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The Cognitive Framework of the Interaction between the Physical and Virtual Water and the Strategies for Sustainable Coupling Management

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Abstract: In the context of a changing environment and economic globalization, the evolution of regional hydrology and water resources systems has undergone profound changes. It is not enough to rely on traditional physical water resources planning, scheduling, and regulation methods to solve problems such as water shortages and imbalances in the water cycle associated with rapid economic development. The theory of virtual water expands the cognitive scope of hydrology and water resources and enriches the solutions to water problems. However, the academic community has not yet reached a consensus on how to build a unified framework of the virtual water theory and traditional hydrology and water resources recognition system, how to understand the new laws of water resources evolution in the natural–economic continuous system, and then how to realize efficient and sustainable usage of water resources through physical water–virtual water integrated management. This paper proposes a basic cognitive model of coupling of physical water–virtual water and discusses the evolution of hydrology and water resources in a natural–economic system, presenting the laws of the coupled flow of physical water–virtual water in natural systems and human economic systems. A quantitative expression equation is proposed for the flow process, and a basic theoretical framework for the coupled flow of physical water–virtual water is preliminarily constructed. At the end of the paper, the basic strategy for the regulation of a physical water–virtual water integrated management system is proposed, which provides a new perspective for the efficient and sustainable use of global water resources in a changing environment.

Keywords: evolution of water resources; physical water; virtual water; coupled flow; integrated management; efficient and sustainable

1. Introduction

The water crisis is a global strategic crisis in the 21st century [1,2]. Currently, there are around 0.7 billion people suffering from severe water scarcity globally [3]. As early as 1975, the members of the European Economic Community conducted research on water management legislation [4–7], and the water resources management framework was gradually improved and matured within the past more than 30 years.

However, in the 21st century, under the dual effects of climate change and human activities, the rapid evolution of water resources systems and large water resources consumption in the economic system

will bring larger damage to the stability and sustainability of water resources utilization [8]. At present, the world is plagued by water scarcity to different extents [9]. Due to extreme climatic events and poor water resources conditions, around 300 million Africans live in extreme poverty, and 60 million die from water shortage annually [10]. In Asia, a previous study showed that there is a high risk of severe water stress in densely populated watersheds by 2050, influenced jointly by climate change and economic development, especially in China, India, and Mainland Southeast Asia [11].

Conflicts induced by water resources happen frequently, especially in arid and semiarid areas [12,13]. The Middle East has always impressed on people that oil is cheaper than water. Indeed, the Middle East is the richest region in terms of oil resources of the world, with more than 65% of the global oil storage. However, it is also an area with extremely deficient water resources. Eleven countries out of the twenty most water-short countries in the world belong to the Middle East [14]. From the perspective of the characteristics of water resources, it is not only a kind of natural resource with natural properties but also an economic resource with economic attributes [15]. Therefore, effective and sustainable management of water resources should not only emphasize the motion law as a natural material, but also consider the characteristics of the value flow of water resources in economic production and consumption. Traditional water resources research has established a theoretical framework of physical water for the purpose of understanding water cycle processes and efficient use of physical water resources [16,17]. With the above mentioned theoretical support, people have made use of the division and storage projects [18], inter-basin water transfer projects [19], water desalination projects [20], water-saving practices [21], water rights system construction, and the strictest water resources management system to improve the water use efficiency and to pursue sustainable water resources management [22,23]. However, it has been proven that measures like increasing water supply, optimizing water distribution, and economizing the use of physical water resources cannot completely solve regional water resource problems [24]. Especially in the context of high marketization and economic globalization, the free market activities and the inequality in regional development exacerbate the contradiction between the supply and demand of water resources in water-deficient areas, which is difficult to solve only based on the regulation of physical water resources [25].

Whether in the most water-deficient parts of Africa, or in the Middle East with its attitude of “oil is cheaper than water”, or in the United States, Japan, or China, which are suffering from regional water shortages caused by uneven spatial–temporal distribution, there is no exception to the “water shortage” problem. Around the world, agricultural water consumption is as high as 70%. To reduce agricultural water use, the measures of minimum tillage and no-tillage farming and crop rotation are widely applied and implemented. Furthermore, organic fertilizer application and film mulching are also efficient agronomic techniques to improve agriculture water use efficiency [26]. For the industrial water user, the best way to achieve industrial water saving is to adopt water circulation use and reuse the water from cooling down. Upgrading the manufacturing processes is also a key factor to tap into water-saving potential [27]. For the domestic water user, Lu et al. found that the domestic water price and the usage rate of water-saving appliances were recognized as the dominant influencing factors for domestic water consumption [28]. Sharma and Vairavamoorthy proposed that, to strengthen demand side management and improve domestic water availability, monitoring and planning are the key measures to control the fast growth of domestic water consumption [29]. Based on the above-mentioned studies, it can be seen that traditional water resources management measures all focus on physical water [30], which includes water storage projects, inter-basin water transfer projects, water-saving society construction, water rights transfer, and the strictest water resources management policy, with the purpose of efficient and sustainable water resources utilization.

However, it turns out that solely relying on physical water resources regulation measures cannot completely solve regional water resources problems [31]. In the context of high-degree marketization and economic globalization, the free market activities and the imbalance of regional development have further aggravated the contradiction between the supply and demand of water resources in

water-deficient areas. The integration of physical water and virtual water management will become an important issue in the field of water resources management under the new situation.

The evolution process of water resources in the modern environment is essentially the intertwining relationship between water as a material entity in the hydrosphere (physical water) and water as natural resource in the economic system (virtual water), which form a complex coupling–feedback nexus [32,33]. This paper proposes the basic cognitive mode of the coupling effect between physical and virtual water and discusses the evolution of the water resources in the natural–economic system, based on which we construct a new cognitive model to depict the coupling flow route of physical water and virtual water, and also establish the quantitative equations to characterize the flowing law. Finally, this study discusses the simulation tools for modeling physical water and virtual water flowing in the natural–economic system and proposes several efficient measures for overall regulating of the physical and virtual water. This study has preliminarily established a basic theoretical framework for physical water and virtual water coupling flow, which could build a theoretical foundation to coordinate the relationship between human economic water use and ecological water use and to attain a harmonious relationship between humans and nature.

2. The Theoretical Base for Integrated Management of the Physical–Virtual Water System

With the increasing enhancement of global warming and human activities and expansion of the space for economic activities, the effect of the physical–virtual water coupling flow has become increasingly apparent [34,35]. Seen from the history of civilization, the intervention of humans in the water resources system is a gradual process, and the understanding of the mechanism for hydrology and water resources is also a gradually deepening process.

Since the Chinese economic reform in 1978, the country has entered a stage of large-scale industrialization and urbanization. In this period, the economy developed rapidly, and industries achieved a leap-forward advancement, with industrial water consumption increasing from 50.8 billion m³ in 1980 to 140.6 billion m³ in 2014 [36]. At the same time, with the advancement of urbanization, there has also been a substantial increase in urban domestic water use. The development of agriculture, industry, urban life, and the tertiary industry has had a great impact on hydrology and water resources systems, which has brought forth many water-related problems, such as the deterioration of the water ecological environment and competition and expulsion among water users [37,38].

In this context, to solve the issues of regional water resources, some new theories and perspectives—e.g., cloud water resources [39], pan-river-basin management [40,41], and virtual water strategy—have been proposed as a supplement for water conservancy project regulation within basins, and traditional water conservation and efficiency-enhancing water resources management [42]. This indicates that the understanding of the water resources systems has further deepened.

The process of human cognition of hydrology and water resources systems can be divided into three periods, according to the evolution of economic development. The first period can be regarded as the stage before 1900 A.D., when the productive forces level was low, the human influence on the water resources system was small, and the driving force of water resources systems was almost natural power (e.g., gravity, solar energy). Thus, the water flow route of water resources systems in this phase can be defined as a “one dimension–one element” flow. “One dimension” mainly refers to physical water, and “one element” refers to the fact that the water flowing path of water resources systems is only in the natural cycling route [43]. The second period can be regarded as the stage from the 1900s to the 1990s, when the productive forces level was greatly improved, and human influence on water resources systems was correspondingly enhanced. Therefore, the water flow route of water resources systems during this time is defined as a “one dimension–two element” flow. Here, the term “two element” refers to the fact that the water flowing paths of water resources systems are not only in the natural cycling route but also in artificial canal systems. Wang and Jia [44] and Liu et al. [45] investigated the two element characteristics of the water resources system and proposed the theory

of a dualistic water cycle, which deeply expanded the cognition scope of the traditional one element physical water cycle.

The third period can be regarded as the current stage we are undergoing. Since the 21st century, the contradiction between water supply and demand has become more prominent, and the regional water crisis has gradually evolved into a global crisis. Thus, water resources have become strategic resources. Allan firstly proposed the virtual water theory and virtual water strategies in 1993, to relieve the pressure of water scarcity by importing water-intensive commodities [46]. The virtual water theory [47,48] expanded the cognitive scope of water resources systems [49,50] from a physical water dimension to a physical–virtual water dimension, which has enriched the content of water resources research by adding the movement of virtual water in the progress of trade, consumption, and dissipation of economic processes to the traditional natural hydrological process [51,52]. Nowadays, with the fast development of economic globalization and international trade, there is not only a huge amount of real water exchanged through large water projects but also a large amount of virtual water embedded in commodities transported between the regions of different countries. As a consequence, the water flow route in the water resources system in the new conditions is defined as “two dimension—three element” flow. Here the term “two dimension” refers to physical water and virtual water, and the term “three element” refers to the fact that the water coupling flowing paths of the new water resources system include three routes—the real water flowing route, the physical water being transformed to virtual water route, and the virtual water flowing route in the industrial structure.

In the context of economic globalization and high-degree commercialization, the law of the coupling flow of physical water resources and virtual water resources is predicted to be one of the most significant features of the water resources system in the modern environment [53,54]. The evolution process of the understanding of water resources systems can be summarized as shown in Figure 1.

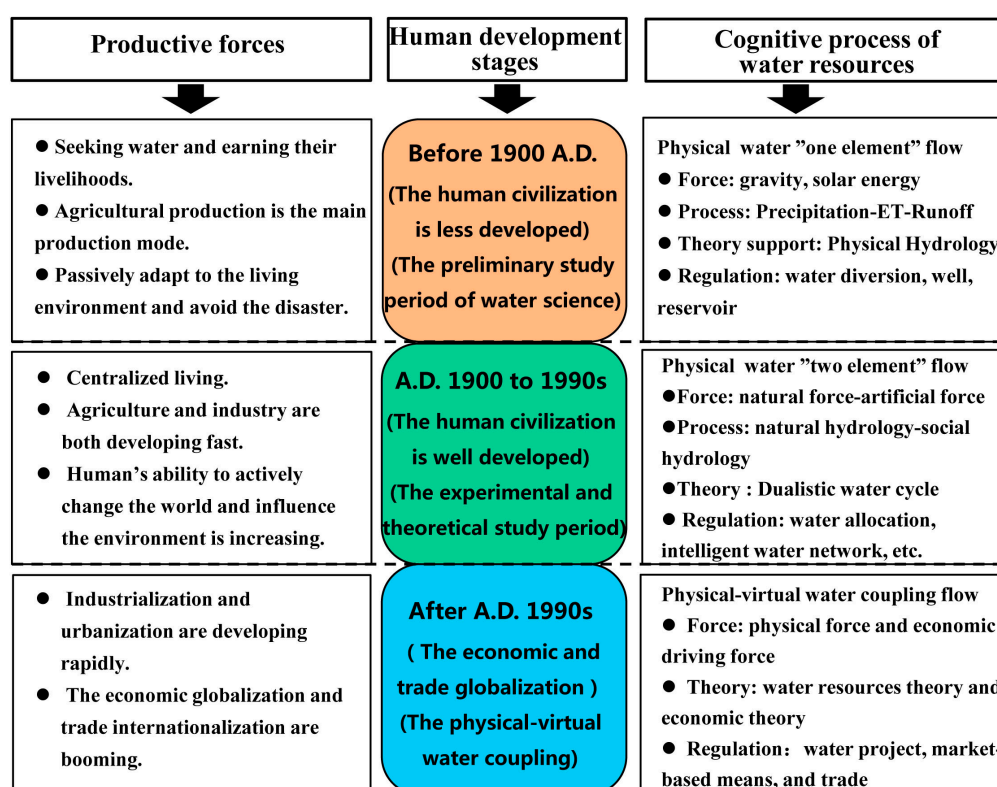


Figure 1. The evolution process of human cognition for hydrology and water resources systems [55,56].

The theory of the physical–virtual water coupling flow is an important theoretical basis for the combined management of physical and virtual water. Essentially, the physical–virtual water coupling flow pattern is determined by the “two-dimensional” property of water

resources. On the one hand, as a natural material (physical water), water is flowing, forced by solar energy, earth gravity, and artificial forces in socioeconomic systems, along the route of precipitation–evapotranspiration–runoff–water–consumption–water returned to the river [57,58]. On the other hand, as an economic resource (virtual water), water is embedded in commodities and flowing with the process of commodity production, trade, and consumption, along the route of commodity production (virtual water embedding)–commodity trade (virtual water trade)–commodity consumption (virtual water consumption)–commodity recycling (virtual water reuse). In reality, the flow of physical water is closely coupled with the flow of virtual water, and they are deeply intertwined and frequently interact with each other. To realize the integrated management of physical–virtual water, it is necessary to clarify the water resources in physical form (physical water flow) and virtual form (virtual water flow) in the domestic economic system, and their driving mechanism on the basis of the theoretical framework of a physical–virtual water coupling flow. Based on this, a comprehensive allocation and utilization model for the overall water resources of regional physical–virtual water could be established, to maximize the effectiveness and utility of unit water resources and serve the sustainable development of the economy and the ecological environment.

3. The Mechanism of Physical–Virtual Water Coupling Flow and Their Relationships

3.1. Physical–Virtual Water Coupling Mechanism

The physical–virtual water coupling effect is derived from the economic value and function of water resources, and this coupling effect occurs on the condition of a highly developed economic market and the mature mechanism of interregional trade. It should be pointed out that the complicated water resources allocation systems and the various production and consumption chains in the socioeconomic system are important links to transmit the physical–virtual water coupling effect. Under the modern environment, the evolution of water resources closely accompanies the complex natural economic giant system. The coupling relationship between physical–virtual water is only limited to the natural economic system, which includes two major processes: production and consumption. Production is the process of transforming physical water into virtual water, and consumption is the process of virtual water trade. During the operation of the system, physical water and virtual water flows have obvious coupling characteristics in two major aspects: flowing path and process flux, as shown in Figure 2.

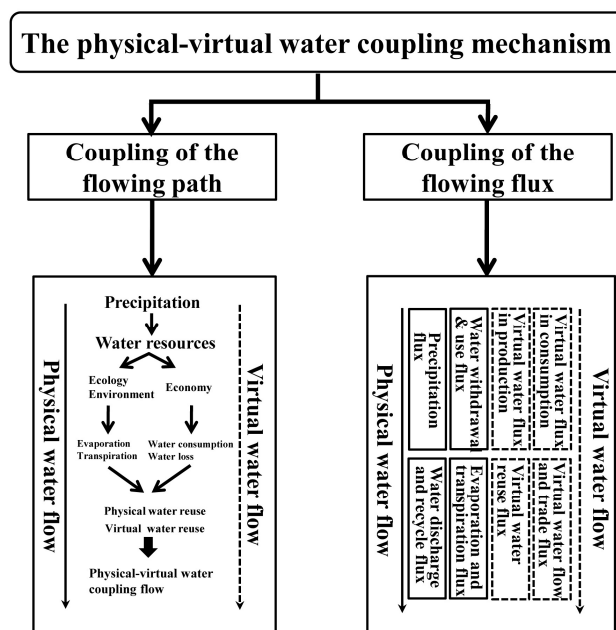


Figure 2. Mechanism of the physical–virtual water coupling effect.

In terms of the flowing path, the physical water path and virtual water production and consumption path are intertwined and coupled with each other. This coupling effect is mainly reflected in the production process, which is the process where physical water is embedded into the commodity as virtual water. Physical water flow could affect the industrial structure, the production mode, and the production capacity of the economic system, and thus has a great impact on the transformation, accumulation, flow, and consumption of virtual water. In general, an industry with relatively large physical water input will inevitably bring about an expansion of the production capacity. Conversely, an industry with relatively less water input will lead to the shrinkage of this industry. In essence, the coupling and interweaving of physical water and virtual water flowing paths are determined by the irreplaceable value of water resources for domestic economic development.

In terms of process flux, the flux of physical water is closely associated with the production and consumption flux of virtual water. Flux is an important indicator in the process of water circulation and water flow, and it is also a key parameter to measure the evolution characteristics of water resources systems. The coupling effect of physical water flux and virtual water flux is the fundamental feature of the physical–virtual water coupling flow. The utilization flux of physical water determines the flux of virtual water production and trade. At the same time, the demand flux of virtual water also affects the physical water resources system and promotes the optimized layout and efficient allocation of regional physical water resources systems.

3.2. Analysis of Physical–Virtual Water Coupling Flow Paths

Combined with previous analysis, the coupling flow of physical–virtual water is essentially a mutual-feeding process of the physical flow and value flow of water resources. The natural water cycle in the past has gradually evolved into the flow path of the natural–artificial dualistic water cycle, as the physical flow of water resources speeds up with the strengthening of human activities and the increase of total economic water consumption. The physical water resources movement objectively increases the speed of physical water flowing, as well as the evolution rate of water resources in the basin.

At the same time, accompanied by commodity production and consumption, the water resources which embed into the commodity form a virtual flow path in the economic system. Seen from the physical–virtual water coupling flow process, the physical–virtual water coupling flow can be divided into three independent stages. Firstly, there is the physical water resources flowing process, which mainly includes the conversion process from natural precipitation into water resources and the process of being extracted and used by the economic water users. The physical water resources flowing process could be regarded as the physical water flow. The second is the process of production in which water resources are used as raw material. This process is essentially the conversion process between physical and virtual water. Through the production, water resources are consumed or embedded in commodities. The third is the process of virtual water trade and consumption. In this process, people consume the virtual water embedded in commodities or transfer virtual water through commodity trade, through which the spatial and temporal distribution of virtual water is changed.

In general, the physical–virtual water coupling flow process can be summarized as a two-dimensional structure with three elements. ‘Two-dimensional’ describes the movement of water resources from the dimension of physical flow and virtual flow, not only related to the traditional theory of water resources systems but also related to water resources economics, trade, and other related theoretical methods. Three elements describe the flow paths of physical water and virtual water and their transformational relationships in the production and consumption chain. The pattern of “two-dimension and three element” of the physical–virtual water coupling flow is represented in Figure 3.

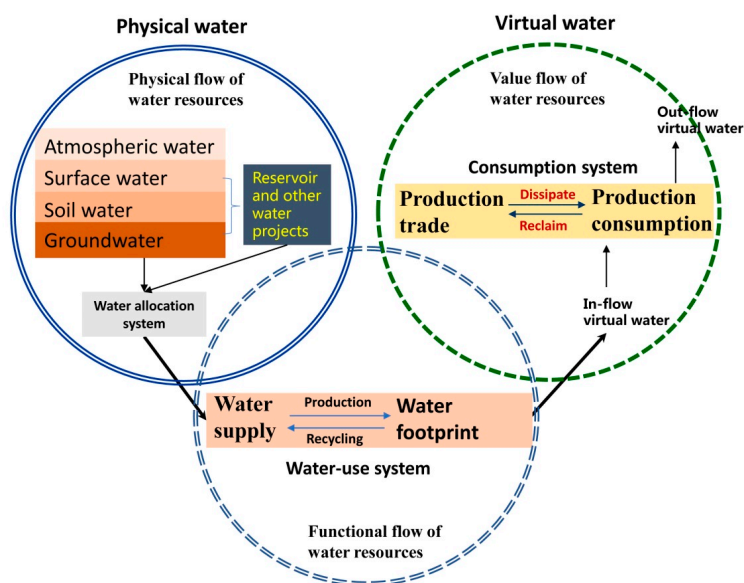


Figure 3. The relationship of the “two-dimension and three element” physical–virtual water coupling flow.

The above diagram describes the coupling flow path of physical–virtual water. Seen from the flowing structure, the coupling flow process of physical–virtual water presents a framework of two mutually-coupled parts. First, the physical water is flowing in the natural–economic system. The forms mainly include precipitation, evapotranspiration, surface runoff, soil water, groundwater, and the processes of intake–consumption–discharge–reuse in economic water resources consumption systems. The second is that virtual water is flowing with the commodity trade and consumption. The main forms of movement include physical water transformed into virtual water along with commodity production, virtual water flow along with commodity trade, and virtual water consumption and reuse along with commodity consumption and recycling.

From the perspective of the flow paths, the physical–virtual water coupling flow can be interpreted as the three joint flows: the physical flow, the functional flow, and the value flow of water resources. The physical flow of water resources mainly refers to the water flowing process. As the essential material for economic production and consumption, the movement and spatial–temporal evolution of physical water is the foundation to study the physical–virtual water coupling flow process. The functional flow of water resources refers to the processes of physical water flowing into economic industries and being transformed into virtual water through production activities. It is an important link for the conversion between physical water and virtual water. The value flow of water resources is essentially the process of consumption activities. From the perspective of water resources consumption, the consumption of virtual water is behind the consumption of commodities. The value flow of water resources refers to the movement of virtual water in commodities in the production, trade, and consumption chain. The typical value flow of water resources starts when the products leave the factory, and then the products go into the consumers’ hands. When the service life of the product is over, the virtual water embedded in the product is also consumed.

4. Characterization of Physical–Virtual Water Coupling Flow and its Combined Regulation

4.1. Description of the Status of Physical Water–Virtual Water Coupling Flow Systems

Under the modern environment, the rule of the physical–virtual water coupling flow is a new evolution pattern of water resource systems. With the prosperity and development of the economy, the demand for water resources by human beings continues to grow, and the contradiction and water-related problems become more and more prominent. These problems can be summarized as the availability of water resources and the healthy and sustainable development of water environment

system. Therefore, an important purpose of the physical–virtual water coupling flow system is to explore the interaction of water resources in natural and economic systems. Considering the flow flux and environmental impact, the description of the physical–virtual water coupling flow process can be expressed by Equation (1):

$$\{W_p, W_v, E\} = \Phi(Q_{pin}, Q_{pout}, Q_{vin}, Q_{vout}, S, P, C), \quad (1)$$

where W_p represents the flux of physical water in the process of physical–virtual water coupling flow, which is a multidimensional vector, including green water flux, blue water flux, physical water consumption flux, physical water drainage flux, and physical water recycling flux. W_v represents the flux of virtual water in the process of physical–virtual water coupling flow, which is also a multidimensional vector, including the production flux of virtual water, consumption flux of virtual water, trade (input and export) flux of virtual water, and the reuse flux of virtual water. E represents the environmental impact of the physical–virtual water coupling flow, which includes the vector components of water resources pressure, environmental discharge stress, and ecological impact effects. The water resources pressure can be represented by the ratio of physical water consumption to the total available water resources. The effect of the environmental impact can be represented by the proportion of the actual gray water footprint to the system's maximum carrying capacity of the gray water footprint. The ecological impact effect can be expressed as the degree of water demand satisfaction of the ecosystem in the context of coupling flow. Φ is the expression function of the physical–virtual water coupling flow process. The physical–virtual water coupling flow is the multidimensional flow of the physical and value flow of water resources in the complex natural–economic system, and its driving forces, flow paths, and parameters are all complicated, involving hydrology and water resources science, economics, trade studies, optimization, and other multidisciplinary theories. Therefore, the Φ function is difficult to characterize with a single analytical function, and it needs a set of functions to characterize and express the coupled flow relationship between physical water and virtual water from different perspectives. Generally, the Φ function is mainly characterized by seven parameters. Of these, Q_{pin} represents the input of the physical water resources, which mainly includes surface water, soil water, groundwater resources, and the imported water by diversion project. Q_{pout} represents the output of the physical water resources, which mainly includes the exported water by water diversion and reclamation within the region. Q_{vin} represents the input volume of virtual water. Along with commodity trade, commodities in the outer region enter the region through trade flows. In some areas, the import of virtual water through trade cannot be ignored, which plays an important role in the economic development of the region. Q_{vout} represents the output of virtual water, mainly referring to virtual water in the region exported to other regions through commodity trade. The above four parameters are the main initial parameters and boundary conditions of the physical–virtual water coupling flow system, which can reflect the basic conditions of the water resources background and commodity trade in the study area. S represents the allocation pattern of physical water resources in the economic and environmental systems. This parameter represents the consumption structure of physical water resources in the three major industries of the domestic economy. P represents the parameters of water use efficiency and the environmental impact in the economic production system, including the water use efficiency and the discharge of pollutants in the production process, which can be depicted by the index of water footprint. C represents the parameters of consumption structure and consumption demand, and the characteristics of the consumption process in the economic and environmental systems. Essentially, C is the parameter to describe the patterns of virtual water demand, trade, and consumption. The abovementioned seven parameters can effectively describe the demand, consumption intensity, and consumption rate of physical–virtual water resources in the economic system.

4.2. Description Equations of Physical–Virtual Water Coupling Flow

The coupling flow of physical–virtual water is the new pattern of the water resources system in the modern environment. The assessment criteria and regulation objectives of sustainable and healthy water resources systems mainly include the following three aspects. First, the high security within the system, which mainly refers to the safety and reliability of the physical–virtual water coupling flow process, including the flood control security, physical water supply security, virtual water supply safety, and virtual water trade security. The second is the high efficiency of the physical–virtual water coupling flow system. The main purpose of water resources management is to increase the utilization efficiency. In a broad sense, improving the efficiency of water resources utilization is not only to improve its economic benefits but also to take into account the reasonable allocation of water resources among industries and achieve a synergistic increase in economic and ecological benefits. The indicators of the efficiency of system operation can be characterized by the integrated benefits of the physical–virtual water flow configuration pattern and water resources input. The third is the low environmental impact of water resources systems, which is also the sustainability of the water system. Externality is one of the fundamental characteristics of the water resources system. In the early stage of human development, the natural water system attained a balanced and sustainable state through long-term self-adaptation. The fast development of the economy had a great impact on water resources systems, and the balanced water system thus broke down. The disorderly development and overuse of water resources have had a number of adverse effects on resources, ecology, and the environment, destroying the sustainability of the water resources system. Therefore, the purpose of water resources regulation is to reduce this negative effect from the external and rebuild the new balance of the water resources system. The system sustainability of physical–virtual water coupling flow can be measured by three indicators, including the balance between water resources carrying capacity and water consumption flux, the balance between environmental carrying capacity and pollutant discharge volume, and the balance between ecological water consumption flux and economic water consumption flux. Based on the above analysis, the three equations to describe the physical–virtual water coupling flow patterns are proposed as follows:

(1) Water resources flux characterization equation:

The water resources flux characterization equation mainly expresses the quantitative relationship between the supply of regional physical water and virtual water and the demand in the region. In a relatively independent production cycle (usually one year), the physical water characterization equation is shown as in Equation (2):

$$RW = \begin{bmatrix} RW_a \\ RW_i \\ RW_e \end{bmatrix} = \begin{bmatrix} U_a + G_a + S_a + C_a \\ U_i + G_i + C_i \\ U_e + G_e + S_e + C_e \end{bmatrix} = \begin{bmatrix} \frac{1}{1-\eta_a}, 0, 0 \\ 0, \frac{1}{1-\eta_i}, 0 \\ 0, 0, \frac{1}{1-\eta_e} \end{bmatrix} \begin{bmatrix} RD_a \\ RD_i \\ RD_e \end{bmatrix}, \quad (2)$$

where RW represents the supply flux of physical water in the process of physical–virtual water coupling flow, which is a three-dimensional vector whose components include agricultural water supply (RW_a); industrial water supply (RW_i); and ecological water supply (RW_e). Of these, U_a , G_a , S_a , and C_a represent the water supply flux of surface water, groundwater, soil water, and recycled water to agriculture, respectively; U_i , G_i , and C_i represent surface water, groundwater, and the recycled water supply flux to industry, respectively; U_e , G_e , S_e , and C_e represent the water supply flux to the ecology from surface water, groundwater, soil water, and recycled water, respectively; η_a , η_i , and η_e represent the water loss rate of the agricultural water supply, industrial water supply, and ecological water supply, respectively; RD_a , RD_i , and RD_e represent physical water demand for agriculture, industry, and ecosystems. It should be pointed out that physical water supply security is mainly reflected in the process of water allocation and distribution. On the premise of satisfying environmental and ecological

water demand, the security of the physical water supply system can be guaranteed only when the supply of physical water could meet the demand of each industry in the economic system.

The flow of virtual water is mainly reflected in the production and consumption process of the economy. Consumption pulling force is the main driving force of the virtual water flow. In a relatively independent consumption cycle (usually one year), the virtual water characterization equation is as follows:

$$\mathbf{VW} = \begin{bmatrix} VW_a \\ VW_i \\ VW_l \end{bmatrix} = \begin{bmatrix} AVW_{in} + AVW_p - AVW_{out} - \Delta AVW \\ IVW_{in} + IVW_p + IVW_{rp} - IVW_{out} - \Delta IVW \\ LVW_{in} + LVW_p - LVW_{out} - \Delta LVW \end{bmatrix}, \quad (3)$$

where \mathbf{VW} represents the consumption flux of virtual water in the process of physical–virtual water coupling flow and is a three-dimensional vector. The components include agricultural product consumption flux (VW_a), industrial product consumption flux (VW_i), and consumption of living products (VW_l). AVW_{in} represents the inflow of virtual water through the import of agricultural products; AVW_{out} represents the outflow of virtual water through the export of agricultural products; AVW_p represents the net increment of virtual water brought by producing agricultural products; ΔAVW represents the change of the regional virtual water storage within agricultural products during the consumption period. IVW_{in} represents the virtual water inflow brought to the region by the import of industrial products; IVW_{out} represents the virtual water outflow through the export of industrial products; IVW_p represents the net increment of virtual water through the producing activity of industrial products; IVW_{rp} represents the amount of virtual water recycled through the recovery of the residual value of industrial products; ΔIVW represents the net change of virtual water stored in the industrial products during the consumption period. LVW_{in} represents the regional virtual water inflow through the import of living products and tertiary industrial products; LVW_{out} represents the virtual water outflow through the export of living and tertiary industrial products; LVW_p stands for amount of virtual water added to the region through the production of living and tertiary industry products; ΔLVW is the net change of virtual water stored in the living and tertiary industrial products during the consumption period. In general, the residual value of industrial consumer goods at the end of service life is relatively large, containing virtual water that can be reused again. For agricultural products and tertiary industrial products, there is hardly any residual value at the end of their service life. Therefore, virtual water recycled for agricultural products and tertiary industrial product could be neglected.

(2) Water resource efficiency characterization equation:

Efficiency is an important target for water resources management. Water resource efficiency mainly means earning greater output benefits by less water resources input in the economic production process. However, water resource benefits not only refer to the economic output but also to ecological and environmental benefits. Therefore, the evaluation of water resources efficiency belongs to a problem of multi-objective optimization. This paper proposes a multi-objective comprehensive evaluation function to quantify the water resource efficiency in the physical–virtual water coupling system, which is shown in Equation (4):

$$H = U[f_e(w), f_n(w)] \quad (4)$$

where H is the synthetic benefits of the water resources system and $U[x, y]$ is the multi-objective comprehensive evaluation function of economic benefits and ecological environmental benefits. $f_e(w)$ indicates the objective function of economic benefits brought by water resources, which can be represented by the gross national product (GDP), and $f_n(w)$ is the ecoenvironmental benefit function brought by water resources, which can be represented by the green equivalent area. The green equivalent area refers to the standard area converted by forest, grass, water, and artificial green area.

(3) Water system sustainability characterization equation:

As mentioned above, the sustainability of physical–virtual water coupling flow refers to a balance characteristic during the operation of the system. From the perspective of the coordinated development

of resources, the environment, and the economy, the system's sustainability characteristics mainly include the balance between the water resources carrying capacity and water flux, the balance between natural environmental capacity and economic pollutant discharge amount, and the competitive water use balance between ecological water consumption and economic water consumption. The equation to characterize the sustainability of the coupling flow of a physical–virtual water system is shown in Equation (5):

$$BLC = \begin{bmatrix} BLC_w \\ BLC_e \\ BLC_c \end{bmatrix} = \begin{bmatrix} \frac{TD}{MAW_{res}} \\ \frac{TP}{CAP_{env}} \\ \delta \cdot \frac{WU_{eco}}{WU_{soc}} \end{bmatrix}, \quad (5)$$

where *BLC* represents the sustainability index in the physical–virtual water flowing system, which is a three-dimensional vector. The components include the index of balance between the physical water resources carrying capacity and the water flux (*BLC_w*); the index of the balance between natural environmental capacity and the economic pollutant discharge amount (*BLC_e*); the index of the competitive water use balance between ecological and environmental water consumption, and economic water consumption (*BLC_c*). *BLC_w* can be characterized by the ratio of total water resources demand (*TD*) to maximum available water resources (*MAW_{res}*); *BLC_e* can be described by the ratio of total pollutant discharge (*TPD*) over system environmental carrying capacity (*CAP_{env}*); *BLC_c* can be characterized by the ratio of ecological water flux (*WU_{eco}*) and economic water flux (*WU_{soc}*), and δ is an adjustment factor.

4.3. Regulation of the Physical–Virtual Water Coupling Flow Process

The purpose of regulation of the physical–virtual water coupling flow system is to improve the water supply security and water use efficiency in the water resources system, while reducing the risk and negative effect on the environment, ecosystems, and economic system. Based on the above analysis, the regulation criteria of the physical–virtual water coupling flow system can be summarized as follows:

(1) Criterion for water resources supply safety:

The fluxes of the physical–virtual water coupling flow system mainly include the physical water flux (intaking flux and consumption flux) and the virtual water flux (trade flux and consumption flux). The safety criterion for the physical–virtual water coupling flow system can be expressed as:

$$\left\{ \begin{array}{l} \left[\begin{array}{l} SU_a + SG_a + SS_a + SC_a \\ SU_i + SG_i + SC_i \\ SU_e + SG_e + SS_e + SC_e \end{array} \right] - \left[\begin{array}{l} \frac{1}{1-\eta_a}, 0, 0 \\ 0, \frac{1}{1-\eta_i}, 0 \\ 0, 0, \frac{1}{1-\eta_e} \end{array} \right] \left[\begin{array}{l} RD_a \\ RD_i \\ RD_e \end{array} \right] \rightarrow \mathbf{0} \\ \left[\begin{array}{l} AVW_{in} + AVW_p - AVW_{out} - \Delta AVW \\ IVW_{in} + IVW_p + IVW_{rp} - IVW_{out} - \Delta IVW \\ LVW_{in} + LVW_p - LVW_{out} - \Delta LVW \end{array} \right] - \left[\begin{array}{l} DVW_a \\ DVW_i \\ DVW_l \end{array} \right] \rightarrow \mathbf{0} \end{array} \right. \quad (6)$$

Generally, the safety criterion is that both the physical and virtual water supply fluxes can meet the water demand. *SU_a*, *SG_a*, *SS_a*, and *SC_a* represent fluxes of surface water, groundwater, soil water, and reclaimed water available for agriculture, respectively; *SU_i*, *SG_i*, and *SC_i* are the fluxes of surface water, groundwater, and reclaimed water available for industry, respectively; *SU_e*, *SG_e*, *SS_e*, and *SC_e* represent fluxes of surface water, groundwater, soil water, and reclaimed water available for the ecological environment, respectively; *DVW_a*, *DVW_i*, and *DVW_l* represent the consumption demand flux of regional agricultural products, industrial products, and tertiary industry products, respectively; the remaining symbols are same as the symbols in Equations (2) and (3).

(2) Criteria for maximizing water resources efficiency:

Water resources benefits refer not only to the economic benefits of water resources but also to the environmental benefits. The utility function was introduced above to characterize the synthetic benefits of water resources in Equation (4) above. Therefore, the criteria for maximizing water resources efficiency can be expressed by the following:

$$(H - \max U [f_e(w), f_n(w)]) \rightarrow 0. \quad (7)$$

The efficiency criterion is that the synthetic benefits of the water resources system can infinitely approach the maximum value of the multi-objective comprehensive evaluation function. The symbols are the same as those in Equation (4).

(3) Criteria for the sustainability of the physical–virtual water coupling flow system:

The criteria of sustainability of the physical–virtual water coupling flow system can be expressed by the following:

$$BLC = \left[\begin{array}{c} \frac{TW}{CAP_{res}} \\ \frac{TP}{CAP_{env}} \\ \delta \cdot \frac{WU_{eco}}{WU_{soc}} \end{array} \right] \rightarrow \left(\left[\begin{array}{c} 1 \\ 1 \\ 1 \end{array} \right] + \eta \right), \quad (8)$$

where the optimal value of *BLC* is 1. η is a random small vector, which is introduced as a threshold to describe the elasticity of the equilibrium state. When $BLC = \left[\begin{array}{c} 1 \\ 1 \\ 1 \end{array} \right] + \eta$, the physical–virtual water coupling flow system is considered to be in a sustainable equilibrium state. The remaining symbols are the same as the symbols in Equation (5).

5. Simulation of the Physical–Virtual Water Coupling System and the Combined Regulation

The physical–virtual water coupling flow process is a complicated giant system. The coupling flow process is difficult to characterize with simple mathematical analytical methods. In recent years, the development of computer numerical technology and a water cycle simulation model has provided an important tool for analyzing the physical–virtual water coupling flow process. The availability and allocation pattern of physical water resources are important input conditions for the entire physical–virtual water coupling flow description, which also exert great influence on the economic industrial structure and consumption patterns. Meanwhile, the characteristics of economic production and consumption also determine the virtual water flow behaviors and patterns. Based on this, the core content of physical–virtual water coupling flow simulation mainly focuses on the physical water cycle process simulation and the virtual water flow and consumption process accompanied with economic trade and consumption.

5.1. Physical Water Cycle Simulation Framework

Undoubtedly, under the joint influence of natural changes and human activities, the physical water cycle in the basin exhibits a distinct “nature–economy” characteristic, based on which Wang and Jia [44] proposed the nature–economy dualistic water theory. In this context, the driving forces, flowing paths, and evolution characteristics of the physical water cycle are very different from the traditional natural water cycle. In order to precisely describe the process of the physical water cycle under the “nature–economy” condition and quantitatively assess the availability of physical water, it is important to establish a new simulating method and develop tools based on the nature–economy dualistic water theory.

A complete water cycle simulation model should include a rainfall forecasting module, a land surface hydrological simulation module, an economic water cycle simulation module, and a water balance verification module. The first three modules are used to simulate the water cycle process, and the water balance verification module is used to improve the accuracy of the simulation results

and to evaluate the simulated hydrological variables output through the water balance mechanism. Generally, the rainfall forecasting module is composed by the atmospheric circulation models, regional climate models, and weather generators, etc. The surface hydrological simulation module and the economic water cycle simulation module are the core procedures of physical water cycle simulation, which is developed through the integration of a traditional hydrological model and economic water cycle simulating model. The framework of the physical water cycle simulation is shown in Figure 4.

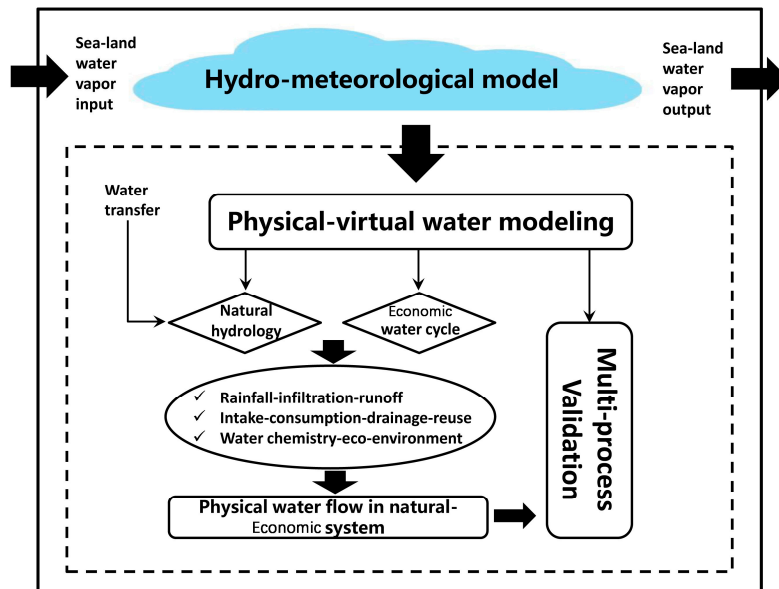


Figure 4. Schematic diagram of water cycle simulation.

5.2. Physical–Virtual Water Input–Output Model

Input–output analysis was first proposed by the American economist Wassily Leontief in the 1930s [59]. Its basic principle is to formulate the socioeconomic input–output table and build a corresponding mathematical model to reflect the correlations between various industries of the economic system, and to describe the interactions between the production processes in the industries. The input–output analysis of physical–virtual water is based on the generalized input–output analysis and is an important quantitative tool to describe the physical–virtual water coupling flow. The primary mathematical structure of the input–output model is shown in Equation (9):

$$x_i = \sum_{j=1}^n \alpha_{ij}x_j + y_i. \quad (9)$$

The above equation depicts the dependent relationship of the economic department's output and interdepartmental linkages and final demand, where x_i represents the total output of the i th sector of the domestic economy; α_{ij} represents the direct consumption coefficient, which means the ratio of consumption of the i th sector for j th sector production to the total output of j th sector; x_j is the total output of the j th sector; and y_i is the final output of the j th sector.

The above Equation (9) can be expressed in matrix form:

$$X = AX + Y, \quad (10)$$

where A , X , and Y represent the total output matrix of the domestic economy, the direct consumption coefficient matrix, and the final output, respectively, and Equation (10) can be changed to be:

$$X = (I - A)^{-1}Y, \quad (11)$$

where $(I - A)^{-1}$ is the Leontief inverse matrix.

After the water resources are introduced into the input–output analysis method, in order to analyze the water flowing pattern in the economic system, it is necessary to determine the water resources consumption per unit of output, that is, it is necessary to determine the direct water use coefficients and the complete water use coefficients of different industries in the economic system. The direct water use coefficient is expressed as follows:

$$\omega_j = \frac{w_j}{x_j}, \quad (12)$$

where ω_j represents the direct water use coefficient; w_j is the direct water consumption per unit of output in the j^{th} sector; and x_j represents the total production output of in the j^{th} sector. After the direct water coefficient matrix is obtained, the complete water coefficient matrix can also be obtained by matrix conversion.

The direct water use coefficient and the complete water use coefficient can reflect the water consumption intensity of the entire industrial chain of the economic system. Therefore, it can quantitatively describe the virtual water flowing patterns in the production, trade, and consumption process. The water resources input–output theory tightly combines the econometrics and water resources economics, which can easily simulate the physical and virtual water flowing paths in the complicated economic system. However, due to the limitation of the availability of input parameters, it is still difficult to establish an inter-annual dynamic water resources input–output model. In recent years, with the development of statistical methods and optimization theories, many dynamic adjustment theories and methods of input–output coefficients have been proposed, which effectively support the further development of the physical–virtual water simulating model.

5.3. Combined Regulation of Physical–Virtual Water Coupling Flow

The purpose of combined regulation and management of physical–virtual water coupling flow is to satisfy the three criteria, including the safety, the high efficiency, and the sustainability of the water resources system. Of these, water safety is the basic premise, and the high efficiency of water resources utilization is an important goal, and the sustainability of water resources system is a rigid constraint condition.

(1) Improve water security through physical–virtual water coupled allocation

Water allocation is one of the important means of traditional water resources management. The limited water resources were allocated to various departments of the economic system by calculating the scale of water use in different industries, based on the principle of fairness and efficiency. Traditional water allocation basically involves only physically visible water resources. With the contradiction between supply and demand for water becoming increasingly prominent, the shortage of physical water resources makes it difficult for the water allocation scheme to meet the water demand in the economic system or to achieve the optimization of the allocation. Under the theoretical framework of physical–virtual water coupling flow, this paper proposes the concept of overall water resources allocation and co-ordinates physical water and virtual water allocation. For water-rich areas, the scale of the production of water-intensive products can be expanded appropriately to produce more water-intensive products; for water-poor areas, the scale of water-intensive products production should be shrunk, and the gap can be filled through virtual water trade from water-rich areas. In general, in the physical–virtual water coupling allocation system, it is necessary to consider the conditions of local water resources, the scale of economic production and consumption, and to control the total economic water demand reasonably, to thus realize the water security and sustainability.

(2) Improve the high efficiency of water resources utilization through input–output dynamic modeling in the economic system

The assessment of economic benefits is the main purpose of the water resources use efficiency assessment. The input–output analysis method is one of the important methods for macroeconomic evaluation, which can reflect water consumption and utilization efficiency in various industries of the economic system. The input–output model of water resources can describe three important aspects in the process of water resources consumption. The first is water consumption in the production process, which can be calculated by measuring the water intake coefficient and the water quota of different industries. The second is the water flow (physical and virtual water) among the consumer sectors, including the intermediate and the final sector. The third is water allocation (physical and virtual water) in the cross-regional trade process. Cross-regional trade not only refers to physical water transfer through a water diversion project but also, more importantly, virtual water flow through merchandise trade. The essence of the input–output analysis of water resources is to analyze the efficiency and values of water consumption in the different industries of the economic system, and to quantify the water resources consumption indices through input and output parameters. The optimal values of the parameters can be determined through dynamic modeling and statistical optimization, which provide important references for decision-making on the structural optimization of the economic system and water resources allocation.

- (3) Implement the strictest water resources management system to achieve sustainability of the water resources system

The strictest water resources management system was first launched by the Chinese government in 2012. The strictest water resources management system restricts the behavior of water resources use from three aspects, including total water consumption control, water use efficiency control, and total pollutants discharge control. The physical–virtual water coupling flow system is also characterized by the balance between water consumption and water resources availability, the competitive balance of water use efficiency among different water sectors, and the balance between pollutant discharge and environmental carrying capacity. Therefore, the purpose of the strictest water resources management system is highly consistent with the physical–virtual water coupling flow regulation, which is an important measure to guarantee water security.

6. Conclusions

The concept of virtual water and related theories was proposed as one of the most important achievements of the discipline of hydrology and water resources at the end of the 20th century. It provides new ideas and methods for ensuring regional, national, and even global water resource security. However, there is still no agreement on the function of virtual water theory in the development of traditional hydrology and water resources discipline, and the cognitive framework unifying the virtual water theory and traditional physical water resources system.

This study explained the preliminary understanding of the physical–virtual water coupling flow process and summarized the general characteristics of the physical–virtual water system. In the modern environment, water resources have the dual properties of significant natural recycling and economic values. The properties of the physical–virtual water coupling flow are, firstly, the transmission, transfer, and allocation process of physical water in the natural–economic system, as the form of physical flow; secondly, it is the process of conversion from physical water to virtual water in the production process; thirdly, it is the virtual water consumption process, which is essentially the process of water value flow in the economic system. Based on these properties, the evolution of the water resources system has successively experienced the “universe” movement stage of physical water, the “binary water circulation” stage of physical water, and the coupled flow stage of physical and virtual water. With the progress of civilization, the cognition scope of the water resources system has gradually expanded from the natural system in early stages to the economic system. At the end of the paper, the mechanism and the structure of physical–virtual water coupling flow characteristics were discussed, and the characterization equations

of physical–virtual water coupling flow were also put forward, which provide support to the efficient and scientific management of the physical–virtual water coupling flow system.

China is a country with one of the most complex and severe water security situations of the major economies of the world. With the development of economic integration and trade globalization, the scope of the water resources problem has not been limited to a basin or a country. The stress of water resources has spread across regional boundaries in the form of virtual water along with regional trade along the path from upstream to downstream of industrial chains. As a result, the water resources problems brought forth by traditional physical water resources planning, allocation, and management alone cannot be solved effectively. Expanding the scope of traditional water resources and constructing a new theoretical framework of water resources for virtual water management will be a new research direction and topic in the global water science field in the new era.

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