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Case Report

External Virtual Water Contributes Greatly to Continual Development in Urumqi

Yong Liu[1, 2, 3, 4]

[1]Qilu University of Technology, Jinan, China

[2]Shandong Academy of Sciences, Jinan, China

[3]Institute of Science and Technology for Development of Shandong, Jinan, China

[4]Information Research Institute of Shandong Academy of Sciences, Jinan, China

Email address:
32516022@qq.com

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Abstract: Previous studies indicated that the population size would arrive at its “upper limits” under the intense water scarcity in Urumqi; yet the “upper limits” had been repeatedly exceeded. Two latest research paper put forward a new term “generalized water”, and estimated it under the framework of a noncompetitive input-output model. It was proved that generalized water made a main contribution to alleviate acute water scarcity in the past 40 years in the arid city, and answered the question why an urban population continues to grow under intensifying water scarcity. Another question is whether and how generalized water contributes to the continual development in the future in this city. This paper applied coefficients deduced from the noncompetitive input-output model, and set up a multi-objective linear programming model to investigate the question. Simulation results indicated that the upper limit of gross domestic products of Urumqi would be at most 1.3 times that in 2012; however, this “upper limit” was far more exceeded in 2018, about 1.7 times that in 2012. This phenomenon indicates that generalized water also made a main contribution to continual development, and this contribution mainly comes from external virtual water embodied in commodities. This contribution from generalized water results from the characteristic of dissipative structure in an urban economy, and it is suggested that polices should be designed to make the most use of generalized water.

Keywords: External Virtual Water, Continual Development, Generalized Water Management, Urumqi

1. Introduction

Water is inextricably linked to all societies and cultures. Water issues have increased globally in recent years [1]. Water scarcity occurs when demands for water resources exceed supplies of water resources, and this scarcity often results from water shortages, supply-driven approaches, rapid growth of population, lack investment of infrastructure investment, or local climate change. The Near East, Africa, Pakistan, and large parts of China are suffering from acute water shortages. More than 1.2 billion people live in areas affected by physical water scarcity, and an additional 1.6 billion people live in areas experiencing economic water scarcity [2]. In addition, the growing scarcity of potable water supplies is a critical issue facing many cities, particularly, those using single sources of water that are climate dependent [3]. In China, water stress issues are serious, and two-thirds of Chinese cities are suffering from water scarcity [4]. In northwestern China, water scarcity problems are more severe. Low rainfall levels result in inadequate water supplies, and high demand intensifies the acute water stress. In addition, considerable volumes of virtual water are traded to meet water demands.

Urumqi is an arid city and one of the most water-scarce cities in northwestern China because of low precipitation, high evaporation, growing demands, and lack of infrastructure investment. Water stress will be a great risk in the future as the urban area continues to expand and the ice cap over the mountains decreases. Water scarcity has been severe since the 1980s, and many studies posited that the water carrying capacity would reach an upper limit [5-7]. However, many of these "limits" on the population size had been exceeded repeatedly, and this phenomenon is interesting to many scholars and officials. This phenomenon was viewed as a mystery of the population carrying capacity of water resources: why the population size continues to grow under intense water scarcity [8]. A noncompetitive input-output model was used to investigate the water allocation patterns in Urumqi, and it generated a robust first-pass diagnostic of water flows [9]. Generalized water resources include both real and virtual water and refer to physical, indirect virtual, and external virtual water in this paper. Results indicated that generalized water amounted to 4.97 billion m^3 in 2012, of which fresh, recycled, indirect virtual, and net external virtual water accounted for 22%, 4%, 12%, and 62%, respectively. The water deficit reached 3.68 billion m^3, amounting to approximately 2.84 times the amount of physical water on hand. External virtual water levels amounted to 3.45 billion m^3, amounting to 3.14 times the volume of fresh water available. Physical water is extremely scarce, and external virtual water has helped to balance water supply and demand. Virtual water makes a main contribution to increase the population scale under acute water scarcity, and this contribution results from the characteristic of dissipative structure in an urban economy [10].

It is a natural conclusion that both physical and virtual water are fundamental resources and generalized water resources management thus involves managing physical and virtual water in a consistent way. However, the noncompetitive input-output model only answers the question about water scarcity in the past 40 years, and another question is whether external virtual water continues its contribution in the future. The answer seems to be “Certain”, and this paper aims to answer this question. As a further study of Liu’s generalized water resources [8-10], the main objective of this paper is to investigate whether and how generalized water contributes to the continual development in the future in this city. The paper is organized as follows. Section 2 introduces the method, section 3 talks about the data collection, and section 4 discusses results.

2. Method

2.1. The Multi-Objective Linear Programming Model

The noncompetitive input-output model was designed to investigate water scarcity in Urumqi and was discussed in detail [8, 9]. To answer the question whether external virtual water continues its contribution in the future, this paper applies a multi-objective linear programming model to estimate the maximum size of an urban economy under acute water scarcity. The noncompetitive input-output model can offer some key coefficients, such as intermediate consumption coefficients, value added coefficients, water resource consumption coefficients, energy consumption coefficients, pollutant emission coefficients, employment coefficients, and so on. These coefficients can give a multi-angle insight of an urban economy, and helps to set up the multi-objective linear programming model. In an urban economy, many problems involve multiple objectives along with constraints on what combinations of those objectives are attainable. For example, an urban economy can achieve an appreciate development; yet it is subjected to several constraints, for example, employees, energy structures, and industrial structures. These constraints are different in different regions, and such differences determine the different paths of regional economic development. Under the framework of the multi-objective linear programming model, the maximum size and the development paths of an urban economy can be estimated.

The multi-objective linear programming model is a basic kind of mathematical optimization with more than one objective function. In mathematical terms, a multi-objective linear programming model can be written as:

$$\begin{aligned} \min \quad & \mathrm{P}x \\ \text{s.t.} \quad & a \le \mathrm{B}x \le b \\ & l \le x \le u \end{aligned}$$

Where B is an $(\mathrm{m}\times\mathrm{n})$ matrix, P is a $(\mathrm{q}\times\mathrm{n})$ matrix, a is an m-dimensional vector with components in $\mathrm{R}\cup\{-\infty\}$, b is an m-dimensional vector with components in $\mathrm{R}\cup\{+\infty\}$, l is an n-dimensional vector with components in $\mathrm{R}\cup\{-\infty\}$, u is an n-dimensional vector with components in $\mathrm{R}\cup\{+\infty\}$.

Under the framework of the noncompetitive input-output model, for example, water consumption can be formulated as:

$$\mathrm{w}^{\mathrm{u}} = \sum_i w_i = \sum_i a_i^w x_i .$$

Here, a_i^w, x_i, w_i, and w^{u} represent direct water consumption coefficient of sector j, total outputs of sector j, water consumption by sector j, and water consumption by the urban economy, respectively.

As one of the objective functions, water consumption can be minimized as:

$$\min \quad \mathrm{w}^{\mathrm{u}} = \sum_i a_i^w x_i$$

As one of the constraints, the total volume of water consumption should be no more than total supply of water, and can be formulated as:

$$\text{s.t.} \quad \sum a_i^w x_i \le \mathrm{W}$$

Here, W represents the total volume of water supply.

Similarly, to the minimized-water-consumption objective function and the water-consumption constraint inequation, other objective functions can be written as linear equations, and constraint conditions can be written as linear inequations. In an urban economy, gross domestic products and employment should be as large as possible; while total water use, wastewater emission, energy consumption, and wasted gas emission should be as small as possible. In addition, an urban economy is unlikely to experience too drastic industrial adjustment and the Euclidean distances between x_i and x_i^0 should be as small as possible. However, gross domestic products, employment, total water use, wastewater emission, energy consumption, and wasted gas emission are subject to its upper or lower limit, respectively. The multi-objective linear programming model can be formulated as:

$$\min \quad \begin{aligned} GDP &= -\sum_i a_i^v x_i \\ Water &= \sum_i a_i^w x_i \\ P.water &= \sum_i a_i^{pw} x_i \\ Labor &= -\sum_i a_i^l x_i \\ Energy &= \sum_i a_i^e x_i \\ P.gas &= \sum_i a_i^{pg} x_i \\ dist. &= \sum_i (x_i - x_i^0)^2 \end{aligned} \qquad s.t. \quad \begin{aligned} &(I-A)X \geq Y \\ &\sum_i a_i^l x_i \geq L \\ &\sum_i a_i^{xj} x_i \geq M^{xj} \\ &\sum_i a_i^{na.} x_i \geq M^{na.} \\ &\sum_i a_i^{ov.} x_i \geq M^{ov.} \\ &\sum_i a_i^w x_i \leq W \\ &\sum_i a_i^{co.} x_i \leq E^{co.} \\ &\sum_i a_i^{oi.} x_i \leq E^{oi.} \\ &\sum_i a_i^{pw} x_i \leq P^w \\ &\sum_i a_i^{pg} x_i \leq P^g \\ &\sum_i x_i / x_i^0 \leq \beta \\ &\sum_i x_i / x_i^0 \geq \alpha \end{aligned}$$

Here, a_i^v, a_i^w, a_i^{pw}, a_i^l, a_i^e and a_i^{pg} represent direct coefficients of values added, water consumption, wasted water emission, employees, energy consumption, and wasted gas emission by sector i, respectively, and these coefficients can be deduced from the noncompetitive input-output model. x_i is a variable and represents the total output of sector j. x_i^0 is a constant and represents the total output of sector j in 2012. Y, L, V, M^{xj}, $M^{na.}$, $M^{ov.}$, W, $E^{co.}$, $E^{oi.}$, P^w and P^g represent final outputs, employees, goods from other regions in Xinjiang, goods from other provinces, imports from overseas, coal consumption, oil consumption, water use, wastewater emission and wasted gas emission of industrial sectors, respectively. Under normal circumstance, a tremendous industrial change might be infeasible in a short time, for example in 5 years. α and β represent the lower and upper limits of change ratios of industrial sectors, respectively. The direct coefficients are applied as constants, and it is only an approximation in the next few years, for example, in the next 5 years. In this paper, $\alpha = 0.5$ and $\beta = 1.5$.

Estimating the maximum size of an urban economy under the framework of the multi-objective linear programming model can be viewed as the process of finding a point along the boundary of the constraint convex concluding kinds of constraint conditions, where multiple objectives can be achieved.

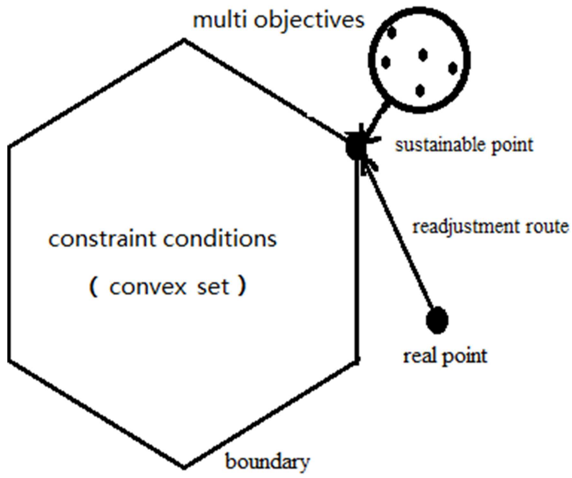

Figure 1. *The Geometric Interpretation of Multi-Objective Linear Programming Model.*

2.2. Data Collection

A most formidable challenge involves assembling and processing detailed data in practice, and data of generalized water resources was discussed in detail [8, 9]. The Bureau of Statistics of Urumqi conducted its 6th input-output survey in 2013 using 490 firms as samples. The sampled firms generated roughly 80% of the total values added of the urban economy. Each sample firm completed a standard survey table to offer information on value added intermediate materials, employees, energy consumption, wasted water, and wasted gas. The external-product row includes three sub-rows: products from other regions in Xinjiang, from other provinces, and from overseas. Industrial figures were revised as commodity data under industry-technology assumptions [11, 12]. The intermediate and primary inputs of each sector equaled the consumption structure multiplied by the total inputs. Liu completed the noncompetitive input-output model in 2015 and introduced a completed table of 11 commodity sectors (as Table 1 shows).

3. Results and Discussion

With the software MATLAB 2009b and the function module FGOALATTAIN, the maximum size of the Urumqi economy was estimated. With different weight vectors, results varied differently. However, most of these results were infeasible in practice, and when the weight vector was assigned to a given value $[0.2, 0.15, 0.2, 0.15, 0.1, 0.1, 0.1]$, the mathematical results of the values added of each sector and industrial adjustment routes seemed to be most reasonable both in practice and theory.

First, the upper limit of gross domestic products of the Urumqi economy would be around 228.7 billion RMB yuan under this hypothesis condition, 1.34 times that in 2012 (as Table 2 shows). Mathematical results indicated that the Urumqi economy would grow around its upper limit of gross domestic products under the year-2012 conditions; yet the price-invariant gross domestic products of the Urumqi economy was 275.4 billion RMB yuan in 2018, 1.62 times that in 2012 [13]. In addition, the total supply of physical water was about 1.13 billion m^3 both in 2012 and 2018, nearing the upper limit of physical water supply; while the total volumes of generalized water were about 4.937 billion m^3 in 2012 and 6.766 billion m^3 in 2018, respectively. The mathematical result of the total volumes of generalized water was 6.249 billion m^3, less than that in 2018. Policy Research Office of Urumqi pointed out, the urban economy had arrived at the "red line of water"[14]. Results indicate that the upper limit of gross domestic products was exceeded in 2018, and a larger economic scale needs a huger volume of generalized water.

Second, the industrial readjustment route can be drawn out according to mathematical results. Each sector experienced a certain degree of development. The values added of water sector, agriculture, mineral products, food, textile & clothing, wood, furniture & paper, petroleum, coke & chemical product, non-metallic & metallic product, equipment, electricity, heat & gas, building, services increased by 25%, 29%, 30%, 36%, 38%, 56%, 60%, 52%, 45%, 39%, 70%, respectively in 2018 (as Table 2 shows). Compare to industrial values added in 2018, the mathematical results of industrial values added were smaller. Both results indicated that high water-consuming sectors experienced a smaller development. The industrial adjustments can be drowned out as followed: reducing high energy-consuming or pollutant-emitting industries and encouraging low energy-consuming, low pollutant-emitting industries, or industries that are severely unable to meet the local requirements.

Third, these results also offer a strong conclusion that virtual water makes a main contribution to its continual development under acute water scarcity. It is proved that generalized water is an answer to the mystery of the population carrying capacity of water resources in the past 40 years, and a huge volume of external virtual water helped to balance water supply and demand [10]. With the mathematical results, the external virtual water would grow to about 3.89 billion m^3 at most; however, the external virtual water grew to about 4.22 billion m^3 in 2018, far more than that in 2012. The total supply of physical water remains about 1.13 billion m^3. It is certain that errors exist between these results, however, these results also offer a strong conclusion that virtual water makes a main contribution to its continual development under acute water scarcity. This phenomenon results from the fact that Urumqi is suffering from physical water scarcity, and a huger number of external virtual water embodied in commodities flowed into Urumqi to balance generalized water supply and demand. Virtual water makes a relatively larger contribution to maintain its continual development, and this contribution results from the characteristic of dissipative structure in an urban economy.

4. Conclusion and Recommendations

This manuscript is a further study of Liu's theory of generalized water resources. Urumqi is an arid city and one of the most water-scarce cities in northwestern China. Water scarcity has been severe since the 1980s, and many studies posited that the water carrying capacity would reach an upper limit. A noncompetitive input-output model was designed to investigate water scarcity in Urumqi. It is proved that a huge volume of external virtual water flowed into Urumqi, and helped to balance water supply and demand. Virtual water makes a main contribution to increase the population and economy scales under acute water scarcity, and this contribution results from the characteristic of dissipative structure in an urban economy.

In this paper, a multi-objective linear programming model was applied to estimate the maximum size of an urban economy. The upper limit of gross domestic products of Urumqi would be around 1.3 times that in 2012, however, it had been exceeded. In fact, virtual water makes a main contribution to the continual development in Urumqi, and this contribution results from the characteristic of dissipative structure. In addition, there are other factors that also influence the urban economy size, for example virtual energy, virtual employees, and so on, and these factors would be discussed in further studies. However, our innovative findings point out that external virtual water makes an important contribution both in the past and future. Generalized water resources can offer more accesses to water resources for regions which often use single sources of water that are climate dependent. Generalized water resources management is dependent on the following two basic measures: improving the water infrastructure construction mechanisms to increase physical water supplies and improving trade with water-rich regions to increase virtual water supplies.

Author Contributions

This paper t is a further study of Liu's generalized water resources, and investigates how external virtual water contributes to local economic growth under the framework of a MOLP model. It re-indicates virtual water trade plays a more important role to maintain the continual development in an urban area, and this phenomenon results from the characteristic of dissipative structure.

Conflict of Interest Statement

All data, models, and code generated or used during the study appear in the submitted article. The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Appendix

Table 1. *The Noncompetitive Input-Output Model for Urumqi (11 commodity sectors).*

Unit: ¥ 10000	Water sector	Agriculture	Mineral product	Food, textile & clothing	Wood, paper and furniture	Petroleum, coke, and chemical products	Non-metallic and metallic products
Water sector	1534	0	75	699	77	923	508
Agriculture	25	10655	1	101878	11	20344	2403
Mineral product	0	380	146476	1579	2000	16003	33005
Food, textile & clothing	121	2254	1867	66180	292	7269	7372
Wood, furniture and paper	1885	473	350	17122	6085	15904	7592
Petroleum, coke and chemical products	4735	48225	14097	68948	22177	211529	87385
Non-metallic & metallic products	934	330	7712	15307	11705	20113	1353321
Equipment	394	10630	13634	2836	2921	3253	51101
Electricity, heat and gas	2512	12788	10663	12962	6980	61349	293169
Building	735	15	3001	1400	71	1980	1375
Services	36129	490	84883	91671	20277	249619	447843
Total local products	49004	86241	282760	380582	72597	608286	2285073
Total products from other regions in Xinjiang	5510	159231	14075	359755	67293	3746065	3001085
Total products from other Provinces	219	3	82	9243	66389	263068	1615397
Total products from other Countries	0	0	0	0	5923	538853	193567
Value-added	52481	250218	292600	215452	42433	1164170	790411
Total Outputs	107214	495694	589517	965031	254634	6320442	7885533
Physical water (m^3)	145022460	669997400	8253290	7291866	1693166	68709607	55332552
Energy (ton of standard coal)	4364	0	1412221	242232	77665	13204463	6819469
Employee (person)	3583	24996	19209	22201	10291	55519	32121
Exhaust emission (ton)	0	0	1996232	2455991	3623149	17223109	13595278
Wasted water emission (ton)	0	0	11905	0	1495	79817	55694

Table 1. *Continued.*

Unit:¥ 10000	Equipment	Electricity, heat and gas	Building	Services	Total intermediate use	Total final use	Total outputs (or inflow products)
Water sector	222	1531	2179	21503	29249	77965	107214
Agriculture	16	247	1275	28935	165791	329903	495694
Mineral product	698	0	19063	44804	264009	325509	589517
Food, textile & clothing	1443	77	4729	84687	176293	788739	965031
Wood, furniture and paper	3043	4813	15150	108513	180929	73705	254634
Petroleum, coke and chemical products	223179	10610	99759	2316573	3107219	3213223	6320442
Non-metallic and metallic products	378087	11242	1522870	40812	3362432	4523102	7885533
Equipment	273812	38139	73300	32458	502478	2208701	2711179
Electricity, heat and gas	15249	1434	39437	397792	854336	2568943	3423279
Building	364	3663	137922	57819	208346	5758934	5967280
Services	178777	151734	195935	4555275	6012634	17635783	23648418
Total local products	1074890	223490	2111620	7689173	14863716	37504506	52368221
Total products from other regions in Xinjiang	537491	2373589	2067321	4333408	16664825	15001802	31666627
Total products from other Provinces	451819	130394	8138	423705	2968456	21817284	24785740
Total products from other Countries	105183	4395	0	0	847921	2157753	3005675
Value-added	541796	691411	1780201	11202131	17023304		
Total Outputs	2711179	3423279	5967280	23648418	52368221		
Physical water (m^3)	1415445	54074704	8281900	275364100	1195436490		
Energy (ton of standard coal)	45110	8364511	0	0	30170036		
Employee (person)	21249	21216	145989	1081868	1438242		
Exhaust emission (ton)	599549	9397741	0	0	48891048		
Wasted water emission (ton)	956	90149	0	0	240447		

Table 2. *Results Under Three Situation.*

Sectors \ Results	Results of 2012		Results of 2018 (Invariable price)		Mathematical Results	
	Value-added (Unit: ¥ 10000)	Generalized water (billion m^3)	Value-added (Unit: ¥ 10000)	Generalized water (billion m^3)	Value-added (Unit: ¥ 10000)	Generalized water (billion m^3)
Water sector	52481	0.780	65601	0.975	68225	1.014
Agriculture	250218	2.975	322781	3.838	302764	3.600
Mineral product	292600	0.080	380380	0.104	362824	0.099
Food, textile & clothing	215452	0.111	293015	0.151	297324	0.153
Wood, furniture and paper	42433	0.014	58558	0.019	55163	0.018
Petroleum, coke and chemical products	1164170	0.118	1816105	0.184	1338796	0.136
Non-metallic & metallic products	790411	0.064	1264658	0.102	916877	0.074
Equipment	541796	0.104	823530	0.159	679412	0.131
Electricity, heat and gas	691411	0.026	1002546	0.038	829693	0.032
Building	1780201	0.005	2474479	0.007	2225251	0.006
Services	11202131	0.700	19043623	1.189	15795005	0.986
Sum	17023304	4.937	27545275	6.766	22871333	6.249

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