

Article

Inter-Regional Coordination to Improve Equality in the Agricultural Virtual Water Trade

Dong Yan ¹, Zhiwei Jia ¹, Jie Xue ^{2,3}, Huaiwei Sun ^{1,*}, Dongwei Gui ^{2,3,*}, Yi Liu ^{2,3} and Xiaofan Zeng ¹

¹ School of Hydropower and Information Engineering, Huazhong University of Science and Technology, Wuhan 430074, China; yandong@hust.edu.cn (D.Y.); m201873747@hust.edu.cn (Z.J.); zengxiaofan@hust.edu.cn (X.Z.)

² State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; xuejie11@mails.ucas.ac.cn (J.X.); liuyi16@mails.ucas.edu.cn (Y.L.)

³ Cele National Station of Observation and Research for Desert-Grassland Ecosystems, Cele 848300, China

* Correspondence: huaiweisun@whu.edu.cn (H.S.); guidwei@ms.xjb.ac.cn (D.G.)

Received: 15 September 2018; Accepted: 21 November 2018; Published: 3 December 2018



Abstract: Sustainable agriculture in China is threatened by rapid socioeconomic development, urbanization, and climate change. In addition, the distribution of freshwater resources between regions is highly unequal, and water shortages are common in arid regions. The virtual water trade can help to ease water shortages in arid areas by utilizing the comparative advantage of water resources in other areas. However, sometimes the patterns of the virtual water trade do not fit the distribution of water resources and, in these instances, inter-regional coordination would help to improve the level of equality in the virtual water trade. We combined the concept of the Gini coefficient with a multi-objective optimization model to investigate the inter-regional coordination of the virtual water trade in an arid region of China. Agricultural data from different regions of Gansu Province in 2014 were used to explore methods of improving the equality of virtual water flow patterns in the agricultural sector. Three constraints (a crop supply constraint, an irrigation water constraint, and an economic benefit constraint) were set up to investigate the relationship between different challenges and the effects of inter-regional coordination. Our results validated the use of the proposed method in Gansu Province and indicated that it could be applied to other arid regions. Variations in crop supply, irrigation water, and economic benefits were found among the different constraint scenarios, illustrating the trade-offs between water-saving and agricultural objectives. Our results also showed the balance between various factors, including the equality of the virtual water patterns, water-saving measures, and economic benefits. These results support the effectiveness of inter-regional coordination and indicate that the improvement in equality and the adjustment cost should be balanced. Our findings will help to guide the planning of local crop acreages to achieve the best virtual water balance model between regions.

Keywords: sustainable agriculture; virtual water trade; equality; inter-regional coordination

1. Introduction

Meeting the growing world population's demands for food is a challenge, with limited freshwater resources and agricultural land under increasing pressure from climate change, population growth, and socioeconomic development [1]. In the past decade, research and policy have focused on the rapidly-increasing scarcity of natural resources, with water–energy–food interdependencies increasingly framed as a nexus or resource trilemma [2]. The agricultural sector has become the largest consumer of

the Earth's available freshwater over the last 50 years, comprising 70% of withdrawals of blue water from watercourses and groundwater are for agricultural use [3]. Efforts to reduce water use in agriculture have intensified as other sectors have increased their demand for water. The virtual water transfers (VWTs) associated with the food trade save ~6% of the water used in agriculture [4], and it is therefore interesting to explore VWTs in arid regions where there is increasing concern about the sustainability of water resources [5] and the expansion of agricultural land [6].

Virtual water is the amount of water required to produce a food or commodity, and is measured in cubic meters of water per ton of crop or product [7–9]. In this study, the virtual water content (VWC) of every commodity has two meanings. The first meaning refers to the water consumed during the production process in the place of origin; the other meaning refers to the water consumed if the same commodity is produced within the area in which it is consumed. The latter meaning indicates the water-saving effect and the effect of importing commodities on the local water deficit. Correspondingly, the VWT also has two meanings. A virtual water exporter both consumes water and exports water to other areas; a virtual water importer replaces the water used and also uses imported water to supply other needs. VWTs can change the structure of the supply and demand of water and take advantage of water-rich areas, improving the supply of water in arid areas or in dry periods [10,11]. Montesinos et al. [12] estimated the virtual irrigation water balance for the spatial redistribution of irrigated crops in arid regions. Su [13] and [14] considered VWTs in the allocation of agricultural water and integrated this concept into real water management scenarios.

The direction and amount of virtual water flows (VWFs) do not always match the distribution of water resources. With this in mind, the management of agricultural water resources is particularly important. China is facing many challenges to sustainable agriculture as a result of climate change, rapid urbanization, and rapid socioeconomic development, combined with very limited water resources and arable land per capita. The management of agricultural water is urgently required to cope with the severely-limited water resources in China, especially in arid regions, and is related to national economic and social sustainable development [15]. China is a large agricultural country, and agricultural problems have always been considered at a national level. The management of agricultural water makes an important contribution to mitigating water crises and conflicts between regions. The pressure of water shortages is not always alleviated in water-scarce areas, or may be shifted to other regions [16,17] because the virtual water often flows to water-rich areas from water-scarce areas [18]. This results in negative impacts on both ecosystems and economic development [19], and increases the inter-regional inequality in the utilization of water resources [20]. Water equality emphasizes equal rights in sharing water between different areas and different social classes.

There are two important inequalities in VWTs. First, there are differences between different areas in the ratio of the virtual water outflow to the amount of water in the region. Second, the ratio of the inflow of virtual water to the amount of local water available is lower in water-scarce areas, which means that the water replaced by imports is insufficient to support sustainable development. This inequality leads to an excessive consumption of local water resources and difficulties in exploiting the comparative advantage of water-rich areas.

Inequalities in water resources affect the patterns of both the export and consumption of virtual water, and therefore, a nationwide compensation scheme may be required to support both economic development and the protection of water resources in arid regions [21]. Efficiencies in the use of water in agriculture, especially in arid and semi-arid regions, face challenges from the limited availability of water and intense competition from other water-demanding sectors [22]. Hassan and Thiam [23] recommended improvements in the efficiency of water use and the competitiveness of agriculture in achieving lower net exports of water and food security objectives in arid regions. The realization of these recommendations requires inter-regional coordination. When different areas are linked geographically and through economic ties, VWTs will help to achieve efficiencies in water use in different areas, and improve economic contacts between areas [24]. This shows that the management of VWTs is an inter-regional problem and requires the coordination of all the relevant areas to adjust

the spatial redistribution of the controlling factors, including, but not limited to, the population, the level of technological development, and the supply and demand of commodities [25].

There are two key questions related to inter-regional coordination. First, what is the objective and, second, how can VWFs be controlled from an integrated perspective. Seekell et al. [20] used the United Nations human development index for each country to evaluate inequalities in water use. With the aim of improving the suitability of the trade in virtual water for the management of water resources, we propose methods of evaluating the equality of VWFs and implementing inter-regional coordination.

The structure of this paper is as follows. Section 2 defines the inter-regional coordination of VWTs, including the calculation of agricultural VWFs. The first two parts of Section 3 describe the study area and the types and sources of data used. Sections 3.3 and 3.4 explain the assessment of VWF patterns, and the optimization of inter-regional coordination models. Section 3.5 defines three different constraints in this study. Section 3.6 explains the pattern of VWFs using the particle swarm optimization (PSO) algorithm. Section 4 discusses the results before and after adding three constraints. Section 4.3 discusses the limitations of this study, and the conclusions are presented in Section 5.

2. Estimation of Agricultural VWFs

The difference between the supply and demand of water by crops greatly affects the import and export of water [26,27]. Agricultural VWFs can be estimated as follows.

2.1. Virtual Water Outflows

The virtual water outflow is estimated by

$$VWO^k = \sum_m PW_m^k XL_m^k \quad (1)$$

where $k = 1, 2, \dots, n$ represents the district, n is the number of districts, VWO^k is the virtual water outflow of district k , m represents the type of crop, PW_m^k is the water consumption per unit mass of crop m in district k , and XL_m^k is the volume of locally produced crop m exported out of district k .

$$XL_m^k = \begin{cases} y_m^k - d_m^k & y_m^k - d_m^k > 0 \\ 0 & y_m^k - d_m^k \leq 0 \end{cases} \quad (2)$$

where y_m^k is the yield of crop m in district k , and d_m^k is the demand for crop m of district k .

2.2. Virtual Water Inflows

The virtual water inflow from the trade in crops is equal to the amount of water consumed if the same amount of imported crop is produced in the local area. It is estimated by

$$VWI^k = \sum_m PW_m^k XS_m^k \quad (3)$$

where VWI^k is the amount of virtual water inflow in district k and XS_m^k is the volume of crop m imported into district k .

$$XS_m^k = \begin{cases} d_m^k - y_m^k & d_m^k - y_m^k > 0 \\ 0 & d_m^k - y_m^k \leq 0 \end{cases} \quad (4)$$

where y_m^k is the yield of crop m in district k , and d_m^k is the demand for crop m of district k .

3. Study Area and Methods

3.1. General Characteristics of the Study Area

The study area is Gansu Province in northwest China, which lies in the temperate monsoon climate zone, but has lower rainfall than similar regions. The average annual precipitation decreases from southeast to northwest and varies from 96 to 615 mm. The population of Gansu Province and the land area used for crops have both increased over the past 20 years. The combination of the requirement for large amounts of water for the population and agricultural use and the province's severely-restricted water resources poses significant challenges to sustainable development. The provincial government is responsible for ensuring food security and the sustainability of water resources, and also manages inter-regional coordination.

Figure 1 shows that Gansu Province is divided into nine areas [28]. Based on the river network [29], these areas are found in three different river basins. The SLRD, HRD, and SYRD are located in the Northwest Inland Basin; the FRD, JRD, DRD, YRD, and WRD are part of the upstream area of the Yellow River Basin; and the CJD is in the upper reaches of the Yangtze River Basin. Figure 1 also shows the mean annual precipitation of the different areas. Precipitation in Gansu Province shows large spatial differences. A shortage of precipitation is illustrated by the minimum annual precipitation of 96 mm in the SLRD, whereas the largest annual precipitation is 615 mm in the FRD. The FRD is excluded from our analysis, however, because the size of the cropped area is not reported in the statistical yearbook [30].

3.2. Data Used

We selected two crops of corn and wheat growing in Gansu Province for analysis. These crops accounted for a large proportion of the virtual water trade between regions in Gansu Province. According to the *Gansu Statistical Yearbook* [30] and the *Water Resources Bulletin of Gansu* [28], the consumption of agricultural water by corn and wheat in Gansu Province is 6.43 billion cubic meters, accounting for 65.75% of the total consumption of agricultural water (9.78 billion cubic meters) in this province.

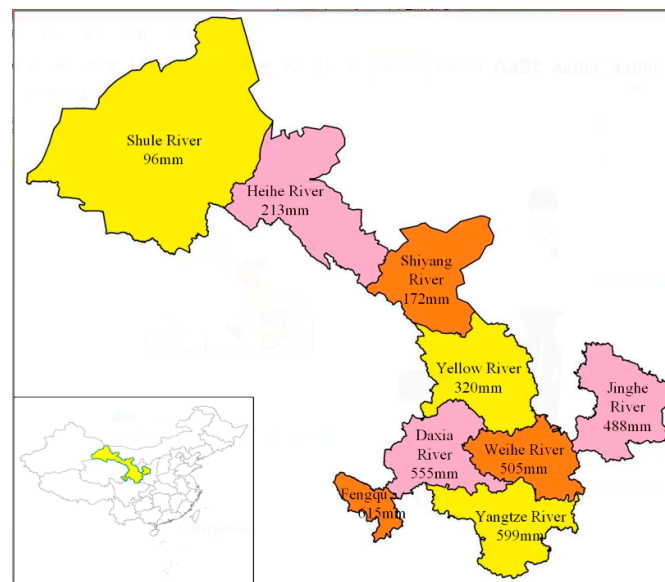


Figure 1. The nine divisions located in Gansu province and the average annual precipitation in different divisions. The nine divisions are shown in three different colors: the Shule River Division (SLRD), the Yellow River Division (YRD), and the Yangtze River (Chang Jiang) Division (CJD) in the yellow area; the Shiyang River Division (SYRD), the Weihe River Division (WRD), and the Fengqu River Division (FRD) in the orange area; and the Heihe River Division (HRD), the Daxia River Division (DRD), and the Jinghe River Division (JRD) in the pink area. Source: Gansu Provincial Water Conservancy Department [28].

The crop yield is the product of the planting area and the yield per unit area. The demand for corn is the sum of the amount of corn consumed as food and fodder and the losses of corn during production and transportation. The demand for wheat is equal to the amount of wheat consumed as food and seed. The demand for a crop as food is the product of the population and the amount of the crop consumed per capita. The demand for corn as fodder consists of two parts. The first part is the product of the output of livestock products and the fodder quota per kilogram of weight; the second part is the product of the number of large animals and the fodder quota per animal. The corn loss is equal to a defined percentage of the demand for corn as food and fodder. The demand for wheat as seed is the product of the planting area and crop quota per unit area. The benefit of a crop plantation is the product of the crop yield and the benefit per unit of weight.

The percentage loss of corn and the quotas are taken from [31]. The other data take the values for 2014. The other data were obtained from the *Gansu Statistical Yearbook* [30], except the benefit per unit of weight, which was obtained from the National Development and Reform Commission [32]. The amount of irrigation water is the product of the planting area and the irrigation quota per unit area. The irrigation water quotas for corn and wheat were obtained from The People's Government of Gansu Province [33]. The amount of water resources in a particular division is the sum of the average annual value of the water resources and the river flow entering the division [28]. Table 1 lists the data used, the initial values of the VWFs, and the level of equality.

Table 1. Data, initial values of virtual water flows and level of equality.

		Unit	Division							Gansu Province ^[1]	
			SLRD	JRD	WRD	SYRD	HRD	DRD	CJD		YRD
Corn	Demand ^[2]	10 ³ t	23.0	167.4	312.3	192.9	210.3	152.3	173.0	297.8	1528.9
	Yield ^[3]	kg/ha	43.6	1324.2	1290.4	841.2	822.0	380.5	371.2	1000.1	6073.3
	Unit area yield ^[3]	10 ³ ha	8.2	4.9	5.3	10.8	8.4	7.5	5.3	5.6	
	Planting area ^[3]	m ³ /ha	5.3	268.2	242.7	77.8	97.3	50.5	69.7	179.3	991.0
	Irrigation quota ^[4]	m ³ /t	7.2	2.7	2.7	7.2	7.2	3.0	2.7	4.5	
	Virtual water content		633.9	382.8	355.5	479.6	613.7	278.8	355.1	564.9	
Wheat	Demand ^[2]	10 ³ t	61.7	631.0	957.0	271.9	270.7	495.9	465.9	705.2	3859.4
	Yield ^[3]	kg/ha	44.2	652.0	595.7	260.0	392.3	176.8	371.8	325.3	2818.1
	Unit area yield ^[3]	10 ³ ha	6.7	3.2	2.7	6.3	6.8	4.4	3.6	3.3	
	Planting area ^[3]	10 ³ m ³ /ha	6.6	202.8	222.2	41.3	58.0	40.4	104.5	99.0	774.7
	Irrigation quota ^[4]	m ³ /t	5.7	2.7	2.7	5.7	5.7	3.0	2.7	4.5	
	Virtual water content		613.5	587.7	531.1	651.9	607.0	479.4	531.1	958.4	
Benefit of crop plantation		10 ⁶ ¥	115.9	2669.3	2551.0	1504.6	1640.5	753.2	980.6	1809.5	12,024.6
Water resources per unit area		10 ³ m ³ /km ²	16.2	36.8	44.7	50.4	67.0	141.4	304.1	541.4	
Water resources ^[4]			2428.1	1275.7	1391.7	1778.7	4145.0	4801.5	10,960.1	23,972.4	50,753.3
Irrigation water ^[4]			76.0	1271.7	1255.2	795.8	1031.3	272.7	470.3	1252.4	6425.5
Virtual water outflow		10 ⁶ m ³	13.1	455.8	347.8	311.0	449.3	63.6	70.3	396.9	2107.6
Virtual water inflow			10.8	0.0	254.9	7.6	0.0	153.0	49.9	363.5	839.7
Virtual water net outflow ^[5]			2.3	455.8	92.8	303.3	449.3	−89.4	20.5	33.4	1267.9
Gini _{vwo}											0.643
Gini _{vwi}											0.533

^[1] The values for Gansu Province do not exactly sum up to the total value as a result of rounding after the FRD was excluded. ^[2] The demand values were calculated by the methods described in Section 3.2. ^[3] Source: Gansu Province Bureau of Statistics [30]. ^[4] Source: Gansu Provincial Water Conservancy Department [28]. ^[5] Virtual water net outflow = virtual water outflow – virtual water inflow.

3.3. Evaluation of Equality in VWF Patterns

The Gini coefficient [20,34] and the entropy index [35,36] are the most commonly-used measures of the degree of equality. In addition to its use to measure inequalities in the distribution of income, the Gini coefficient has also been applied to non-monetary inequalities [37,38] and inequalities in resources by region [39]. The entropy index is a log-weighted sum that varies nonlinearly with the distribution of inequality. The fluctuation in the entropy index is small when the fairness of distribution is centralized. The generalized entropy index is therefore less sensitive to changes in inequality than the Gini coefficient, which is a linear-weighted sum. Taking these factors into consideration, we used

the concept of the Gini coefficient to measure inequalities in the distribution of freshwater resources. Inter-regional VWFs are dynamic and unstable, but are appropriate for modeling water resources and economic development in each region.

The concept of the Gini coefficient was used to evaluate the degree of uniformity of the relative distribution of two indexes, $Gini_{VWO}$ and $Gini_{VWI}$, which were designed to evaluate the equalities in virtual water outflow and inflow patterns to the distribution of water resources, respectively. These indexes are defined as:

$$Gini_{VWO} = 1 - \sum_i \left(P_{VWO}^i + P_{VWO}^{i-1} \right) \left(r^i - r^{i-1} \right) \quad (5)$$

$$Gini_{VWI} = 1 - \sum_j \left(P_{VWI}^j + P_{VWI}^{j-1} \right) \left(r^j - r^{j-1} \right) \quad (6)$$

where i and j represent the districts sorted in ascending order by values equal to the outflows and inflows of virtual water over water resources, respectively, P_{VWO}^i and P_{VWI}^j are the cumulative proportions of the outflow and inflow of virtual water, respectively, and r^i and r^j are the accumulated proportions of water resources. When $i, j = 1$, the values of P_{VWO}^{i-1} , r^{i-1} and P_{VWI}^{j-1} are zero. Like the Gini coefficient, the values of $Gini_{VWO}$ and $Gini_{VWI}$ vary between 0 and 1.

$Gini_{VWO}$ is related to the amount of water used by exported products. An outflow of virtual water will decrease the amount of water that could be used in local ecosystems and human society, and may damage the sustainability of arid regions. Exporters in arid regions should therefore favor production methods with a highly-efficient use of water and low overall water consumption. In water-rich regions, however, exporters can afford a greater outflow of virtual water and production methods with a high virtual water density. Inter-regional coordination in crop planting between water-scarce and water-rich areas helps to fit the use of water by the agricultural sector and the pattern of VWFs to the regional distribution of water resources.

In terms of the consumption of water, $Gini_{VWI}$ is related to amount of local water replaced by imports. For importers in water-scarce regions, the inflow of virtual water is of more practical significance than the consumption of water in the original production of the imports. Importers in water-scarce regions are more likely to prefer a greater inflow of virtual water and commodities that consumed greater amounts of water during production elsewhere. For a single water-scarce district, more imports manufactured elsewhere are therefore preferable to locally-produced goods. Districts should collaborate to identify individual import scales, and to guarantee maximum crop yields and economic benefits [6].

3.4. Optimization Model for Inter-Regional Coordination

Lower values of $Gini_{VWO}$ and higher values of $Gini_{VWI}$ indicate higher levels of equality—that is, the districts with smaller water resources export less virtual water, and their resources are replaced by more real water. Sun et al. [40] improved the equality of the allocation of wastewater discharge permits by minimizing the Gini coefficients. Based on this concept, the objectives of inter-regional coordination are:

$$\min Gini_{VWO} \quad (7)$$

$$\max Gini_{VWI} \quad (8)$$

It is easier to manage the crop supply, which is mainly related to the planting area under certain economic or technological conditions, than to manage the crop demand, which is determined by the population and the structures of consumption.

3.5. Three Different Constraints

Rapid socioeconomic development, urbanization, and climate change in China have challenged the expansion of agriculture and the country's aim to become self-sufficient in food [41]. Because policy-makers are concerned about both environmental conservation and self-sufficiency in food [42], we need to estimate several different effects of VWTs. In managing water resources, policy-makers should aim to increase the crop yield, decrease the amount of irrigation water, and increase economic benefits. Inter-regional coordination aims to determine the optimum acreage of crop planting in particular areas to adjust the spatial distribution of crops. The constraints depend on the specific circumstances. This study set three constraints based on changes in crop supply, irrigation water, and economic benefits to determine the effects of inter-regional coordination.

It is possible to model these constraints using the multi-objective optimization algorithm. The crop supply constraint specifies that the total supply of corn and wheat in Gansu Province should not decrease, which means that the scale of crop production should be maintained. The irrigation water constraint specifies that the use of irrigation water should not increase, and represents the requirement to conserve agricultural water. The economic benefits constraint specifies that the economic benefit of crop planting should not decrease, and therefore, guarantees farmers' profits. These constraints are introduced into the algorithm one-by-one.

3.6. Particle Swarm Optimization

Optimization algorithms are often used to solve multi-objective optimization problems. Many different optimization algorithms are used in water resources management and prediction, such as the PSO algorithm, the neural network algorithm, the genetic algorithm, the local search algorithm, and the random forest algorithm [43].

The PSO algorithm was proposed by Eberhart and Kennedy [44] and then developed as a mature algorithm by Blackwell and Clere [45]. The PSO algorithm has the advantages of no crossover and mutation calculation, a fast search speed, a strong memory, few parameters, and a simple structure. The PSO algorithm is widely used and is easy to obtain, but has not previously been applied to virtual water balance studies.

The PSO algorithm first initializes a group of particles (random solution), and then finds the optimum solution through iteration. In each iteration, the particle updates itself by tracking two extreme values. To solve the optimization problem in the allocation of water resources, the particle coding, the construction of fitness function, and the processing of constraints are adjusted in the PSO algorithm. The decision variables are the planting areas of the main crops (corn and wheat) in each division. As there is no crop plantation in the FRD, this division was excluded from the inter-regional coordination. To compare the impacts of different ranges of variation in planting areas, we designed five scenarios in which the ranges of the planting areas for corn and wheat in each division were 0.9–1.1, 0.8–1.2, 0.7–1.3, and 0.6–1.4 times their respective initial values. Figure 2 shows the flow chart for optimizing the inter-region virtual water coordination model with the PSO algorithm.

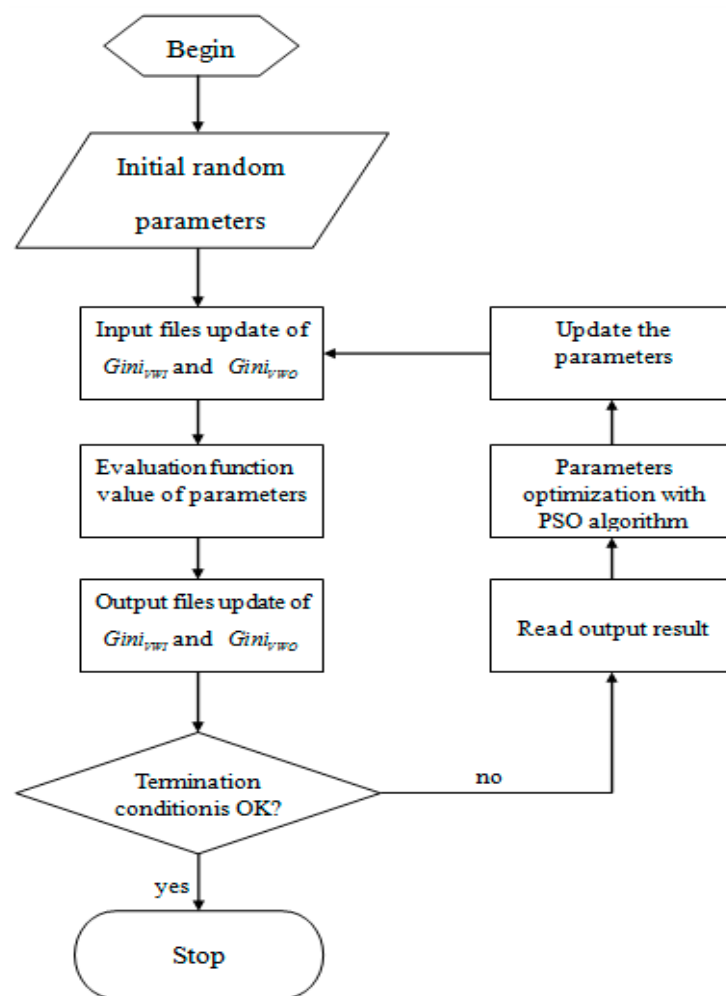


Figure 2. Procedure for optimizing the inter-region virtual water coordination model with the PSO algorithm.

4. Results and Discussion

4.1. Results with No Constraints

Figure 3 describes the equality values of the non-inferior solutions produced by the algorithm. The solid lines correspond to different ranges of planting areas. The $Gini_{vwi}$ coefficient increases and the $Gini_{vwo}$ coefficient decreases relative to their respective initial values in every scenario, indicating an improvement in equality. The shape of the solid lines explains the competition between the two objects—that is, $Gini_{vwi}$ cannot be maximized at the same time that $Gini_{vwo}$ is minimized. The trail crosses the point representing the initial values and the inflection points of the solid lines at the coordinates of the points given in Figure 3. This shows that a greater improvement in the level of equality requires a larger adjustment in the size of the planting area.

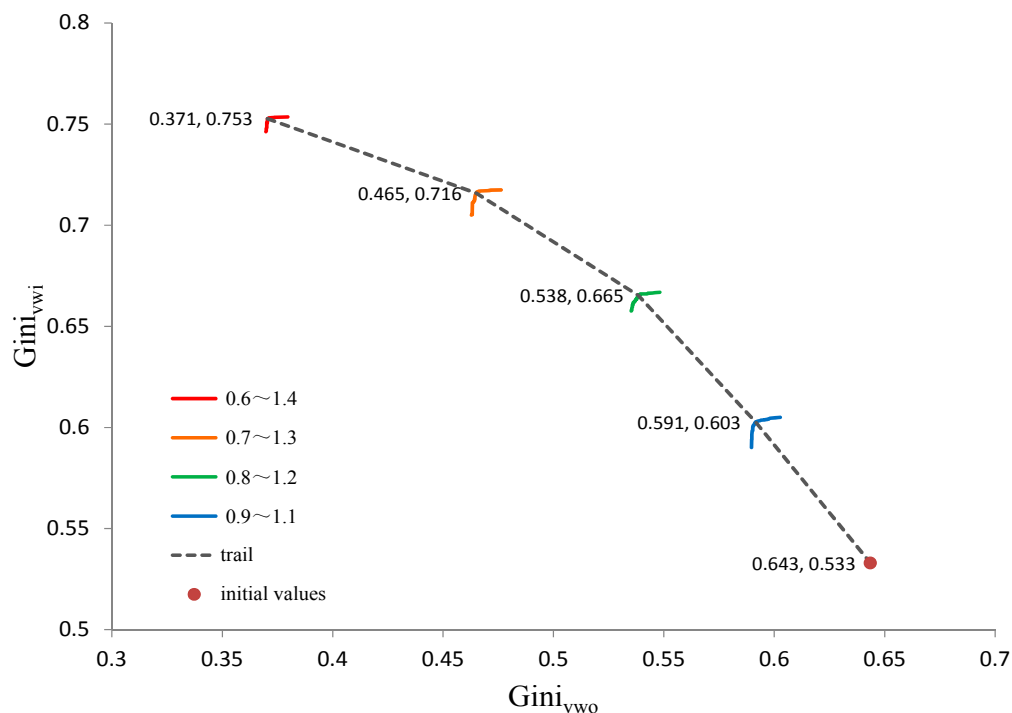


Figure 3. Equality values in different scenarios: 0.6–1.4 indicates the multiple of the crop planting area relative to the initial value, and the connection point between them is the point that satisfies the maximum $Gini_{vwi}$ and the minimum $Gini_{vwo}$ at the same time.

Table 2 lists the results for different size ranges of planting areas. The last row in Table 2 shows that the benefits of crop planting and the crop planting area are directly proportional to each other in Gansu Province. The total amount of irrigation water used and the total outflow of virtual water both decrease as the total planting area decreases and the inflow of virtual water increases after an initial decrease. However, the virtual water balance tightens all the way. A lower benefit is generated by crop planting (Tables 1 and 2). This is the balance between the level of equality and the economic benefit. Gansu Province has to pay more to achieve a higher level of equality. The amount of corn or wheat grown is reduced in about half of the divisions, but increased in the other divisions. Lower amounts of irrigation water, the net outflow of virtual water and economic benefits are seen in JRD, WRD, SYRD, and HRD, with the reverse in SLRD, DRD, CJD, and YRD. The water-scarce divisions reduce their planting area, suffer economic losses, reduce their exports of virtual water, and expand their imports of virtual water. By contrast, the water-rich divisions grow more crops, receive higher benefits, export more virtual water, and import less virtual water. These changes affect the pattern of the VWFs.

Table 2. Results for different size ranges of planting areas with no constraints.

Variation Range of Planting Area		Division								Gansu Province
		SLRD	JRD	WRD	SYRD	HRD	DRD	CJD	YRD	
The change ratio of corn planting areas (%)										
0.6~1.4	38.2~38.4	−40.0~−37.7	−40.0~−39.9	−40.0~−39.0	−40.0~−39.2	33.5~35.8	38.9~40.0	39.2~39.8	−15.7~−15.2	
0.7~1.3	26.8~28.6	−30.0~−29.2	−30.0~−29.2	−29.7~−24.0	−27.2~−23.5	26.3~28.8	28.7~29.7	29.2~30.0	−11.3~−10.4	
0.8~1.2	14.5~17.0	−19.9~−19.1	−20.0~−17.4	−17.8~−16.6	−18.8~−13.8	10.5~14.7	19.0~20.0	19.7~20.0	−7.8~−6.8	
0.9~1.1	4.0~9.0	−10.0~−8.4	−10.0~−4.0	−9.5~−5.4	−9.7~−4.7	9.0~9.8	8.3~10.0	9.8~10.0	−3.8~−1.5	
The change ratio of wheat planting areas (%)										
0.6~1.4	39.7~39.9	−40.0~−31.1	−40.0~−39.5	11.4~12.4	−31.3~−30.7	−29.25~−28.9	39.4~40.0	39.9~40.0	−14.4~−11.9	
0.7~1.3	24.3~27.9	−5.9~−0.1	−30.0~−29.2	10.1~11.6	−28.4~−27.1	−23.2~−21.5	29.4~30.0	28.1~30.0	−4.7~−3.1	
0.8~1.2	16.7~18.7	−4.2~−1.8	−20.0~−19.9	4.0~8.5	−17.5~−15.7	−6.1~−1.2	19.9~20.0	18.9~20.0	−2.8~−1.9	
0.9~1.1	3.7~5.8	−3.9~−1.3	−10.0~−8.0	5.3~6.9	−9.5~−1.5	−7.1~0.6	8.5~10.0	8.5~10.0	−1.6~−0.6	
The change ratio of irrigation water (%)										
0.6~1.4	39.0~39.1	−39.8~−36.2	−40.0~−39.7	−24.8~−23.8	−37.2~−36.5	5.8~6.9	39.2~39.9	39.5~39.8	−13.3~−12.5	
0.7~1.3	25.6~27.7	−19.6~−16.7	−29.9~−29.5	−17.7~−13.5	−27.6~−24.6	4.8~6.4	29.1~29.9	29.0~30.0	−7.6~−6.2	
0.8~1.2	16.6~17.2	−13.0~−11.7	−20.0~−18.6	−11.3~−9.2	−18.4~−14.5	3.1~7.6	19.6~20.0	19.5~20.0	−5.0~−3.8	
0.9~1.1	4.9~6.4	−7.4~−5.3	−9.8~−6.9	−5.1~−1.8	−9.6~−3.7	2.0~5.7	9.1~10.0	9.4~10.0	−2.6~−0.5	
Virtual water outflow (10 ⁶ m ³)										
0.6~1.4	23.7~23.7	240.2~252.0	164.3~164.9	161.4~167.1	173.9~178.3	99.2~101.6	149.6~151.9	618.1~621.6	1637.7~1652.2	
0.7~1.3	20.5~21.0	290.9~307.1	210.3~213.6	202.0~226.1	244.7~266.4	91.5~94.2	116.4~118.8	562.0~566.3	1745.5~1807.5	
0.8~1.2	17.1~17.8	342.3~351.7	256.1~268.0	239.5~250.7	312.9~341.8	74.8~79.2	95.5~96.7	508.3~509.7	1854.4~1907.6	
0.9~1.1	14.2~15.6	392.2~408.3	302.0~329.3	274.1~293.2	377.8~422.1	73.2~74.1	81.2~83.5	451.9~453.3	1972.3~2069.8	
Virtual water inflow (10 ⁶ m ³)										
0.6~1.4	0.0	106.4~140.4	420.8~422.9	0.0	0.0~0.8	177.5~177.8	0.0	238.8~239.0	944.8~980.4	
0.7~1.3	3.2~4.2	0.0~9.7	377.6~380.9	0.0	0.0	171.2~172.7	0.0	270.0~276.0	825.6~834.8	
0.8~1.2	5.7~6.2	0.0~3.2	338.5~338.9	0.0~0.8	0.0	154.0~158.2	10.4~10.5	301.2~304.7	811.9~818.4	
0.9~1.1	9.2~9.7	0.0~2.0	288.4~296.9	0.0	0.0	152.5~159.1	30.1~33.1	332.3~336.9	820.5~828.0	
Virtual water net outflow (= Outflow − Inflow, 10 ⁶ m ³)										
0.6~1.4	23.7~23.7	101.3~133.9	−258.5~−256.3	161.4~167.1	173.3~178.3	−78.3~−76.2	149.6~151.9	379.3~382.5	658.6~694.3	
0.7~1.3	16.3~17.5	281.7~307.1	−170.2~−166.8	202.0~226.1	244.7~266.4	−80.2~−77.2	116.4~118.8	287.7~296.2	916.0~980.9	
0.8~1.2	11.4~11.7	339.8~351.7	−82.9~−70.8	238.7~250.7	312.9~341.8	−83.4~−74.9	85.0~86.3	204.5~208.3	1035.9~1093.4	
0.9~1.1	5.0~5.8	390.3~408.4	6.5~32.6	274.1~293.2	377.8~422.1	−85.6~−78.4	50.5~53.3	115.9~120.9	1149.7~1243.1	
Benefit of crop planting (10 ⁶ ¥)										
0.6~1.4	161.0~161.1	1606.9~1673.6	1531.0~1535.3	1067.9~1083.0	1027.2~1038.2	869.7~881.2	1364.3~1372.0	2521.6~2529.9	10,172.9~10,248.4	
0.7~1.3	145.6~148.0	2064.8~2121.7	1787.5~1799.7	1188.1~1257.4	1189.1~1238.0	845.8~859.9	1265.3~1273.0	2336.0~2352.1	10,869.7~11,027.6	
0.8~1.2	134.9~135.7	2267.3~2297.5	2040.9~2088.2	1307.9~1335.0	1338.7~1403.9	796.2~829.1	1171.4~1176.7	2165.0~2170.6	11,222.4~11,436.8	
0.9~1.1	121.5~123.5	2452.0~2502.9	2301.6~2404.9	1409.3~1462.7	1482.7~1579.2	787.5~807.2	1069.6~1078.5	1983.3~1990.3	11,641.4~11,903.2	

Lorenz curves were used to assess the relationship between the $Gini_{VWO}$ and $Gini_{VWI}$ indexes (Figure 3), similar to the study of Seekell et al. [20]. The dots in the curves represent the divisions. As the range of variation in the planting area increases, the convexity of the Lorenz curves for $Gini_{VWO}$ and $Gini_{VWI}$ becomes weaker and stronger, respectively. This shows an improvement in the level of equality, and proves the effectiveness of our proposed method in this case study.

Figure 4a shows that the order of the divisions remains unaltered in the Lorenz curves. The proportion of virtual water outflow increases in the four divisions plotted to the left and decreases in the four divisions plotted to the right. The three divisions with the highest proportions are always YRD, JRD, and HRD in descending order, but the numerical gap in proportion among the three divisions increases for wider ranges of planting area. Figure 4b shows that the order of the divisions differs in some of the Lorenz curves. The proportion of virtual water inflow increases in HRD, JRD, and WRD, and decreases in the remaining five divisions. YRD, WRD, and DRD are the top three divisions, and WRD is the highest division when the variation in the size of the planting area is >20%.

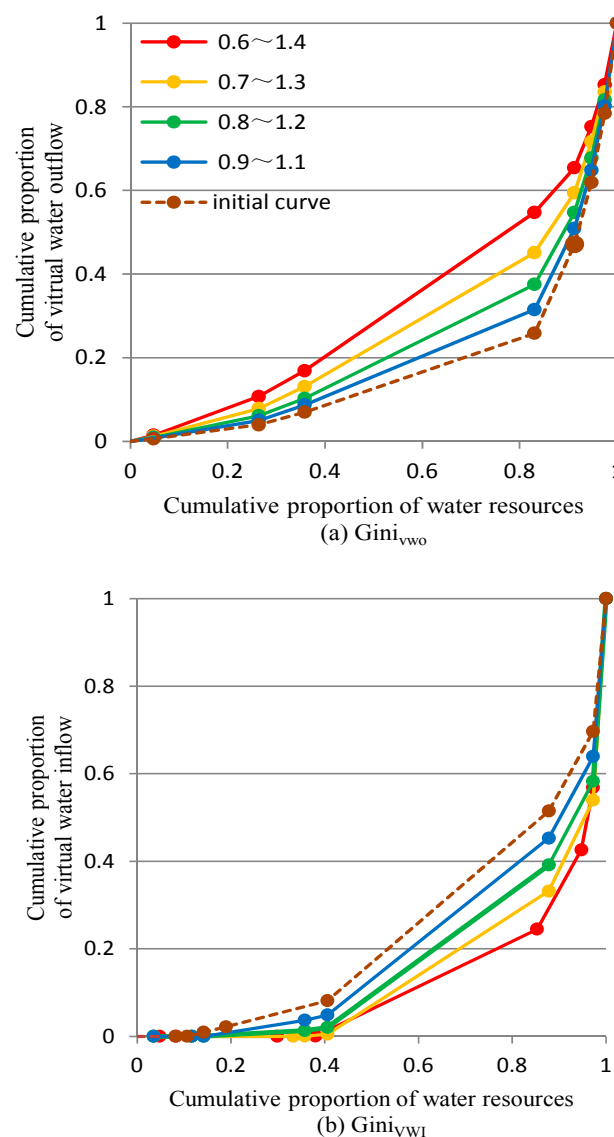


Figure 4. Lorenz curves for $Gini_{VWO}$ and $Gini_{VWI}$. Different colors represent different crop planting areas and the points represent different areas (from left to right: SLRD, CJD, DRD, YRD, HRD, SYRD, WRD, and JRD). (a) the order of the divisions remains unaltered in the Lorenz curves; (b) the order of the divisions differs in some of the Lorenz curves.

4.2. Results with Constraints

It is interesting to compare the variations in crop supply, irrigation water use, and economic benefits under the three different constraints. Figure 5 shows the resulting equality values for crop planting areas in the range 0.8–1.2. Every constraint has an effect on $Gini_{VWO}$, whereas only the irrigation water constraint affects $Gini_{VWI}$. Other values in different ranges of crop planting areas (e.g., 0.6–1.4, 0.7–1.3, and 0.9–1.1) can also be obtained, but are omitted here for simplicity.

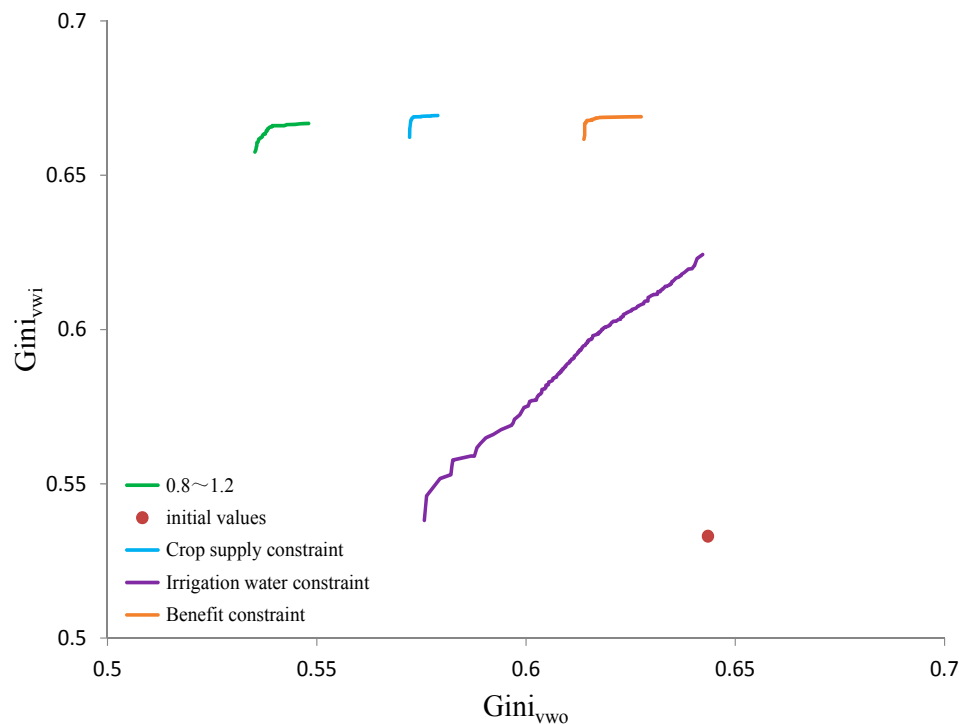


Figure 5. Equality values after adding the three constraints when the crop planting area was 0.8–1.2 times the initial value.

Table 3 lists the results for the three different constraints when the crop planting area was 0.8–1.2 times the initial value. The three different constraints give different variations for different indexes. The index of the change in the ratio of the corn planting area in Gansu Province decreases from -7.8% to -6.8% (no constraint) to -17.4% to -9.0% (irrigation water constraint), indicating the high level of irrigation water use when there is no constraint. However, this index increased by 0.3% – 11.5% under the crop supply and economic benefits constraints. The index of the change in the ratio index of the wheat planting area changes from -9.8% to 1.2% , which may suggest that decreasing the area of wheat planting is the best practice for Gansu Province. Contrasting the results obtained under constrained and unconstrained conditions, it was found that the distributions of crop supply, VWFs, and benefits were all very different after adding the constraints. The total crop supply increased and there was a greater demand for irrigation water when the crop supply constraint or economic benefits constraint was introduced, which means that a greater economic benefit is achieved, and the outflow of virtual water increases. By contrast, the crop area and use of irrigation water decreased when the irrigation water constraint was introduced, indicating a lower economic benefit and a greater inflow of virtual water.

Table 3. Results for different size ranges of planting areas with different constraints ^[1].

Constraints	Division								Gansu Province
	SLRD	JRD	WRD	SYRD	HRD	DRD	CJD	YRD	
The change ratio of corn planting areas (%)									
None	14.5~17.0	−19.9~−19.1	−20.0~−17.4	−17.8~−16.6	−18.8~−13.8	10.5~14.7	19.0~20.0	19.7~20.0	−7.8~−6.8
CSC	18.6~19.9	0.1~0.8	−19.8~−18.8	−5.5~−5.1	−5.9~−5.1	16.6~19.9	19.9~20.0	19.8~20.0	0.3~0.7
IWC	−15.8~−13.6	−20.0~−18.2	−20.0~−18.1	−20.0~−16.4	−19.8~−8.2	−12.6~10.7	−17.2~11.3	−14.0~9.0	−17.4~−9.0
EBC	14.5~15.4	0.9~3.5	9.1~14.5	3.6~11.5	9.1~14.7	19.4~19.8	10.0~17.2	16.1~16.7	9.0~11.5
The change ratio of wheat planting areas (%)									
None	16.7~18.7	−4.2~−1.8	−20.0~−19.9	4.0~8.5	−17.5~−15.7	−6.1~−1.2	19.9~20.0	18.9~20.0	−2.8~−1.9
CSC	19.8~20.0	−1.6~0.2	−20.0~−17.7	5.6~14.5	−3.3~−2.9	−19.0~−14.9	19.4~20.0	19.2~20.0	−1.3~−0.7
IWC	−19.5~5.9	−2.0~0.6	−20.0~−13.2	5.6~18.8	−14.2~−6.3	−13.6~−11.1	−8.8~7.2	−16.9~16.3	−9.8~−2.6
EBC	18.0~19.9	3.1~4.4	−20.0~−18.7	8.5~13.1	−7.9~7.3	−15.5~−15.2	18.5~20.0	17.9~20.0	−0.2~1.2
The change ratio of irrigation water (%)									
None	16.6~17.2	−13.0~−11.7	−20.0~−18.6	−11.3~−9.2	−18.4~−14.5	3.1~7.6	19.6~20.0	19.5~20.0	−5.0~−3.8
CSC	19.3~19.9	−0.7~0.5	−19.9~−18.7	−2.2~0.7	−5.0~−4.5	0.8~4.4	19.6~20.0	19.7~20.0	0.8~1.3
IWC	−16.9~−5.0	−12.1~−10.4	−19.9~−16.4	−12.0~−7.5	−16.1~−10.1	−11.8~−0.1	−1.9~−0.7	−2.3~0.0	−10.6~−8.7
EBC	16.6~17.4	2.4~3.3	−4.7~−2.0	5.1~11.9	7.5~8.5	3.9~4.3	16.0~18.8	17.1~17.8	6.6~7.9
Virtual water outflow (10 ⁶ m ³)									
None	17.1~17.8	342.3~351.7	256.1~267.9	239.5~250.7	312.9~341.8	74.8~79.2	95.4~96.7	508.3~509.7	1854.4~1907.6
CSC	18.2~18.6	450.0~460.3	256.8~261.5	290.9~307.4	412.5~415.8	81.2~84.8	96.6~96.7	509.0~509.8	2120.2~2150.7
IWC	8.7~9.3	348.0~363.3	256.0~264.7	234.5~260.4	329.9~374.4	50.3~75.0	47.7~85.2	317.9~447.7	1649.7~1860.3
EBC	17.1~17.3	477.1~485.3	389.5~414.2	332.4~371.8	504.6~512.5	84.2~84.6	83.5~93.0	487.8~491.1	2397.3~2448.6
Virtual water inflow (10 ⁶ m ³)									
None	5.7~6.2	0.0~3.2	338.5~338.9	0.0~0.8	0.0	154.0~158.2	10.4~10.5	301.2~304.7	811.9~818.4
CSC	5.3~5.4	0.0	329.1~338.9	0.0	0.0	165.7~169.1	10.4~11.6	301.3~303.5	813.8~825.0
IWC	8.6~16.0	0.0	310.2~338.9	0.0	0.0	162.3~164.6	33.2~67.2	303.9~416.2	845.7~988.5
EBC	5.4~5.9	0.0	333.6~338.9	0.0	0.0	165.9~166.2	10.4~13.4	301.2~307.7	819.6~828.4
Virtual water net outflow (= Outflow − Inflow, 10 ⁶ m ³)									
None	11.4~11.7	339.8~351.7	−82.9~−70.8	238.7~250.7	312.9~341.8	−83.4~−74.9	85.0~86.3	204.5~208.3	1035.9~1093.4
CSC	12.9~13.2	450.0~460.3	−81.9~−71.5	290.9~307.4	412.5~415.8	−87.9~−81.0	85.0~86.2	206.1~208.5	1302.7~1325.7
IWC	−7.0~−0.4	348.0~363.3	−81.9~−51.3	234.5~260.4	329.9~374.4	−112.0~−89.6	14.2~18.0	13.2~33.4	785.0~871.7
EBC	11.4~11.8	477.1~485.3	51.9~75.3	332.4~371.8	504.6~512.5	−82.0~−81.3	73.1~82.2	183.2~189.7	1568.9~1626.6
Benefit of crop planting (10 ⁶ ¥)									
None	134.9~135.7	2267.3~2297.5	2040.9~2088.2	1307.9~1335.0	1338.7~1403.9	796.2~829.1	1171.4~1176.7	2165.0~2170.6	11,261.7~11,394.8
CSC	138.1~138.9	2657.6~2684.9	2044.3~2064.0	1458.1~1491.1	1558.1~1565.8	800.7~827.0	1173.6~1176.6	2167.8~2171.0	12,040.3~12,090.1
IWC	96.4~109.5	2283.5~2326.3	2043.6~2102.5	1292.6~1354.5	1371.9~1477.7	662.1~780.8	929.8~999.3	1689.6~1868.4	10,517.1~10,949.0
EBC	135.1~135.9	2721.3~2759.1	2571.7~2667.4	1574.8~1682.2	1772.4~1781.1	823.3~826.1	1124.5~1160.8	2115.8~2124.1	12,883.1~13,081.1

^[1] The crop supply constraint (CSC) is designed as maintenance of the food supply in Gansu Province above the normal level. The irrigation water constraint (IWC) and the economic benefits constraint (EBC) are designed for individual divisions. The range of crop planting areas is set as 0.8–1.2 the initial value for the simplicity.

These results describe the contradiction between the level of equality of the VWF model, water conservation, and crop supply (and its benefits) under the current economic and technological conditions in Gansu Province. Inter-regional coordination should be carried out to strike a balance between these factors. However, the land area suitable for the cultivation of corn and wheat is limited by the constraints of soil texture, climatic conditions, and the availability of arable land. Fluctuations in food production will affect food prices. A change in the area of crops planted in each region will affect the income of farmers in various regions. This study is therefore simply a theoretical exploration the feasibility of inter-regional collaboration, and it is necessary to investigate other relevant factors, such as the area suitable for planting crops, in more detail.

4.3. Limitations of This Study

We validated our proposed method through a case study and found that different constraints lead to variations in the planting area, crop supply, irrigation water usage, and economic benefits. However, there are some limitations in this study that need to be improved in future work. First, we ignored green and gray water, and only considered blue water because irrigation is the main use of water resources of crop plantations, and farmland drainage data was not available for Gansu Province. If rain-fed crops are included and non-point pollution is controlled, then the amount of green and gray virtual water will be non-negligible. If green and gray water are included, the objectives of the algorithm are still feasible, but the decision variables and constraints need to be expanded to cover the relevant factors and limits on the use of rainwater, the emission of pollutants, and the water environmental capacity.

This study proposes a reference for integrated water resources management, not a real-time control for crop production. This is because the VWC is estimated based on the quota of irrigation water, not on the actual consumption of water in crop production. The quota represents the technical levels of irrigation and is static over a defined period of time, whereas the actual consumption of water is dynamic as a result of changes in the weather, planting technology, and the method of irrigation. In addition, the current estimation of the crop trade is greatly simplified. It gives the basic pattern of the crop trade, but produces deviations. The factors influencing the distribution of the crop supply extend far beyond virtual water. The growing conditions, crop quality, market preference, and transportation costs all affect or even determine the optimum structure of the crop supply.

5. Conclusions

Agriculture is the largest consumer of water in China, and faces challenges from rapid socioeconomic growth, the associated pressure on water resources, and soil degradation. Because exchanges of virtual water between different divisions may help to save water on the regional scale, it is crucial to evaluate the inter-regional coordination of VWTs in arid areas. We designed two indexes, $Gini_{VWO}$ and $Gini_{VWI}$, to represent the equality of VWFs based on the concept and estimation of the Gini coefficient. We then used an algorithm to optimize the inter-regional coordination of VWFs with the aim of improving the levels of equality and tested the methods in an arid province of northwest China, focusing on the coordination of crop plantations. The test proved the effectiveness of inter-regional coordination, and showed the competition between the improvements in the equality of virtual water outflows and inflows. We validated our proposed method through a case study and found that different constraints lead to variations in the planting area, crop supply, the use of irrigation water, and the economic benefits. The test also showed the balance between the factors, including the level of equality of the VWF pattern, the reduction in water consumption, and changes in economic benefits.

Because the real decision-making processes in crop planting and trade were simplified, we suggest that the results are only used as a reference for the integrated management of water resources. More details about the agricultural production decisions and the circulation of products need to be considered further. Our findings provide important insights to policy-makers on the trade-offs between water conservation and agricultural objectives by considering different constraints in policies. The study

also shows that if a region exports a large number of identical (or similar) commodities to the same region, rather than imported goods in the same region, it also produces a virtual form of net export water flow. In this way, some areas or agricultural areas can support water needs in other areas.

Author Contributions: D.Y. is the developer of this research, and proposes research ideas and research methods. He is the main author of the article; Z.J. is mainly responsible for the improvement of related calculations and methods of some research, and is responsible for modifying the article; H.S. is responsible for some later revisions. And submit articles and editors to communicate; others are primarily responsible for methodological improvements and sources of data.

Funding: This research was funded by CRSRI Open Research Program (CKWV2015207/KY) and the Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research, Grant No: IWHR-SKL-201508). Most of the authors supported by the National Natural Science Foundation of China (41001379, 91547208, 41601595, 51879110, U1603343), Hubei Natural Science Foundation (2017CFB724), Hubei Provincial Water Resources Key Scientific Research Project (HBSLKY201803) and Fundamental Research Funds for the Central Universities (HUST 2016YXZD048). Authors would like to thank anonymous reviewers for the suggestions and comments.

Conflicts of Interest: The authors declare no conflicts of interest.

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