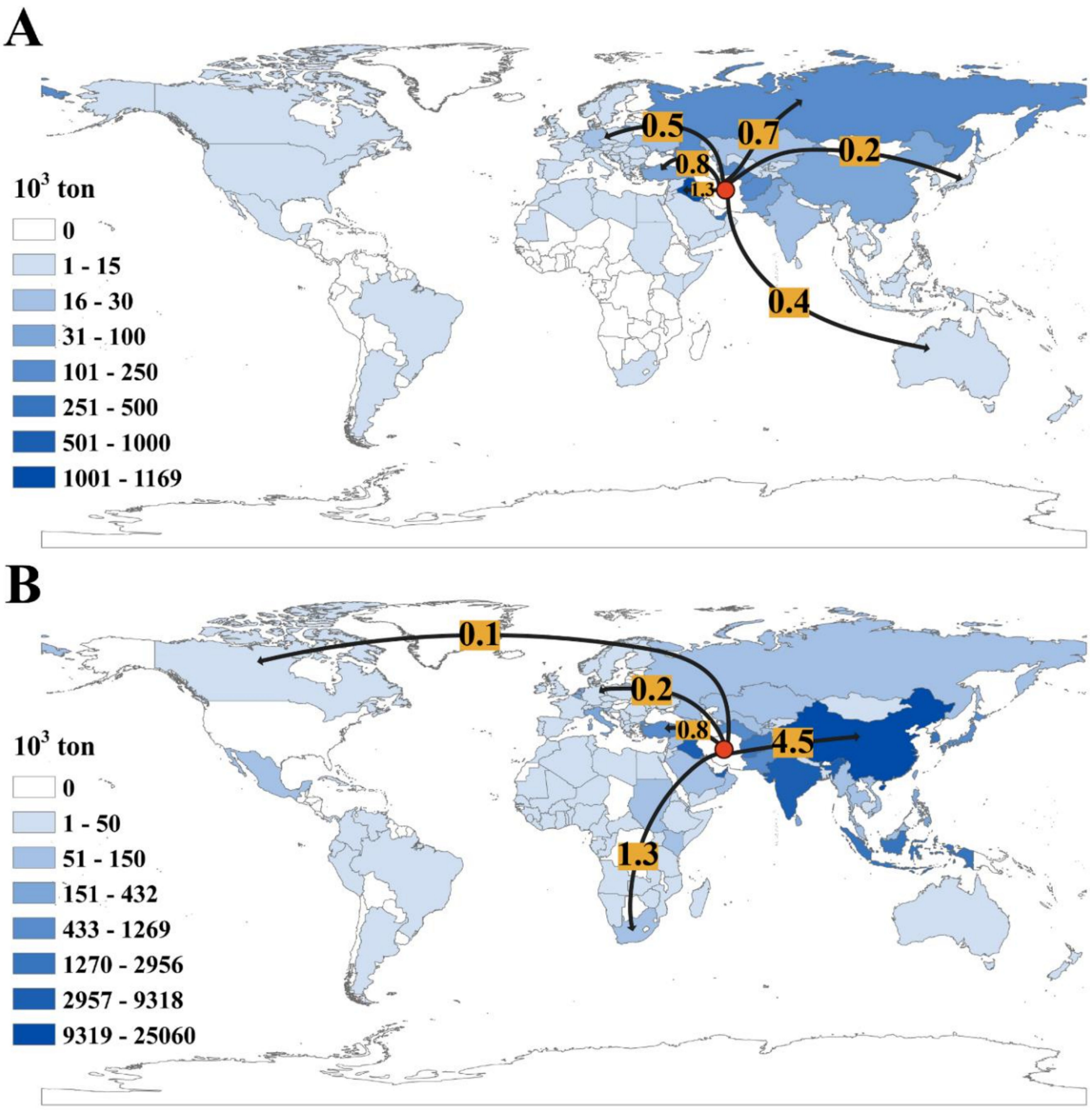


**Figure 5.** Major destinations of exports for agricultural (**A**) and industrial (**B**) products. Arrows and numbers represent the physical units exported per economic value (tons/$10^3$).

### *4.3. Limitations of the Study*

In this study, we used the monetary IO tables to trace and model the virtual water flows that represent a physical concept. It would be desirable to trace the virtual water flows using physical IO tables, yet these are not available for Iran thus far. In Iran, regional IO tables are not released by the government. We thus had to work with some limitations in constructing the multiregional IO table. First, trade data regarding either internal or external imports and exports were not available. Second, final demand figures associated with household consumption, government expenditures and investments were also not available. Third, it should be noted that the national IO tables with all their aforementioned limitations are released merely every 10 years by SCI. We used the most recent national IO table for 2011, which was published with a six-year delay in 2017. In assigning the water use coefficient to a particular sector—industry, for example—we used the average group data, whereas there is a high diversity of products and processes within the industry sector with different water use statistics. For instance, the steel, mining, food and beverages, textile goods, paper production and chemicals industries have different amounts of water as their inputs. As such, the volumes of water attributed to the exports of these have not been assessed separately, and they are all regarded as the industry sector. More detailed water use coefficients are required in order to better quantify the contribution of each specific sector to the virtual water transfer.

There are some other important factors that need to be taken into consideration when it comes to trade policies and decision-making, such as socioeconomic aspects, including employment compensation, urbanization (immigration), adaptive capacity or income status. Environmental issues associated with water quality degradation and wastewater impacts have not been considered in this study due to lack of data, even though they play a critical role and are often missing in coupled quantity and quality water assessments [60]. These are left for future research. Moreover, the distribution of Iran's land and water resources should be taken into consideration since their distribution is unbalanced, i.e., water-abundant regions lack the land resource endowments and vice versa.

## 5. Conclusions

In this paper, we assessed the virtual water trade in Iran based on a multiregional input–output model. Recent policies regarding the expansion of agriculture and the establishment of water-intensive industries in the heart of the desert have resulted in water problems in the country. This has disturbed the balance between the environment and development that has existed for thousands of years. We showed that Iran was a net virtual water exporter, exporting 1811 Mm$^3$ of water. We also showed that there was an inconsistency between the water availability status and trade pattern, whereby regions with severe water scarcity virtually exported a large volume of water to other countries. In contrast, the northern parts of the country with adequate water supplies were net virtual water importers. The current study provides additional insight for policy-makers who may still consider trade liberalization of agricultural products and aim at reaching complete self-sufficiency in food production despite all the environmental issues that come with such a strategy.

Our study also evaluated the contribution of each economic sector to the virtual water trade. As expected, the agriculture sector was responsible for the largest share of 89.1% of exported water, with a small share of 7.6% in the value added and 10.5% of the national income. Overall, Iran was a net virtual water exporter regarding the food trade (2295 Mm$^3$), which can be seen as the main reason for environmental issues that have arisen in the country. The industry sector, though, with much lower direct and indirect water consumption in comparison with agriculture, had the most significant role in the national income. The current inefficient use of limited water supplies in Iran would endanger water and food security. This indiscriminate use of water resources in the past few decades has triggered large interbasin water transfer projects. These projects, apart from their astronomical costs, have serious environmental, social and economic consequences. This highlights the fact that Iran needs to reconsider its water-intensive trade patterns in order to make its limited water supplies available for sectors and processes that can contribute more to the economy. Collaborating internationally in order to increase the imports of water-intensive crops, preferably with countries with sustainable water use, can reduce the pressures exerted on rapidly depleting aquifers in Iran. Sustainable water use measures are key to achieving water security, including eliminating the cultivation of water-intensive crops, subsidizing the improvement of efficiency in irrigation and adequate water pricing.

Based on the most detailed data available to date, this study provided an estimate of the total water footprint of the different regions and sectors. Our results showed that water footprints differed across regions commensurate with their economy. That is, regions with developed economies had higher water footprints and vice versa. Also, the internal water footprint constituted the most considerable share of the total water footprint, confirming the attempts made by the government to produce all goods and services domestically. An adjustment of the international trade pattern and domestic mass production of water-intensive, low-value agricultural products is required to ensure the sustainability of natural resource utilization, guarantee resilience in facing droughts and reduce vulnerabilities.

We confirmed the limitations of this study, including a lack of historical datasets of water allocation, the absence of an up-to-date national IO table, provincial characteristics (land availability in particular) and a lack of detailed water intake data of all economic sectors. As such, further studies are needed to address all these limitations.

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## Appendix A

Table A1 shows the general structure of Iran's MRIO framework used in this study. The procedures for quantifying the presented elements are as follows:

First step: we calculate the $Z^{AA}$, $Z^{BB}$ and $Z^{CC}$ matrices. These matrices are representative of the first part of the IO table attributed to regions A, B and C, which are calculated using the CHARM-RAS (Cross-hauling Adjusted Regionalization Method) method. Readers are referred to [39] for more details. Using this method, we estimate the imports and exports of regions, including intermediate trade, capital and final imports/exports and foreign imports/exports.

**Table A1.** Standard format of Iran's multiregional input–output (MRIO) table.

| **Output/Input** | **Intermediate Demand** | | | **Final Demand** | | | **Total Demand** |
|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **Internal Final Demand** | **Final and Capital Exports to Inside the Country** | **Exports to Outside the Country** | |
| A | $Z^{AA}$ | $Z^{AB}$ | $Z^{AC}$ | $FD^{A}$ | $EI^{A}$ | $EF^{A}$ | $D^{A}$ |
| B | $Z^{BA}$ | $Z^{BB}$ | $Z^{BC}$ | $FDI^{B}$ | $EI^{B}$ | $EF^{B}$ | $D^{B}$ |
| C | $Z^{CA}$ | $Z^{CB}$ | $Z^{CC}$ | $FD^{C}$ | $EI^{C}$ | $EF^{C}$ | $D^{C}$ |
| Value Added | $V^{A}$ | $V^{B}$ | $V^{C}$ | | | | |
| Intermediate Output | $X^{A}$ | $X^{B}$ | $X^{C}$ | | | | |
| Final and Capital Imports from Inside the Country | $MI^{A}$ | $MI^{B}$ | $MI^{C}$ | | | | |
| Imports from Outside the Country | $MF^{A}$ | $MF^{B}$ | $MF^{C}$ | | | | |
| Total Supply | $S^{A}$ | $S^{B}$ | $S^{C}$ | | | | |

Second step: in this step, we calculate the foreign exports and imports using the following equations developed by [61]:

$$EF_i^A = \frac{X_i^A}{X_i^K} * E_i^K \tag{A1}$$

$$MF_i^A = \frac{FD_i^A}{FD_i^K} * I_i^K \tag{A2}$$

where $EF_i^A$ and $MF_i^A$ refer to the foreign exports and imports of sector $i$ in region A, respectively. $X_i^A$ and $X_i^K$ represent the output of sector $i$ in region A and in the country, respectively. $E_i^K$ and $I_i^K$ are the total exports and imports of sector $i$ in the country, respectively. $FD_i^A$ and $FD_i^K$ are the sum of household consumption, government expenditures and investments (internal final demand) in region A and in the country, respectively.

Third step: at this stage, the domestic exports and imports are estimated as follows:

$$EII_i^A = E_i^A - EF_i^A \tag{A3}$$

$$MII_i^A = I_i^A - MF_i^A \tag{A4}$$

where $EII_i^A$ and $MII_i^A$ are the domestic (or internal) exports and imports of sector $i$ in region A, respectively.

Fourth step: this step belongs to the calculation of intermediate imports and exports, which are based on methods developed by [62]:

$$ES^A = A^{B+C} * EII^A \tag{A5}$$

$$MS^A = A^A * MII^A \tag{A6}$$

$ES^A$ denotes the matrix of intermediate exports of region A, and $A^{B+C}$ represents the sum of the technical coefficients matrix of regions A and B. $MS^A$ describes the intermediate import matrix of region A. $A^A$ is the technical coefficients matrix of region A. These equations are also used for the other two regions. For example, for region B, these equations can be formulated as follows:

$$ES^B = A^{A+C} * EII^B \tag{A7}$$

$$MS^B = A^B * MII^B \tag{A8}$$

Fifth step: the final and capital imports and exports of sector $i$ in region A are calculated as follows:

$$EI_i^A = E_i^A - \sum_{j=1}^{i} ES^A \tag{A9}$$

$$MI_i^A = I_i^A - \sum_{j=1}^{i} MS^A \tag{A10}$$

where $EI_i^A$ and $MI_i^A$ denote the final and capital exports and imports of sector $i$ in region A, respectively. The summation notations in Equations (A9) and (A10) refer to the column aggregation of the intermediate exports and intermediate imports matrices, respectively.

Sixth step: inter- and intraregional trade data are not available for Iran. As such, in the final stage of constructing Iran's MRIO table, trade flows between regions are aimed to be estimated. That is, for region A, for example, we aim to quantify the elements of the transaction matrices, $Z^{BA}$, $Z^{CA}$, $Z^{AB}$ and $Z^{CA}$. The gravity model is widely used as a nonsurvey-based method to calculate inter-regional trade matrices. This model uses inter-regional railroad freight transportation and flows of bulk commodities to calculate trade flows between regions [63,64].

$$T_i^{rs} = \frac{X_i^r * X_i^s}{X_i^{r+s}} * Q_i^{rs},\ Q_i^{rs} = \frac{k_i^{rs}}{(d^{rs})^{e_i}} \tag{A11}$$

$T_i^{rs}$ represents the trade flows of sector $i$ between regions $r$ and $s$. $X_i^r$, $X_i^s$ and $X_i^{r+s}$ are the total output of sector $i$ in region $r$, the total output of sector $i$ in region $s$ and the total production of sector $i$ in the two regions. $Q_i^{rs}$ is a parameter comprised of the constant $k_i^{rs}$ and $d^{rs}$, the latter of which represents the distance between the two regions. $k_i^{rs}$ is determined based on empirical observations and is set to one in this study [65]. $e_i$ is the power of $d^{rs}$, which has been set to one based on the suggestion of [64]. Following this, the contribution of regions B and C to the intermediate trade practices of sector $i$ in region A has been calculated as follows:

$$T_i^{AB} = T_i^{BA} = \frac{X_i^B * X_i^A}{X_i^{B+A}} * \frac{k_i^{BA}}{(d^{BA})^{e_i}} \tag{A12}$$

$$T_i^{AC} = T_i^{CA} = \frac{X_i^C * X_i^A}{X_i^{C+A}} * \frac{k_i^{CA}}{(d^{CA})^{e_i}} \tag{A13}$$

The contribution of the other two regions to the intermediate trade practices can also be quantified by sector and region using these equations. It should be noted that the matrices Z and T are conceptually different. The matrix T denotes the trade flows, taking three factors, production, demand and distance, into account. The matrix Z, however, indicates the trade flows of regions considering the intermediate use and intermediate demand in addition to the three factors mentioned earlier. Finally, the RAS method is employed to adjust the estimated intermediate trade of the regions (T), yielding the accurate trade flows (Z).

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