Water Policy 21 (2019) 722–741

Assessing marine equivalent virtual water supplied by the ocean: a case study of China's coastal areas

Caizhi Sun* and Mengfei Zhang

Center for Studies of Marine Economy and Sustainable Development, Liaoning Normal University, Dalian 116029, China
**Corresponding author. E-mail: suncaizhi@lnnu.edu.cn*

Abstract

'Virtual water' represents water resources consumed by industrial, agricultural, and other human activities. Virtual water flow is significant for coordinating the global water balance, but most current research has focused on land. In this study, marine products or services are introduced into the research framework of virtual water, and the concept of 'marine equivalent virtual water' is introduced. The formulas are proposed from three aspects: food, environment, and power generation. The calculation results for China's marine equivalent virtual water content from 2006 to 2015 show a U-shaped characteristic in which different factors change in importance over time. In addition, the marine equivalent virtual water system structure is analyzed and forecasted for China's coastal areas by 2025. Through the changes in the marine equivalent virtual water system entropy, the research area is divided into three development types: equilibrium, orderly, and change. Each area can be targeted to put forward development proposals. The marine equivalent virtual water proposition quantifies the function of the ocean in the supply of freshwater resources. It provides a new perspective for relieving pressure on terrestrial water resources and is of great significance to water resource management and water policy formulation; this concept should be built upon in future research.

Keywords: Coastal China; Energy; Environment; Fisheries; Marine equivalent virtual water; Structural evolution

Introduction

Water resources, as the basic natural resources of human survival and development, are also the basis of national development (Ge *et al.*, 2017). However, water shortages, water regional imbalances, and water pollution have been aggravated to different degrees by a combination of economic, demographic, and climatic factors (Liu *et al.*, 2018). Water resources are becoming more and more restrictive to development and water resource management and rational allocation have become a global concern (Haddad & Lindner, 2001). It is an important way for China to formulate water policy from a macroscopic perspective. Over the

doi: 10.2166/wp.2019.069

past decade, 70% of the nation's population and 60% of its economy have been supplied by 14% of the total water resources in China's coastal regions. Water shortages are particularly acute (Huang *et al.*, 2017).

It is very difficult to properly allocate the physical water resources across a region. In order to coordinate the water resource imbalance among various areas, the concept of virtual water is proposed (Allan, 1993). The water resources contained in agricultural products, industrial products, and related services can be transferred and configured among regions through virtual water trade. This approach provides a new perspective for the global water balance and for alleviating the regional water shortage (El-Sadek, 2010; Schwarz *et al*., 2015; Mohieldeen, 2016). Water-intensive products are transferred from water-rich areas to water-scarce areas, guaranteeing the security of water resources for water-scarce areas. Virtual water strategy is an important part of the national security strategy (Zimmer & Renault, 2003; Nan *et al*., 2017), and it plays an important role in guiding national water resource management (Yang & Zehnder, 2007).

Terrestrial products and services have been the focus of virtual water research up to this point (Dalin *et al*., 2012; Hassan, 2015; Zhang *et al*., 2018). There have been few studies in this field on the ocean, which accounts for 71% of the world's surface area. Land-equivalent products and services, such as food, wastewater purification, and power generation, can be provided by oceanic biological, chemical, and power resources without consuming terrestrial water resources (Mora *et al*., 2009; Zhang *et al*., 2012; Ye & Lan, 2014). In contrast, land products that are equivalent to marine products require a lot of water for their production. In recent years, China's marine fishery production has been about 3 million tons per year, making it one of the countries with the largest amount of marine fishery in the world. Marine wind and tidal power are very significant. The number of offshore wind power installations in China has reached the third largest in the world. Tidal energy reserves are 190 million kW, which account for a tenth of the world's tidal energy (Huang *et al*., 2007). If the marine products or services are developed and utilized properly, significant replenishment to the terrestrial water resource system will occur with few or no side effects. Based on this information, it is necessary to calculate the marine equivalent water resources for land. This will broaden the scope of water resource management and help managers to formulate more comprehensive national and regional water policies.

Therefore, our paper is based on virtual water theory and proposes a new concept of 'marine equivalent virtual water'. Based on the virtual water calculation method, this paper puts forward the components of marine equivalent virtual water from three perspectives: food, environment, and energy. The marine equivalent virtual water content is calculated, and, by analyzing the evolving trend of the marine equivalent virtual water structure, pertinent suggestions for the development of China's coastal administrative areas are identified. This paper consists of four parts: Conceptual definition, Materials and methods, Results and discussion, and, finally, Conclusions. To the best of our knowledge, this study is the first to introduce the ocean into the virtual water study framework. The marine equivalent virtual water from the ocean has been a guarantee for the use of water in coastal areas. The results of the study are of great significance for relieving the pressure on and guiding the management of terrestrial water resources.

Conceptual definition

Theoretical bases

According to comparative advantage theory, regional differences in factor endowments are the prerequisites for the comparative advantages of resources in the region. The coastal climate and agricultural foundation are appropriate for this work. Water resources, however, are in short supply, because of economic and social development factors. Fortunately, the acquisition and use of marine products and services is easier in coastal areas. The endowment of marine resources has gradually become a comparative advantage. The regional comparative advantage is of great importance in guiding water resource management (Costinot, 2009).

Human activities, materials, and energy are flowing and shifting in the resource–environment–social system, according to resource flow theory. Resource flows focus on the process, reflecting dynamic changes in resources. Market mechanisms promote circulation between land and sea resources, and the transfer of resources among regions provides a solution to resource and environmental problems (Zhang & Zhao, 2016).

Resource substitution theory is one of the basic principles of a sustainable economy. Finding and using new resources effectively is inevitable in social development and environmental protection, and water resources are irreplaceable. Within a region, however, water resources can be substituted based on availability. For example, marine products and services can replace the water resources with the same functions on land. This is the process of resource substitution (Andre & Cerda, 2005).

Concepts

Based on the guidance of land–sea coordination (Cao & Gao, 2015), the idea that products and services exhibiting the same function between the sea and land can be converted equivalently, and the traditional definition of virtual water, we define marine equivalent virtual water as the following: in the process of marine resource utilization, marine equivalent virtual water is the freshwater resources embedded in marine products or services that are equivalent to the corresponding land-based products or services. This concept involves food, environment, and energy.

With respect to food, blue agriculture has been a material guarantee of coastal areas for a long time. Marine fishery resources are as important as terrestrial crops for the energy supply (Cai, 2012). 'Marine food equivalent virtual water' is proposed in terms of the food the ocean provides for the land.

Energy is a fundamental property of food (Zhang, 2000). In terms of nutrition, this refers to the total amount of energy produced by the metabolism of nutrients, including protein, fat, and carbohydrates (generally denoted as kilocalories, or KJ) (Guo *et al.*, 2005). Although different foods have different nutritional components and require different metabolic mechanisms in the body, in this study, we consider it feasible to conduct a preliminary investigation from the perspective of total energy. From a nutritional perspective, the United Nation's Food and Agriculture Organization (FAO) states that different crop types can be converted to equivalent levels of food energy at a certain level of production. From a physical perspective, the law of physics that states that energy can change forms but may never be produced or destroyed is a theoretical foundation for this study.

Human life is dependent on the energy supply from various crops, especially grains, but abundant energy is also found in marine fishery resources. As different energy sources are essentially consistent, energy-equivalent conversions can be made between the marine fishery resources and crops, creating the equivalent of further grain production by utilizing marine fishery resources. Growing the corresponding grain on land consumes a vast amount of water, so the utilization of marine fishery resources is equivalent to supplementing the virtual freshwater resources needed for grain production. Therefore, the study defines marine food equivalent virtual water as freshwater resources embedded in marine fishery resources that are equivalent to the grain-growing need.

With respect to the environment, the ocean has a self-purification function, and the dilution, absorption, settlement, and transformation of pollutants can be promoted (Ye & Lan, 2014). The ocean can have the same effect as freshwater resources for effluent treatment. This paper introduces 'marine environment equivalent virtual water' from the perspective that the ocean purifies terrigenous wastewater.

Pollutants discharged into the natural environment need dilution to meet environmental water quality standards; this is known as the gray water footprint (Hoekstra *et al*., 2011). If terrestrial wastewater is completely disposed of into terrestrial water bodies according to such standards, abundant freshwater resources will be required. In coastal areas, however, some of this wastewater can be discharged into the sea, where the ocean's self-purification function can help dilute or clean it. In other words, the utilization of marine water resources for this purpose replaces the equivalently large amount of freshwater resources needed for wastewater purification. Therefore, this paper defines the marine environment equivalent virtual water as freshwater resources embedded in seawater that are equivalent to the need for wastewater purification.

Finally, with respect to energy, the marine wind power, tidal power generation, nuclear power, and other new marine resource energy sources can provide the same support for land activities as terrestrial electricity generation (Zhang *et al*., 2012). The 'marine energy equivalent virtual water' is proposed with respect to the ocean supplying electricity to the land.

Wind energy and tidal power can be generated in marine areas; these forms of clean energy can be converted into electricity to support terrestrial activities. Less water is consumed in these processes than in the equivalent terrestrial power generation methods. In addition, existing Chinese domestic nuclear power plants are located in coastal areas, and most use seawater for cooling (Li, 2015). However, coal is still the foundation of the power supply in China, consuming copious amounts of freshwater in the processes of mining it and generating power. In this context, the utilization of marine water resources for energy generation can supplement freshwater resources by the amount otherwise required for coal-fired or other terrestrial power sources. Therefore, this study defines marine energy equivalent virtual water as freshwater resources embedded in marine energy generation that are equivalent to the need for coal-fired power resources.

Attributes

Integrity. With the tight interdependence, both marine equivalent virtual water and terrestrial water serve the production and lifestyle. They are complementary, forming a unified organic entirety.

Economy and liquidity. Water is an economic resource whose value is evident by its necessity. Marine equivalent virtual water is, essentially, a water resource, and its liquidity occurs in the acquisition and circulation, which flows from the ocean to the land and then from rich areas of marine food equivalent virtual water to scarce areas as the development of fishery trade. The liquidity of the marine energy equivalent virtual water occurs during electrical acquisition and transmission.

Regionalism. The different species and endowments of marine fishery resources as well as grain crops in terms of various coastal areas means the distribution of marine food equivalent virtual water is uneven. Since the self-purification ability of the ocean is affected by the extent of the ocean, the liquidity of water and so on, the limit of marine equivalent virtual water is uneven from a regional perspective. As the location of marine power generation is strict and the power capacity is influenced by natural factors, the distribution of marine energy equivalent virtual water is also regionally uneven.

Renewability and finiteness. Marine equivalent virtual water is renewable because of the reproducibility of marine fishery resources, the restoration of marine self-purification, and the renewability of marine energy. However, this reproducibility could be achieved without damaging the current environment. A sustainable supply of marine equivalent virtual water is guaranteed, unless massive fishing, mariculture, and wastewater pollution exploit the marine energy.

Materials and methods

Study area

The study area includes eight provinces, two municipalities, and one autonomous region in China's coastal areas, excluding Hong Kong, Macao, and Taiwan (Figure 1). The sea and land environment in these areas is very advantageous for human resource development, forming an obvious intersection

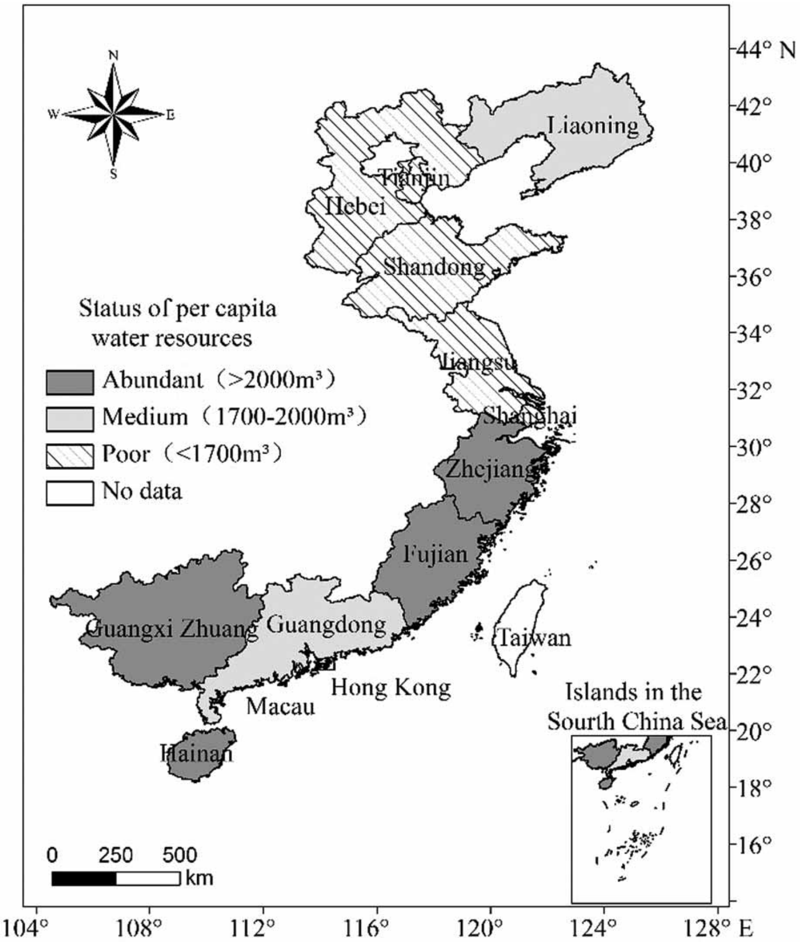

Fig. 1. Chinese coastal regions and their per capita water resources.

between land and sea. The climate difference from north to south is significant, and, thus, the water demand of grain crops increases gradually from north to south. This region is affected by seasonal monsoons, as it faces the largest ocean in the world, and contains abundant resources such as marine wind and tidal energy. The total land area covers about 1.3 million km^2, with a mainland coastline stretching about 18,000 km along a sea area of about 3 million km^2. The physical environmental characteristics of these sea areas are significantly different (FAO, 2009). There are about 3,300 marine biological species with the highest fishing value within the more than 70 fisheries under China's jurisdiction (Zhang, 2015).

The abundant resources within the study area nurture a large population, and the convenient location has promoted rapid economic development. However, economic development and urbanization also drive increasing economic and population density, heightening threats to the quality and quantity of terrestrial water resources. Figure 1 reflects the uneven distribution of per capita water resources in Chinese coastal areas; there are six regions below the world water shortage warning line of 1,700 m^3 (Falkenmark & Widstrand, 1992). Although the concentration of marine pollutants can be decreased or even eliminated through marine physical, chemical, and biological processes, the self-purification capacity of the ocean is limited. Marine pollution has occurred in offshore areas in varying degrees and, on average, mild eutrophication has occurred within the entire coastal area. The utilization of new marine energy resources such as wind and tidal energy is also lacking in planning (Liu *et al.*, 2015). Reasonable utilization of marine resources is the premise of the marine equivalent virtual water concept and is an important approach for addressing the problems of water resources in coastal areas.

Data sources and description

The data for the marine fishery resource production were derived from the China Fishery Statistics Yearbook (Fisheries Administration Bureau of the Ministry of Agriculture, 2001–2016); the grain crop data were collected from the Chinese Rural Statistical Yearbook (National Bureau of Statistics of the People's Republic of China, 2002–2016); the values for the various biological species were derived from China Food Composition, and so on (Yang *et al.*, 2009); data on the pollution discharged directly into the sea were obtained from the Bulletin of the Environmental Quality of China's Coastal Waters (Ministry of Environmental Protection of the People's Republic of China, 2006–2015); and data related to power generation came from the China Marine Statistics Yearbook, the China Electric Power Yearbook, and related literature (Lin, 1999; Lv, 2001; China Electric Power Development Association, 2007–2015; State Oceanic Administration People's Republic of China, 2007–2016; Tang *et al.*, 2017).

Marine food equivalent virtual water

Energy supply of marine fishery resources. Marine fishery resources are provided in three main ways: marine capture (near-shore) fishing, mariculture, and pelagic (deep-sea) fishing. There are six main categories of marine capture species (fish, crustaceans, shellfish, algae, cephalopods, and other classes) and five main categories of mariculture (fish, crustaceans, shellfish, algae, and other classes); many different species are included in each category. Pelagic fisheries do not list specific species. Pelagic fishing occurs in the international high seas zone but is included in this study because the harvest is owned by the coastal areas. In addition to the open ocean, marine capture fishery resources in China are derived from the Bohai, Yellow, East China, and South China Seas. According to the China Fishery Statistics Yearbook, the main areas of fishing activity in Liaoning, Hebei, Tianjin, and Shandong are located in both the Bohai and Yellow Seas. The main areas of fishing activity in Jiangsu and Zhejiang are located in both the Yellow and East China Seas. The main area of fishing activities in Shanghai is located in the East China Sea. The main areas of fishing activities in Fujian are located in the East China and South China Seas. The main areas of fishing activities in Guangdong, Guangxi, and Hainan are located in the South China Sea.

In order to ensure the accuracy of calculations, the main fish species in each area need to be determined for several reasons. First, marine capture fishery resources have regional characteristics; while nearby fishing areas may have similar species, distant areas may be quite different. Second, southern areas are more species-rich than northern areas and yields vary significantly. Third, the energy values for each source category (marine capture, mariculture, or pelagic) are different. Based on data from the China Fishery Statistics Yearbook from 2001 to 2015, we screened the marine fishery species according to high yield, high yield ratio, and high yield stability. The unit energy of the different categories was then estimated by the selected species, using the method below, with results shown in Table 1.

For j region, the total energy of marine fishery resources is obtained through marine capture fishing, mariculture, and pelagic fishing as follows:

$$ME = \sum_{i=1}^{n} MY_{ji} \times MCE_{ji} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{n}(\mathrm{n} = 14) \tag{1}$$

where MY_{ji} and MCE_{ji} denote the yield of marine fishery categories and the unit mass energy value of that category for region j type i, respectively.

Table 1. Units of energy of different categories of marine fisheries in coastal areas of China (unit: kJ/100 g).

Method	#	Categories	Tian jin	He bei	Liao ning	Shang hai	Jiang su	Zhe jiang	Fu jian	Shan dong	Guang dong	Guang xi	Hai nan
Marine capture fishing	1	Fish	632	553	519	490	527	515	515	544	519	502	506
	2	Shrimp	339	360	360	389	373	373	373	373	373	373	385
	3	Crab	398	398	368	398	398	398	398	398	368	368	368
	4	Shellfish	255	268	255	293	293	293	293	255	293	326	306
	5	Algae (dry)	–	–	607	–	712	749	837	607	837	837	992
	6	Head-foot	314	410	410	410	410	410	410	410	410	410	410
	7	Others	222	222	222	222	222	222	222	222	222	222	222
Mariculture	8	Fish	414	414	414	423	452	423	414	427	427	435	419
	9	Shrimp	389	377	373	389	373	389	389	389	410	389	389
	10	Crab	398	398	398	–	398	368	368	398	335	335	335
	11	Shellfish	–	268	255	–	293	293	293	255	293	326	306
	12	Algae (dry)	–	–	607	–	712	749	837	607	837	–	992
	13	Others	–	276	352	–	222	276	352	352	251	113	–
Pelagic fishing	14	Pelagic fishing	573	314	573	573	314	573	573	573	829	829	829

Notes: '–' represents no data, because Hainan Province contains the inedible seawater pearl, and other districts have no yield in this type; algae do not contain the energy of the wet state and are therefore replaced by the energy of the dry state; crustaceans including shrimp and crabs. Because of differences in the energy and yield in the same region, these are counted separately.

Calculation of grain crops virtual water. Rice, wheat, and corn are the most important grain crops in China's coastal areas. From 2001 to 2015, these three accounted for 45–80% of the total crop yield in each coastal provincial administrative area. Therefore, we selected the most productive grain in each area as the basis for calculating marine fishery resources energy conversion: rice in Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan, wheat in Tianjin, Hebei, and Shandong, and corn in Liaoning.

The virtual water content of a selected grain was calculated as follows (Zimmer & Renault, 2003):

$$GVW = GW/GY \tag{2}$$

where GVW, GW, and GY denote the unit mass virtual water of selected grain, the crop water requirement per area, and crop yield per area, respectively.

Calculation of marine food equivalent virtual water. The total energy contained in the marine fishery should be converted to that of the equivalent marine virtual grain yield, considering the virtual water content of the selected grain. For the same region, the type of marine virtual grain crop is the selected grain crop. We calculated the marine food equivalent virtual water (MFW) as follows:

$$MVG = ME/GE \tag{3}$$

$$MFW = MVG \times GVW \tag{4}$$

where MVG and GE denote the yield of marine virtual grain and the energy value of the selected grain, respectively. If the marine capture fishing energy, mariculture energy, and pelagic fishing energy are substituted into ME in Equation (3), the virtual water for all three categories can be obtained.

Marine environment equivalent virtual water

According to the Bulletin of the Environmental Quality of China's Coastal Waters, pollution discharged directly into the sea comes from industrial pollution sources, residential pollution sources, and other comprehensive pollution sources; these are considered point source pollution. The main pollution standards in China consider the levels of chemical oxygen demand and ammonia nitrogen. Based on The Water Footprint Assessment Manual and calculation methods for the gray water footprint (Hoekstra *et al.*, 2011), we calculated the marine environment equivalent virtual water (MEW) as follows:

$$MEV_i = L_i/C_{max} - C_{nat} \tag{5}$$

$$MEW = max\ (MEV_{COD},\ MEV_{NH_4^+-N}) \tag{6}$$

where L_i is the pollutant load discharged directly to the sea as class i pollutants, C_{nat} is the background concentration of pollutants in the natural state of the terrestrial water (assumed to be 0), and C_{max} is the maximum allowable concentration of pollutants in terrestrial water. The first Chinese discharge standard was adopted in the Integrated Waste Water Discharge Standard (GB8978-1996), in which the standard concentrations for chemical oxygen demand (COD) and NH_4^+-N are 60 mg/L and 15 mg/L, respectively. *MEW* is marine environment equivalent virtual water.

Marine energy equivalent virtual water

Wind and tidal energy are the most modern methods for generating electricity from marine resources. Coal power mainly consumes water through cooling and coal washing; there are great differences in the cooling modes and water consumption levels between the southern and northern regions of China. The main cooling mode is circulation cooling in regions north of the Yangtze River, including Liaoning, Hebei, Tianjin, Shandong, and Jiangsu; the water consumption per unit power is 1.9 m^3/MWh. The main cooling mode is direct cooling in regions south of the Yangtze River, including Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan; the water consumption per unit power is 1.2 m^3/MWh. The average water consumption quotas of coal mining and coal washing are 0.47 m^3/t and 0.27 m^3/t, respectively. Chinese nuclear power plants mainly use seawater for cooling, consuming 0.1 m^3/MWh (Zhong *et al.*, 2014; Xiang & Jia, 2016; Hong *et al.*, 2017). Thus, the marine energy equivalent virtual water (*MPW)* can be calculated as follows:

$$MWW = MWE \times (FPC + PSC \times CUW) \tag{7}$$

$$MTW = MTE \times (FPC + PSC \times CUW) \tag{8}$$

$$NW = NP \times NPC \tag{9}$$

$$MPW = MWW + MTW + NW \tag{10}$$

where *MWW* is marine wind energy equivalent virtual water, *MWE* is energy generated by marine wind resources, *FPC* is the water consumption per unit coal power, *PSC* is the standard coal consumption of power generation, *CUW* is the average water consumption quota of coal mining and washing, *MTW* is tidal energy equivalent virtual water, *MTE* is energy generated by tidal resources, *NW* is nuclear power equivalent virtual water, *NP* is energy generated by nuclear power, and *NPC* is the water consumption per unit nuclear power.

Marine equivalent virtual water

The sum of the marine food equivalent virtual water, marine environment equivalent virtual water, and marine energy equivalent virtual water is the marine equivalent virtual water, which is calculated as follows:

$$MVW = MFW + MEW + MPW \tag{11}$$

Gray metabolic GM (1,1) model

Gray system theory can be used to make predictions in information-poor systems with small samples, producing more effective results (Deng, 1982). Generally, the conventional GM (1,1) model is most widely used; this has good prediction accuracy for recent data, less accuracy for medium and long-term forecasts. We used the gray metabolic GM (1,1) model to improve prediction accuracy by changing the data and including disturbance factors over time with regards to developing system forecasts. In this process, a gray prediction is made to get the nearest information $x(0)(n+1)$ and remove the oldest information $x(0)(1)$ in the original data sequence. The metabolic GM (1,1) model calculates this as $x(0) = \{x(0)(2), x(0)(3), \ldots, x(0)(n), x(0)(n+1)\}$. Further details on this common and widespread methodology can be found in many other studies (Wang *et al.*, 2004; Huang *et al.*, 2012).

Information entropy

Information entropy is developed from thermodynamic theory and is an important measure of the degree of system evolution (Huang & Chen, 2014). It has been applied to various fields including the measurement of system structure. We used information entropy to measure the structural evolution trend of marine equivalent virtual water systems. The greater the entropy of a system, the more balanced the development of different factors in the marine equivalent virtual water system. The smaller the entropy, the more dominant a single factor in the system. This was calculated as follows:

$$P_i = W_i / W \tag{12}$$

$$H = -\sum_{i}^{n} P_i ln P_i \quad i = 1, 2, \ \ldots, n(n = 5) \tag{13}$$

where W_i is the marine equivalent virtual water content of type *i*, W is the total amount of marine equivalent virtual water, P_i is the proportion of type i in the amount of marine equivalent virtual water, and H is the information entropy.

Results and discussion

Marine equivalent virtual water content in China

China's *MFW* was calculated from 2001 to 2015 based on the formulas above. Due to fewer statistics on the direct sea-discharged pollutants before 2006 and the limitations of the latest marine statistics, results could only be calculated for *MEW* and *MPW* from 2006 to 2015. The *MVW* from 2006 to 2015 can then be obtained (Tables 2–5).

Analysis of China's current marine equivalent virtual water situation

The evolution of China's *MVW* content during the study period is shown in Figure 2. For further analysis, we focused on the total amount of *MFW* in China showing an upward trend, rising from 9.2×10^9 m^3 in 2001 to 12.4×10^9 m^3 in 2015. This began with slowly rising fluctuations before increasing more rapidly after 2008. Thus, the capacity of the *MFW* to supplement terrestrial water resources is accelerating, with the fastest growth occurring in mariculture. We are therefore optimistic regarding the continued development of *MVW* and expect the total amount to continue improving gradually in the future.

Table 2. China's marine food equivalent virtual water from 2001 to 2015 (unit:$10^8 m^3$).

Regions	2001	2003	2005	2007	2009	2011	2013	2015
Tianjin	0.35	0.42	0.36	0.38	0.33	0.32	0.80	0.82
Hebei	3.99	3.68	4.00	3.74	3.82	3.52	4.01	4.78
Liaoning	17.88	15.58	17.06	17.56	22.35	18.78	19.61	24.80
Shanghai	0.33	0.48	0.59	0.63	0.59	0.45	0.46	0.63
Jiangsu	2.25	2.45	2.72	3.21	3.42	3.60	3.70	3.64
Zhejiang	13.82	13.43	14.07	12.64	12.58	14.47	16.20	17.91
Fujian	16.84	17.05	17.43	16.71	17.13	17.67	18.68	20.64
Shandong	12.09	14.93	13.98	14.63	15.06	15.90	15.81	17.47
Guangdong	13.82	14.10	15.37	15.88	16.29	16.60	18.12	17.77
Guangxi	6.24	6.33	6.68	6.02	6.09	6.65	6.52	6.72
Hainan	4.40	5.93	8.13	6.55	7.03	7.70	8.00	8.90
Total	92.02	94.38	100.39	97.96	104.70	105.67	111.90	124.09

Note: Due to space limitations, only some of the years' calculation results are listed.

Table 3. China's marine environment equivalent virtual water from 2006 to 2015 (unit:$10^8 m^3$).

Regions	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Tianjin	2.27	6.63	0.16	0.41	0.34	0.50	0.33	1.00	2.00	1.67
Hebei	0.80	0.80	0.66	0.46	0.49	0.67	0.33	0.50	0.33	0.83
Liaoning	5.96	6.33	5.68	3.69	3.82	3.50	5.33	5.83	3.17	3.67
Shanghai	2.28	1.90	2.38	1.49	1.29	1.17	1.00	0.67	1.17	1.17
Jiangsu	1.32	0.66	0.65	1.34	0.48	0.33	0.33	0.33	0.33	0.33
Zhejiang	21.29	16.28	15.70	15.39	15.07	13.83	14.00	14.50	13.83	13.67
Fujian	8.22	10.40	4.45	6.20	3.42	5.50	5.67	4.67	4.33	4.33
Shandong	9.26	7.86	4.69	3.71	3.71	3.67	3.67	3.50	3.67	3.83
Guangdong	11.95	9.54	10.86	8.02	5.51	3.33	2.83	2.67	2.67	1.83
Guangxi	14.44	5.87	4.02	2.78	0.76	1.17	1.50	1.50	2.00	2.17
Hainan	3.28	2.88	2.89	1.93	1.69	1.33	1.33	1.67	1.67	1.50
Total	81.08	69.14	52.14	45.43	36.56	35.00	36.33	36.83	35.17	35.00

Table 4. China's marine energy equivalent virtual water from 2006 to 2015 (unit:$10^8 m^3$).

Regions	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Tianjin	–	–	–	–	–	0.05	0.05	0.06	0.06	0.07
Hebei	–	–	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Liaoning	0.02	0.03	0.06	0.09	0.15	0.21	0.27	0.38	0.47	0.72
Shanghai	0.00	0.00	0.01	0.03	0.04	0.06	0.07	0.07	0.07	0.08
Jiangsu	0.03	0.15	0.22	0.34	0.44	0.52	0.59	0.66	0.74	0.96
Zhejiang	1.65	1.65	1.69	1.70	1.72	1.76	1.84	1.86	1.89	1.93
Fujian	0.02	0.04	0.05	0.11	0.15	0.19	0.24	0.36	0.47	0.67
Shandong	0.25	0.29	0.33	0.46	0.53	0.82	1.00	1.17	1.34	1.78
Guangdong	0.35	0.36	0.38	0.43	0.51	0.67	0.76	0.81	0.96	1.12
Guangxi	–	–	–	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Hainan	0.00	0.00	0.01	0.04	0.04	0.05	0.06	0.06	0.06	0.07
Total	2.33	2.53	2.78	3.23	3.58	4.37	4.90	5.47	6.11	7.44

Notes: '–' represents no data; Guangxi is kept to four decimal places because of its small value.

Table 5. China's marine equivalent virtual water from 2006 to 2015 (unit: $10^8 m^3$).

Regions	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	The proportion of MVW in WC (%)
Tianjin	2.65	7.01	0.48	0.74	0.66	0.86	0.76	1.86	2.89	2.52	8.71
Hebei	4.78	4.54	4.49	4.32	4.48	4.22	4.24	4.55	4.84	5.66	2.36
Liaoning	24.25	23.92	22.44	26.13	25.24	22.49	25.61	25.83	32.46	29.19	18.08
Shanghai	3.02	2.54	3.07	2.11	1.79	1.68	1.55	1.19	1.87	1.87	1.75
Jiangsu	4.09	4.02	4.25	5.11	4.47	4.46	4.62	4.70	4.79	4.93	0.81
Zhejiang	35.64	30.57	29.47	29.68	30.55	30.06	30.88	32.56	32.56	33.51	15.69
Fujian	25.16	27.16	21.18	23.44	21.29	23.36	24.09	23.70	24.37	25.63	11.93
Shandong	22.88	22.78	19.90	19.23	19.81	20.39	20.44	20.48	22.16	23.08	9.60
Guangdong	27.99	25.78	27.94	24.74	22.71	20.60	20.38	21.60	21.13	20.73	5.12
Guangxi	21.06	11.89	10.14	8.88	7.03	7.82	7.94	8.02	8.52	8.88	3.27
Hainan	10.54	9.43	9.65	9.00	9.53	9.08	9.18	9.72	10.09	10.48	21.36
Total	182.05	169.63	153.02	153.37	147.54	145.03	149.69	154.20	165.68	166.53	6.25

Notes: WC denotes water consumption; the total amounts of marine equivalent virtual water and consumption were drawn from 2006 to 2015 data.

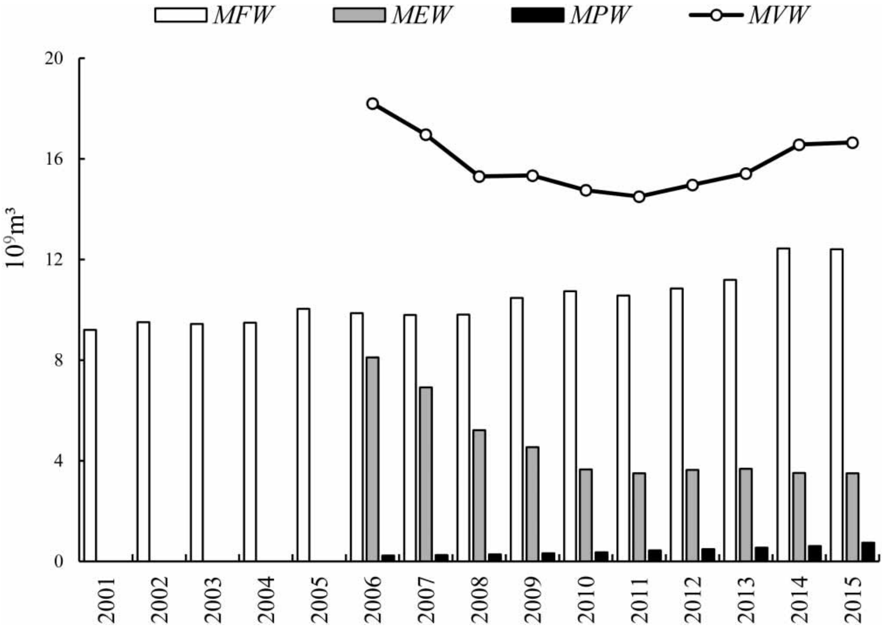

Fig. 2. Development of China's marine equivalent virtual water and its constituents over time.

The total amount of *MEW* in China was reduced from 8.1×10^9 m^3 in 2006 to 3.5×10^9 m^3 in 2015, rapidly decreasing at first before gradually stabilizing after 2011. Building a resource-economical and environmentally friendly society necessitates the oversight of high-pollution industries and the optimization of industrial structures to realize control of the total amount of *MEW*. The acquisition of *MEW* is at the expense of the marine environment, whose reduction and low-level stability are contributing to the protection of the marine environment.

The total amount of *MPW* in China is rapidly increasing, rising from 2.3×10^8 m^3 in 2006 to 7.4×10^8 m^3 in 2015. The *MWW* grew from 1.3×10^7 m^3 to 3.8×10^8 m^3 in that same period, making it the fastest growing and most important component of the *MPW*. Due to the promotion and use of clean energy, virtual water's contribution will be improved continuously, which will be of great significance to future energy, resources, and environmental concerns.

The amount of *MVW* has followed a U-shaped curve over time. Variations in *MEW* resulted in a total decline of *MVW* from 1.8×10^{10} m^3 in 2006 to 1.5×10^{19} m^3 in 2011. Both *MFW* and *MPW* steadily increased from 2006 to 2015, eventually leading to a rise in the total *MVW* from 2012 onwards; the amount of *MVW* in 2015 was 1.7×10^{10} m^3. The growth of *MVW* is promising, and the total amount of *MVW* will likely continue to increase gradually in the future.

Structural evolution classification of China's marine equivalent virtual water system

We input these results into a Data Processing System software package to predict China's marine equivalent virtual water system by 2025. The analysis included five factors, including three from the marine food equivalent virtual water: marine capture fishing equivalent virtual water (*MCW*), mariculture equivalent virtual water (*MUW*), pelagic fishing equivalent virtual water (*PFW*), marine environment equivalent virtual water (*MEW*), and marine energy equivalent virtual water (*MPW*). Next, we calculated the entropy of the system. Representative nodes of the interval 2006–2025 were selected to characterize the evolution of the system, as shown in Figure 3, where H represents the entropy value of the *MVW* system in 2006 (H_1), 2010 (H_2), 2015 (H_3), 2020 (H_4), and 2025 (H_5), as expressed by the secondary axis.

The marine resources endowment, marine economic development capacity, marine science and technology level, and marine environmental consciousness are different in different regions. The structural analysis of *MVW* can help us to clarify the differences in the systems in the future. Based on these different characteristics, guidance for water resource management can be developed.

The system entropy value in all of China's coastal areas rises from 1.2 to 1.4 over this period. The different factors of *MVW* tend to be balanced, but the structure changes significantly over time. The proportion of *MUW*, *MPW*, and *PFW* increases year by year, with the first two being the main driving forces for the growth of *MVW*. Changes in the total amount of *MCW* are small, and its importance decreases the most over time. The range of decline for the *MEW* is large, from 45% in 2006 to 9% in 2025, as China's governance capacity for marine pollution is further enhanced.

After predicting the contents of the five factors for *MVW* in China's 11 coastal administrative areas and calculating the entropy of the system through 2025, we divided the study area into three types according to the structural evolution law of the systems.

Type one is equilibrium development, including Shandong, Fujian, Zhejiang, Liaoning, and Shanghai provinces. Many of these are provinces with rich marine resources or well-developed marine economies. In this type, the entropy value of *MVW* systems increases gradually, and the structure of the *MVW* presents a balanced development trend. In general, the *MVW* systems develop well, and the improvement in marine technology is key.

The maximum entropy value of the *MVW* system in Shandong and Fujian exceeded 1.4, and the system structure gradually presented an advanced equilibrium state. The marine resources are favorable. The proportion of *MCW* and *MUW* remains high, as these are relatively stable parts of the *MVW* structure. Shandong has strong scientific and technological strength, and Fujian's natural

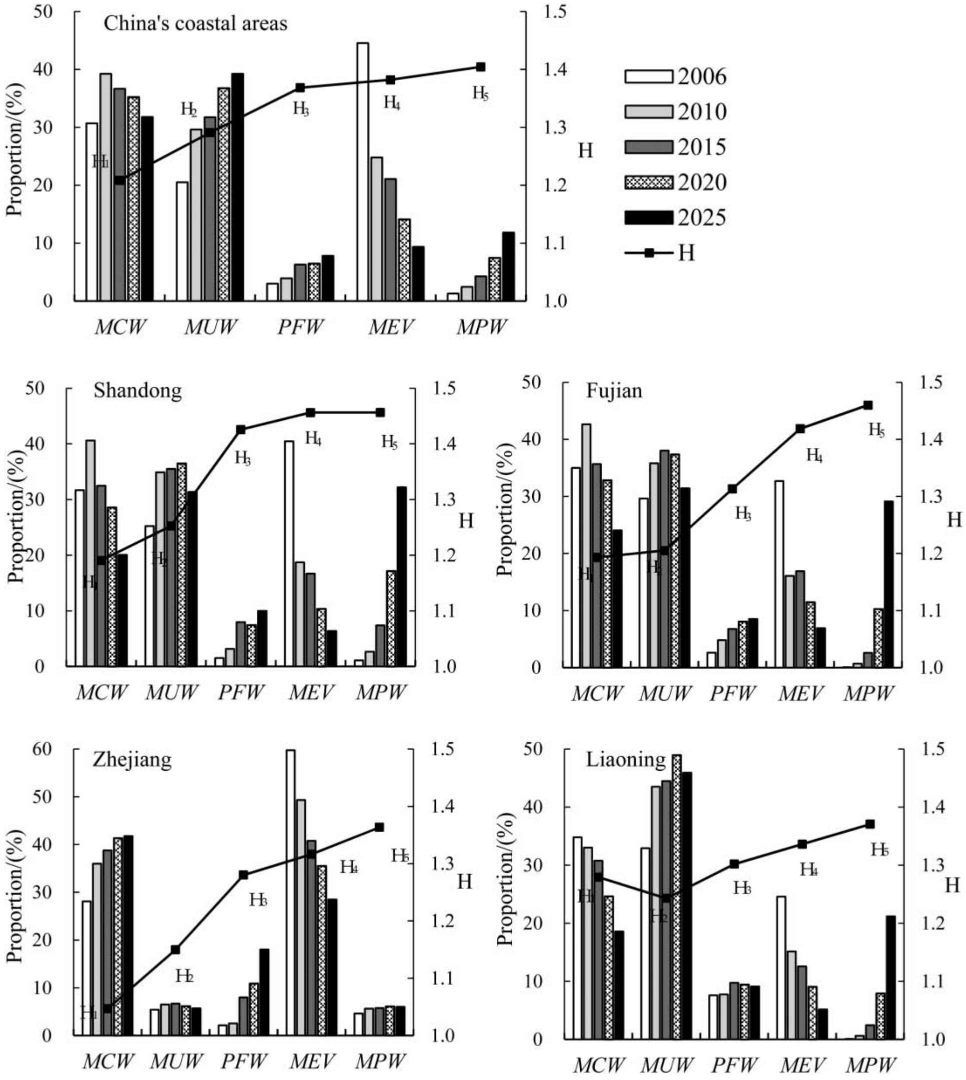

Fig. 3. Structural evolution trend of marine equivalent virtual water systems in the study areas. (*Continued.*)

conditions are superior, promoting the growth rate of *MPW* in both provinces. We estimate that the *MPW* will be as important as the *MUW* by 2025. *MEW* will be better controlled by that time; this is particularly important in Fujian, an ecologically sensitive area that is vulnerable to marine disasters. The further development of *MEW* will be conducive to the protection of terrestrial and marine security. To achieve these goals, the two provinces should encourage advanced awareness of the environment and technology, improve the conversion rate of scientific research achievements, and strengthen the development of marine wind power and nuclear power. The development of deep-water technical equipment needs to be enhanced, and deep-water aquaculture and the construction of marine ranching need to be promoted. Marine environmental governance should be strengthened to ensure ecological security.

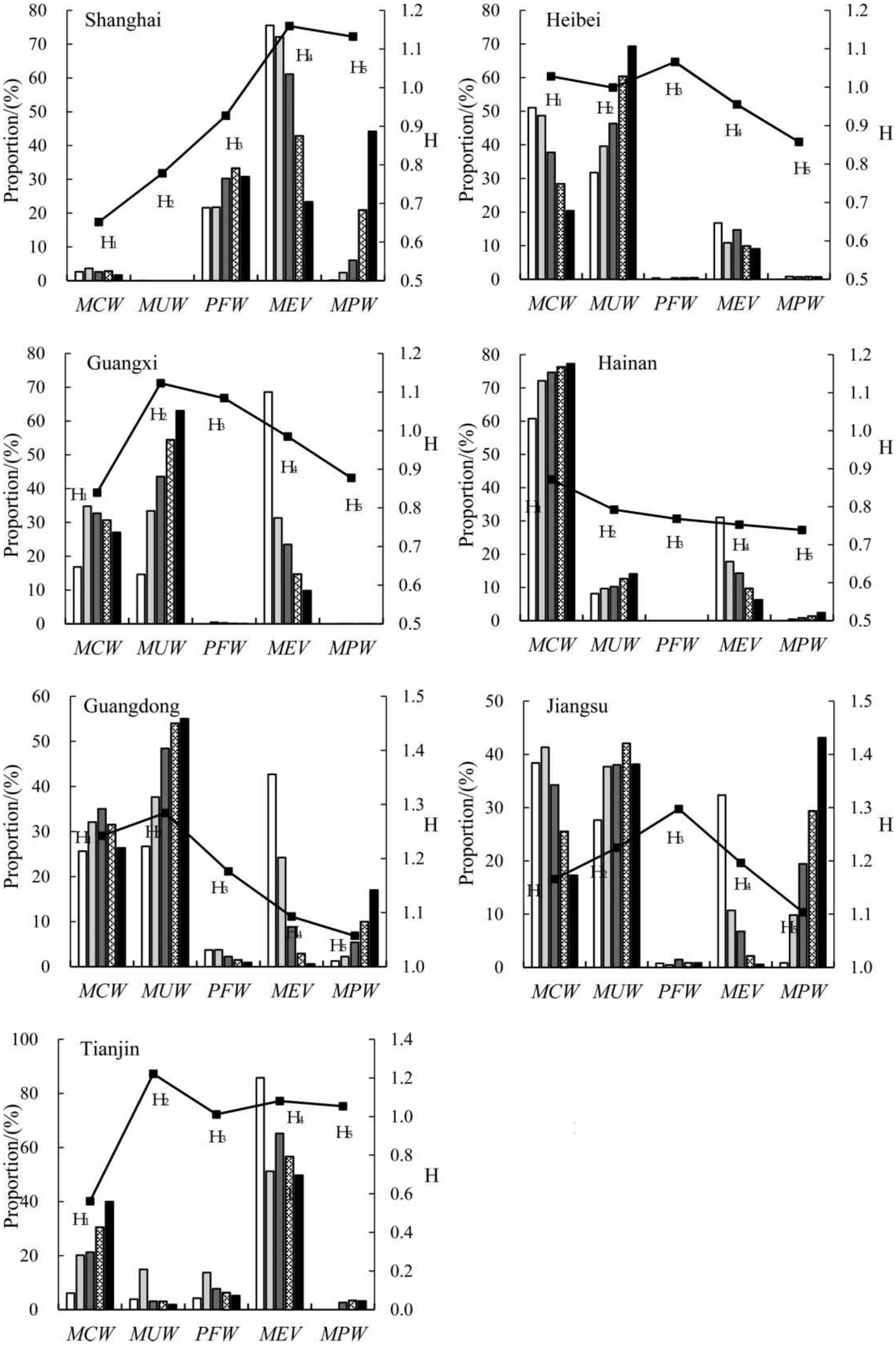

Fig. 3. Continued.

The maximum entropy value of the *MVW* system in Zhejiang and Liaoning was between 1.3 and 1.4, and the system structure gradually presented an intermediate equilibrium state. The proportion of Zhejiang's *MEW* and *MCW* was significantly higher than the proportions of the other three factors, but the gap will gradually narrow. Structural changes in Liaoning's *MVW* system were relatively small. The dominance of *MUW* will remain strong, *MPW* will experience further growth, and *MEW* will be better controlled. Zhejiang should focus on the construction of pollution prevention and control systems, the transfer of some low-end industries, and the reduction of the proportion of *MEW*. The potential of various new energy sources in the ocean is exploited in areas with superior natural environments. The intensity of marine fishing needs to be controlled, the capability of the stereoscopic observation of seawater should be improved, and the mariculture must be developed. Liaoning should improve terrestrial crop planting technology and reduce the supply pressure on *MVW*. The development capabilities of marine wind power and nuclear power technology should be enhanced. The Liaodong Bay area is relatively enclosed, and pollutants are hard to dissipate. Thus, it is necessary to adjust the industrial structure, reduce the proportion of traditional marine polluting industries, and protect the environment of sensitive areas.

The maximum entropy value of the *MVW* system in Shanghai was lower than 1.2, and the system structure gradually presented a low equilibrium state. Under the influence of natural and social conditions, the *MCW* and *MUW* will approach zero, while the pelagic fisheries virtual water and *MPW* will develop rapidly. Meanwhile, better control of the *MEW* will improve the system's equilibrium. Shanghai should actively develop the pelagic fishery, build overseas bases, and expand its share of fishery resources on the high seas. Shanghai's advantage is technology talent, which should be invested in marine wind power construction.

The second type is orderly development, which includes Hebei, Guangxi, Hainan, and Guangdong provinces. Excluding Guangdong, these are areas with relatively weak marine economies. Due to limited marine resources and, thus, the limited ability to develop a marine economy, it is difficult to develop comprehensively. In this type, the entropy value of *MVW* systems mainly decreases gradually. The degree of order of the *MVW* systems increases, with some projects showing trends of concentrated development.

The minimum entropy value of the *MVW* system in Hebei, Guangxi, and Hainan was lower than 1, and the system structure gradually presented an advanced order state. The proportion of *MUW* in Hebei and Guangxi increased over time, and the other factors declined or had not yet developed; these trends are closely related to the marine natural environment and marine development ability. Although the sea area of Hainan is vast, the current fishery resources are drying up. Hebei and Guangxi should improve their utilization rate of the tidal flats. Hainan should actively manage the crisis brought on by the overfishing ecosystem in the northern portion of the South China Sea. The fishery resources should be conserved through proliferation and release. At the same time, Hainan should strengthen the modernization of marine fishing, expand the fishing range of marine fisheries, and vigorously develop offshore farming. To tackle the development deficiency of *MVW*, all three provinces should attach importance to the development of regional soft power. They should actively promote ideological and cultural construction, strengthen regional communication, improve the environment of education and employment, and improve the quantity and quality of talents.

The entropy value of the *MVW* system in Guangdong showed a declining trend but remained higher than 1. The system structure gradually presented a low order state. The coastline of Guangdong is the longest in the country, with wide tidal flats, resulting in a superior natural environment for mariculture.

In addition, enhanced scientific research will promote the prominent development of *MUW*. The development of pelagic fisheries is limited because of weak fishery infrastructure and outdated equipment. In the future, Guangdong should narrow the cultural gap between urban and rural areas, in order to raise the level of the fishermen's culture. Investment in fishery infrastructure should be increased to promote deep-water and intensive aquaculture. The marine ecological red line system should be strictly implemented, and the waste water should be controlled. This will promote the transformation of scientific and technological achievements and implement the development of wind power and nuclear power.

The third type is change development, including Jiangsu and Tianjin provinces. In this type, the evolution of *MVW* systems is more complicated, with an entropy value trend that first increases then decreases. In Jiangsu, the entropy value of the system first increases and then decreases, presenting symmetry characteristics during the study period. There is an obvious change in dominant type in the *MVW* system as this converts from the *MCW* and *MEW* to *MUW* and *MPW*. In comparison, the total variation in the *MVW* systems in Tianjin is not significant, mainly focusing on *MEW*, and the entropy value increases first before fluctuating slightly. Jiangsu should improve the fishery management system, make full use of the sea area and tidal flats, enhance the scientific and technological innovation of the marine breeding industry, and improve the *MUW* steadily. New energy is developing quickly; it is important to encourage and ensure its development and use. Tianjin needs to learn from Shanghai and actively expand its share of marine capture and pelagic fishery resources. In order to reduce negative impacts on the marine environment, it is very important to strengthen the control of marine pollution.

Conclusions

Drawing on virtual water theory, this paper considered the ocean in its research framework and introduced the concept of marine equivalent virtual water. Using China's coastal areas, this study explores the replenishment capability of marine products or services for terrestrial freshwater resources in the process of marine development and utilization. This concept is put forward to emphasize the important role of the ocean in the field of water resource management, broadening the scope of the field and providing background for the formulation of more comprehensive national and regional water resource development proposals and policies.

Using the guidance of land–sea coordination and the idea that products and services with the same functions between the sea and land can be converted equivalently, three calculation formulas for marine equivalent virtual water were proposed: food, environment, and power generation. By using official data in our calculations, our results showed that the amount of marine equivalent virtual water in China from 2006 to 2015 followed a U-shaped pattern over time, from 1.8×10^{10} m^3 in 2006 to 1.5×10^{19} m^3 in 2011 to 1.7×10^{10} m^3 in 2015. The structural ratio between marine food equivalent virtual water, marine environment equivalent virtual water, and marine energy equivalent virtual water changed from 54:45:1 to 75:21:4 from 2006 to 2015. Among them, the marine food equivalent virtual water was highest. Therefore, it is essential to pay attention to the acquisition and circulation management of marine fishery resources. The development capacity of marine environment equivalent virtual water is limited, and it has great adverse effects on the marine environment. The gradual decline of its content is the result of the awareness and strengthening of marine environmental protection. The development of marine energy equivalent virtual water is related to the marine natural environment and technological capabilities.

The range of China's coastal areas is large, and the marine resources, economic conditions, and marine technology levels of various administrative areas are different. Through structural analysis prediction and system entropy change, China's marine equivalent virtual water structure was divided into three categories. Pertinent suggestions were made for the development of marine equivalent virtual water in different areas. We found that equilibrium development-type provinces in which entropy was increasing mainly had rich marine resources or well-developed marine economies. The development ability of each marine equivalent virtual water factor was relatively strong. The improvement of marine technical ability is the key to improving development ability. Orderly development-type provinces in which entropy was decreasing mainly had relatively weak marine economies and are difficult to develop comprehensively. There were significant transformations in the marine equivalent virtual water projects based on the change development type.

This paper focused on the virtual water of marine products or services and its equivalence to terrestrial resources. However, as physical water represented by seawater desalination can supplement oceanic and terrestrial water resources, a more comprehensive future study should consider a combination of the two. Meanwhile, our future research will explore the complementary strengths of marine equivalent virtual water and terrestrial water systems, including ways to determine a reasonable common configuration of marine and terrestrial water systems.

In summary, although the concept and implications of the marine equivalent virtual water approach presented here are imperfect, and the data were limited, this paper's preliminary research results should inspire more researchers to focus on this field and further improve the data and methodology.

References

Allan, J. A. (1993). *Fortunately There are Substitutes for Water – Otherwise our Hydropolitical Futures Would be Impossible*. Overseas Development Institute, London, UK.

Andre, F. J. & Cerda, E. (2005). On natural resource substitution. *Resources Policy 30*(4), 233–246.

Cai, L. (2012). *Study on Population Carrying Capacity of Marine Fishery Resources in new East China (2010–2020)*. China Social Sciences Press, Beijing, China.

Cao, Z. X. & Gao, G. L. (2015). The connotation of and policy recommendation for overall planning development of land and sea in China. *China Soft Science 2*, 1–12.

China Electric Power Development Association (2007–2015). *China Electric Power Yearbook*. China Electric Power Press, Beijing, China.

Costinot, A. (2009). An elementary theory of comparative advantage. *Econometrica 77*(4), 1165–1192.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A. & Rodriguez-Iturbe, I. (2012). Evolution of the global virtual water trade network. *Proceedings of the National Academy of Sciences U S A 109*(21), 5989–5994.

Deng, J. L. (1982). Control problems of grey systems. *Journal of Huazhong University of Science and Technology (Natural Science Edition) 3*, 9–18.

El-Sadek, A. (2010). Virtual water trade as a solution for water scarcity in Egypt. *Water Resources Management 24*(11), 2437–2448.

Falkenmark, M. & Widstrand, C. (1992). Population and water resources: a delicate balance. *Population Bulletin 47*(3), 1–36.

FAO (2009). *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge*. FAO Fisheries and Aquaculture Technical Paper. No. 530. Food and Agriculture Organization, Rome, Italy.

Fisheries Administration Bureau of the Ministry of Agriculture (2001–2016). *China Fisheries Statistics Yearbook*. China Agriculture Press, Beijing, China.

Ge, M., Wu, F. P. & You, M. (2017). Initial provincial water rights dynamic projection pursuit allocation based on the most stringent water resources management: a case study of Taihu Basin, China. *Water 9*(1), 13.

Guo, J., He, M. & Yang, Y. X. (2005). A statistical appraisal on food energy conversion systems: the impact of various energy conversion systems on the energy values of FCT or FCD. *Food Science 8*, 42–51.

Haddad, M. & Lindner, K. (2001). Sustainable water demand management versus developing new and additional water in Middle East. *Water Policy 3*(2), 143–163.

Hassan, R. (2015). Implications of water policy reforms for virtual water trade between South Africa and its trade partners: economy-wide approach. *Water Policy 17*(4), 1–16.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M. & Mekonnen, M. M. (2011). *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan, London, UK.

Hong, S. Y., Wang, H. R., Lai, W. L. & Zhu, Z. F. (2017). Spatial analysis and coordinated development decoupling analysis of energy-consumption water in China. *Journal of Natural Resources 5*, 800–813.

Huang, X. B. & Chen, Z. N. (2014). The retail business structure of the metro site based on the information entropy – a case study of the 15 subway site in Guangzhou. *Economic Geography 3*, 38–44.

Huang, L. M., Lu, Y. X. & Niu, W. Y. (2007). *The Overview of China's Sustainable Development*. Science Press, Beijing, China.

Huang, S. Q., Wang, W. M., Zeng, C., Hao, S. & Cao, X. J. (2012). Application of gray metabolic GM (1,1) in prediction of annual total yields of Chinese aquatic products. *Chinese Agricultural Science Bulletin 17*, 126–131.

Huang, Y., Lei, Y. L. & Wu, S. M. (2017). Virtual water embodied in the export from various provinces of China using multi-regional input-output analysis. *Water Policy 19*(2), 197–215.

Li, Z. (2015). *Study on Improvement of Seaside Passive Safety Technolgy Nuclear Power Plant Service Water System*. Shanghai Jiao Tong University, Shanghai, China.

Lin, C. P. (1999). Comprehensive utilization of tidal energy in Haishan. *Water Resources and Hydropower Engineering 1*, 33–34.

Liu, B. Q., Xu, M. & Liu, Q. (2015). Main problems and countermeasures of offshore wind power development in China. *Ocean Development and Management 3*, 7–12.

Liu, J., Cao, X. C., Li, B. Q. & Yu, Z. B. (2018). Analysis of blue and green water consumption at the irrigation district scale. *Sustainability 10*(2), 305.

Lv, Y. H. (2001). Comprehensive development prospect of tidal power station in Baisha estuary. *Journal of Ocean Technology 3*, 27.

Ministry of Environmental Protection of the People's Republic of China (2006–2015). *Bulletin of the Environmental Quality of China's Coastal Waters*. Ministry of Environmental Protection of the People's Republic of China, Beijing, China.

Mohieldeen, Y. E. (2016). More water flows from Western Sudan as virtual water than the flow of the River Nile in former Sudan. *Water Policy 18*(3), 533–544.

Mora, C., Myers, R. A., Coll, M., Libralato, S., Pitcher, T. J., Sumaila, R. U., Zeller, D., Watson, R., Gaston, K. J. & Worm, B. (2009). Management effectiveness of the world's marine fisheries. *Plos Biology 7*(6), 11.

Nan, G. W., Sun, H. & Song, Y. Y. (2017). Optimization of agricultural production spatial distribution in Loess Plateau based on virtual water strategy – a case study of Yulin City. *Economic Geography 10*, 197–205.

National Bureau of Statistics of the Peoples Republic of China (2002–2016). *China Rural Statistical Yearbook*. China Statistics Press, Beijing, China.

Schwarz, J., Mathijs, E. & Maertens, M. (2015). Changing patterns of global agri-food trade and the economic efficiency of virtual water flows. *Sustainability 7*(5), 5542–5563.

State Oceanic Administration People's Republic of China (2007–2016). *China Marine Statistical Yearbook*. China Ocean Press, Beijing, China.

Tang, S. J., Zhang, L. X., Pang, M. Y. & Hao, Y. (2017). Energy-based analysis of sustainability of tidal power plant in China: a case study of the Jiangxia tidal power. *Chinese Journal of Ecology 4*, 1060–1066.

Wang, H. Y., Ma, F., Yang, K. & Lv, B. (2004). A study of information renewal GM(1,1) model for predicting urban medium and long-term water demand. *Engineering Journal of Wuhan University 6*, 32–35.

Xiang, X. Z. & Jia, S. F. (2016). Estimation and trend analysis of water demand of energy industry in China. *Journal of Natural Resources 1*, 114–123.

Yang, H. & Zehnder, A. (2007). 'Virtual water': an unfolding concept in integrated water resources management. *Water Resources Research 43*(12), 10.

Yang, Y. X., Wang, G. Y. & Pan, X. C. (2009). *China Food Composition*. Peking University Medical Press, Beijing, China.

Ye, H. Q. & Lan, N. (2014). Causes and prevention mode on marine pollution from the land-based activities or sources (MPLBA) in China. *China Soft Science 2*, 22–31.

Zhang, F. S. (2000). Blue agriculture of China in 21st century. *Engineering Sciences 12*, 21–28.

Zhang, Y. G. (2015). *Marine Economic Geography in China*. Southeast University Press, Nanjing.

Zhang, X. L. & Zhao, Y. (2016). Rethinking of connotation and constituent elements of resources flow based on spatial perspective. *Journal of Natural Resources 10*, 1611–1623.

Zhang, L. Y., Feng, J. & Yang, T. (2012). Water use efficiency in thermal power industry and countermeasures for water-saving in China. *Water Resources and Power 2*, 190–192.

Zhang, Y., Zhang, J. H., Tian, Q., Liu, Z. H. & Zhang, H. L. (2018). Virtual water trade of agricultural products: a new perspective to explore the Belt and Road. *Science of the Total Environment 622*, 988–996.

Zhong, R., Zhao, P., Zhang, H. W., Wang, Y. & Mao, G. Z. (2014). Global embodied water flows in relation to energy trade and its effect on water resources. *Resources Science 36*(01), 103–109.

Zimmer, D. & Renault, D. (2003). Virtual water in food production and global trade: review of methodological issues and preliminary results. In: *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade; Value of Water Research Report Series No.12*. UNESCO-IHE, Delft, The Netherlands.

Received 11 April 2018; accepted in revised form 19 February 2019. Available online 26 March 2019