Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268 e-ISSN: 2395-3454	Vol. 17	No. 4	pp. 1161-1165	2018

Original Research Paper

Open Access

Evaluation of Influence Factors in Virtual Water Flow

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 06-09-2018
Accepted: 08-11-2018

Key Words:
Virtual water flow
Influence factors
Evaluation index

ABSTRACT

Virtual water trade provides a new way to solve the problem of uneven distribution of water resources in regional entities. An evaluation index system with 13 indexes of three levels was established to identify the influence factors in virtual water flow. A consistency test was completed, and the weight value of each index was calculated by using the analytic hierarchy process. Results show that the most important factor that affects the degree of virtual water flow is the water footprint per capita, with a weight of 0.27. The sum of weights of per-capita water footprint, per-capita water resources, dependency index, food security index, food self-sufficiency, and water-resource pressure index is up to 0.79, which indicates that the six influence factors determine the virtual water flow. The conclusions provide references in formulating measures to alleviate water resource shortages.

INTRODUCTION

Water is the source of life. Humans are closely related to water since birth, and then survive, multiply, and develop in an environment with water resources. According to statistics of the World Resources Institute, approximately 232 million people in 26 countries are facing the problem of water shortage, another 400 million people use water faster than the rate of resource renewal, and approximately a fifth of the world's population cannot meet the sanitary standards of fresh water. The water crisis comes after the global oil crisis, which has become the main factor that restricts social, economic, and ecological development.

Compared with other countries, China faces a serious situation on water resources. China's total water resources are only 2.812 billion m^3, which accounts for 6% of the world's water resources and ranks fourth in the world after Brazil, Russia, and Canada. However, the per-capita water resources are only 2,200 m^3, only 1/4 of the world's per capita, 1/5 of the United States', and 1/50 of Canada's and ranking 110th in the world. Thus, China is one of the 13 countries with the poorest per-capita water resources in the world. Moreover, the spatial and temporal distributions of water resources are extremely uneven, and water pollution is serious. At the same time, China is a large grain-producing country, where agricultural water consumption accounts for a large proportion of the national economy. All of these conditions make China's water management complex. Although mature research on water assessment and configuration has been conducted at home and abroad, most studies are confined to the narrow sense of the concept of water and is therefore limited.

A virtual water strategy aims to find the best way to address the water shortage in the population-grain-trade cycle from a macroscopic point of view. This theory has great theoretical and practical significance because it is the strategic basis for countries to adjust their industrial structures and import and export trades to solve the problem of water shortage in the context of globalization. In China, solving the problem of water resources from the perspective of virtual water theory is an effective idea that broadens the horizon for solving regional water shortage issues. However, implementing a virtual water strategy is not simply determined by the principle of comparative advantage and demand theory, but is due to the interweaving of multiple factors and complex effects. Thus, the influence factors in the virtual water strategy have to be studied.

STATE OF THE ART

The virtual water concept was proposed by Professor John Anthony Allan, a geographer from the United Kingdom. This concept initially referred to the amount of water consumed in generating agricultural products (Allan 1994). With the deepening of related research, Professor Allan revised the concept of the amount of water resources consumed in producing goods and services (Allan 1993). The premise and foundation of virtual water research is the calculation of virtual water in products or services. Agricultural water consumption accounts for approximately 80% of the global water consumption, industrial product data are difficult to obtain, calculation is complex, and the service industry water consumption is small. Thus, the existing virtual water quantitative calculation mainly focuses on agricultural virtual water. The following two methods are used to calculate the virtual water content of agricultural products: studying the production tree of various products and calculating the water content based on different product types (Zimmer et al. 2003). The former considers the input of the natural form of water and encounters difficulty in fully reflecting the virtual water contained in the product. The latter adopts the Penman standard formula recommended by the World Food and Agriculture Organization; this formula is relatively simple and feasible, but involves a large error. Input-output analysis and calculation method can reflect the flow of resources in the production and consumption processes, and the calculation of virtual water is more comprehensive than the previous two methods (Huang et al. 2005, Guan et al. 2007, Lenzen 2009).

Virtual water is transactional and flows with the import and export of commodities in international and domestic trades. In September 2005, the German Development Institute established a virtual water trade workstation. The empirical research scope of virtual water trade has been expanding in recent years. Two main research ideas in virtual water trade exist. One is based on the water footprint of the virtual water trade calculation method, and the other is based on the water input and output of the same method. Many studies have focused on the mechanism and ways of virtual water trade in solving water resource problems and promoting coordinated economic development. Some scholars have also analyzed the relationship between virtual water trade and economic development from the perspective of interprovincial or watershed areas. The study of virtual water trade extends to the virtual water strategy, which refers to the export of water-intensive products from water-rich countries or regions to water-poor countries or regions through physical trade (Li et al. 2008). The study of virtual water strategy involves two aspects: one is virtual water strategy and water security (Yang et al. 2006, Yang et al. 2002), and the other is the impact of virtual water strategy on water resource management, ecology, and economy (Long et al. 2003), which reflects the political and social roles of virtual water.

The concept of water footprint is derived from the ecological footprint and is defined as the amount of water needed by any given population (country, region, or individual) for all products and services consumed over a given period of time (Hoekstra et al. 2006). Water footprint theory studies the quantity of water resources that correspond to the resources and services consumed directly and indirectly by people, which can truly reflect the demand and occupancy of water resources. Two methods, namely, top-down and bottom-up, are generally used in calculating water footprint. In the top-down method, the water footprint is equal to the amount of water used in the region and the virtual water flow into the region (Hoekstra et al. 2007). The bottom-up method is based on the amount of water contained in the products consumed by the residents. The amount of goods and services consumed is multiplied by the virtual water content of each unit product, and the sum is added up with the amount of water consumed by the living and ecological environment (Wang et al. 2005). Although the results of the two calculation methods are different, they can reflect the general rule of the water footprint distribution.

Virtual water and water footprint are adopted to study the utilization of regional water resources from the perspectives of production and consumption, respectively, which broadens the horizon of water resource research and expands the research and application fields. Studies include virtual water and water resource management policy formulation (Wichelns 2010), virtual water and water resource security relationship (Cheng 2003), water resource dependence based on virtual water, water resource self-sufficiency, water footprint growth index (Rui et al. 2011), and virtual water and regional water resource allocation. On the basis of the research on virtual water, some scholars have discussed the basic law of virtual water flow (Seekell et al. 2011), but scientific establishment and systematic evaluation of the index system of influence factors in virtual water flow hardly exists.

MATERIALS AND METHODS

Construction of index system: The virtual water flow involves a wide range of areas; therefore, the index system of its construction system is both natural and social, both dynamic and static, and both qualitative and quantitative, and each index system should have a certain hierarchical structure. The index system should include political, economic, social, and ecological issues. However, on the one hand, the increasingly perfect market economy facilitates the flow of virtual water, similar to political disturbances and regional conflicts, and other special circumstances are disregarded. On the other hand, the government is assumed to support all policy proposals that are conducive to sustainable economic and social development, thereby breaking away from the vicious cycle of regional economic development at the expense of the environment. A good economic environment and an appropriate policy system are also assumed to be prerequisites for implementing virtual water flow. On this basis, the influence factors in regional virtual water flow are divided into three layers, namely, the target, criterion, and index layers. The evaluation index system of the 3 criteria layers and 13 indexes of the virtual water flow influence degree is determined, and the evaluation index system of the virtual water flow influence factors is established, as shown in Table 1.

Table 1: Evaluation index system of virtual water flow influence factors.

Target Layer	Criterion Layer	Index Level	Index Interpretation
A: Virtual water flow influence degree	C_1: Social factors	P_1: Per-capita water footprint (m^3/people)	Ratio of industrial water consumption to industrial water yield
		P_2: Agricultural water use ratio (%)	Proportion of agricultural water used in all sectors of the national economy
		P_3: Industrial water consumption ratio (%)	Ratio of industrial water consumption to industrial water intake
		P_4: Per-capita water resources (m^3/people)	Per-capita value of regional water resources
		P_5: Dependence index (nondimensional)	Reflecting a country's dependence on foreign water resources
	C_2: Economic factors	P_6: Water satisfaction index (%)	Ratio of agricultural water supply to water demand
		P_7: Grain security index (%)	Ratio of available food production to food demand
		P_8: Agricultural water productivity (kg/m^3)	Quantity of agricultural products produced by unit moisture
		P_9: Grain self-sufficiency (%)	Ratio of local production to demand
	C_3: Ecological factors	P_{10}: Water resource development and utilization level (%)	Annual utilization of freshwater that accounts for percentage of available (renewable) freshwater resources
		P_{11}: Annual drop in groundwater level (m/year)	Annual average decline of groundwater in an area
		P_{12}: Water resource modulus (m^3/km^2)	Per square kilometer of water resources
		P_{13}: Water resource pressure index (%)	Ratio of water footprint to amount of renewable water resources in a country or region

Evaluation method: Analytic hierarchy process (AHP), proposed by Thomas L. Saaty in the 1970s, and is a simple and easy way to formulate solutions for complex and vague problems (Saaty 1977). As a qualitative and quantitative decision-making analysis method, AHP models and quantifies the thinking process of decision makers for complex systems. The basic principle of AHP is to form an orderly hierarchical structure of a complex appraised system based on its intrinsic logical relationship and represented by the evaluation index. According to the index of each layer, and using the knowledge, experience, information, and values of experts, the indexes of the same layer are compared in two ways. A comparison discriminant matrix $A=\{a_{ij}\}$ is constructed according to the prescribed scaling value (generally using 1-9 scaling method). The maximum eigenvalue $\lambda_{\max}$ of the comparison discriminant matrix is calculated by the organizer, and the following formula is introduced:

$$AX=\lambda_{\max} X \qquad ...(1)$$

The corresponding eigenvector $X=\{X_1, X_2, \cdots, X_n\}$ is obtained by solving Formula (1). Normalization of feature vectors is used to obtain the weight values of each index. AHP is used to evaluate the influence factors in virtual flow.

RESULTS AND ANALYSIS

In this study, 10 experienced experts in water resource management are selected to form an expert group to set the weight of each level. First, the experts are divided into five groups, and each group determines the weight of different indicators. Second, each group is assigned a comparison according to the 1-9 scale method on the basis of the principle of pairwise contrast. Finally, the weight set by each group is collectively discussed. Then, the relationships among the indicators are shown in Tables 2 to 5.

According to the index weight contrast value set by the aforementioned expert group, the corresponding judgment matrix can be constructed, and then the consistency of the judgment matrix can be tested. If the confidence interval (CI) value is greater than 0.1, the contrast value between two indexes should be reset. The weight value of each index is represented by A_i, and the test results of weights of each level are obtained. After testing, CI values are less than 0.1, which indicate that the composition of the index matrix set by the panel members has a relative consistency, the calculated value is effective, and the revision of the relative weight value need not be discussed. The calculation results of the weight of each layer index to the target layer are presented in Table 6.

According to the total ranking of the hierarchy, the weight allocation set of the evaluation index is as follows:

A= {0.27, 0.03, 0.05, 0.15, 0.10, 0.02, 0.13, 0.04, 0.07, 0.03, 0.02, 0.01, 0.06}.

The results show that the influence factors in virtual water flow are classified according to the degree of influence, namely, per-capita water footprint (P_1) > per-capita

Table 2: Scale comparison matrix A-C.

A	C_1	C_2	C_3
C_1	1	3	4
C_2	0.33	1	3
C_3	0.25	0.33	1

Table 3: Scale comparison matrix C_1-P.

C_1	P_1	P_2	P_3	P_4	P_5
P_1	1	7	5	2	3
P_2	0.14	1	0.5	0.25	0.33
P_3	0.2	2	1	0.33	0.33
P_4	0.5	4	3	1	2
P_5	0.33	3	3	0.5	1

Table 4: Scale comparison matrix C_2-P.

C_2	P_6	P_7	P_8	P_9
P_6	1	0.2	0.5	0
P_7	5	1	3	2
P_8	2	0.33	1	1
P_9	3	0.5	2	1

Table 5: Scale comparison matrix C_3-P.

C_3	P_{10}	P_{11}	P_{12}	P_{13}
P_{10}	1	3	4	0.5
P_{11}	0.33	1	3	0.25
P_{12}	0.25	0.33	1	0.17
P_{13}	2	4	6	1

Table 6: Calculation results of weight of each layer index to target layer.

Indicators	C_1	C_2	C_3	Weight value
	0.61	0.27	0.12	
P_1	0.45			0.27
P_2	0.05			0.03
P_3	0.08			0.05
P_4	0.25			0.15
P_5	0.17			0.10
P_6		0.09		0.02
P_7		0.48		0.13
P_8		0.16		0.04
P_9		0.27		0.07
P_{10}			0.30	0.03
P_{11}			0.13	0.02
P_{12}			0.07	0.01
P_{13}			0.50	0.06

water resources (P_4) > food security index (P_7) > dependence index (P_5) > grain self-sufficiency (P_9) > water resource pressure index (P_{13}) > industrial water consumption rate (P_3) > agricultural water productivity (P_8) > water resource development and utilization (P_{10}) > agricultural water use ratio (P_2) > water content index (P_6) > annual decline of groundwater level (P_{11}) > water resource modulus (P_{12}). Therefore, the most important factor that affects the degree of virtual water flow is water footprint per capita. The weights of the indexes P_1, P_4, P_5, P_7, P_9, and P_{13} are 79%, which indicate that the virtual water flow is determined by the water footprint per capita, water resource per capita, food security index, dependence index, grain self-sufficiency, and water-resource pressure index.

CONCLUSION

Based on the analysis of the influence factors in virtual water flow, an evaluation index system of the influence factors in virtual water flow was established. The system consists of 3 levels and 13 indexes. The weight of each index is sorted, and two main conclusions are drawn. First, per-capita water footprint is the primary factor that affects the virtual water flow. Second, per-capita water footprint, per-capita water resources, food security index, dependence index, grain self-sufficiency, and water-resource pressure determines the virtual water flow.

The disadvantages of this study are that AHP has a certain subjectivity and the selection of evaluation index may not be sufficiently comprehensive. This study can be perfected in two aspects. First, the evaluation index of cultivated land resources and population status should be increased. Cultivated land resources and population status are important factors that affect the flow of virtual water; thus, they should be converted into quantitative indicators and included in the evaluation system of virtual water flow. Second, an empirical test on the evaluation results of the influence factors should be conducted. The evaluation results are verified through comparative analysis of typical cases in the virtual water flow area or the use of econometric test method.

ACKNOWLEDGEMENT

The study was supported by 2017 Henan philosophy and Social Science Planning Project: Zhengzhou water resources carrying capacity research based on virtual water (2017BJJ041). Doctoral research fund project of North China University of Water Resources and Electric Power.

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