water

Article

Changing Characteristics of the Water Consumption Structure in Nanjing City, Southern China

Hao Wu [1], Xiaojun Wang [2,3,*], Shamsuddin Shahid [4] and Mao Ye [5]

1 School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, China; wuhaocx@gmail.com
2 State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing 210029, China
3 Research Center for Climate Change, Ministry of Water Resources, Nanjing 210029, China
4 Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia; sshahid@utm.my
5 China Institute of Water Resources and Hydropower Research, Beijing 100038, China; yemao@iwhr.com
* Correspondence: xjwang@nhri.cn; Tel.: +86-25-8582-8539

Academic Editors: Y. Jun Xu, Guangxin Zhang and Hongyan Li
Received: 17 May 2016; Accepted: 20 July 2016; Published: 25 July 2016

Abstract: Understanding the changes in water consumption structure in order to take measures for demand control is very important for sustainable water resources management. In this study, using the Southern China area of Nanjing as an example, we employed the information entropy method to analyze the water consumption structure, as well as the grey incidence analysis to analyze synthetic incidence degree of the factors associated with agricultural, industrial, domestic, and ecological water consumption. The results show that the degree of balance among water consumption sectors has increased from 0.755 to 0.825 between 1993 and 2014. Gradual decrease of the relative proportion of a single water user structure in a water consumption system has made the utilization of water resources in Nanjing rational and diversified. The study identifies three stages of transformation of water structure in Nanjing, namely, a growth period from 1993 to 2002, an adjustment period from 2003 to 2010, and another growth period from 2011 to 2014. The synthetic incidence degree analysis indicates that adjustments of the agricultural and industrial water consumption as well as water saving measures are the main factors that affected water consumption structure in Nanjing. It is expected that the results obtained from this study will provide references to optimize the utilization of urban water resources.

Keywords: information entropy; Nanjing city; water consumption structure; water resources management

1. Introduction

The shortage of water resources due to rapid economic development, population growth, urbanization and climate change have hindered future economic and social development in many countries [1–6]. Usually, agricultural water (AW) consumption accounts for the largest proportion of total water consumption, but with population growth and economic development, industrial water (IW) and domestic water (DW) consumption have been growing rapidly in recent decades [7–9]. Furthermore, ecological water (EW) consumption has also been given emphasis in recent years [9]. More and more researches showed that these changes are relevant to the climate, food demand, economic activity, irrigation methods, national income, conservation potential, and other factors. Therefore, how to understand the changes of water consumption structure in order to adopt future demand reduction measures is a key research field during recent years [7–10].

Different methods have been proposed in the literature to understand water consumption structure, such as: principal component analysis [11], partial least-squares regression [12], Lorenz curves and Gini coefficients [13], multi-objective automatic partitioning [14,15], information entropy [16], grey incidence analysis [17], etc. Among these methods, the information entropy method and the grey incidence analysis method from grey system theory have gained popularity as ways to analyze the water consumption structure and the impacts of different water consuming sectors [11,16–21].

Entropy is a measure of the degree of disorder or chaos in a system [22,23], which can be used to identify the changes in a system without making any assumption about the underlying system dynamics or the relationships among the system variables [24,25]. Therefore, the application of the information entropy concept and theory can solve many problems related to hydrology and water resources [26–32]. In recent years, information entropy has been applied in the assessment of the status of water consumption structure [16–20].

On the other hand, the grey incidence analysis allows the assessment of the closeness of a relationship based on the level of similarity of the geometrical patterns of sequence curves [33,34]. The method is applicable to the study of problems with unascertained and limited data [35]. Since the relationship between water utilization structure and its impact factors is grey, grey incidence analysis is found to be suitable to analyze the degree of relationship among the factors [11,17,19]. Therefore, information entropy and grey incidence analysis were used in this study to analyze the changes of water utilization structure and its cause, respectively.

China accounts for 20% of the global population, but it has access to only 7% of the world's freshwater reserves [36]. However, there are large differences in water resources between the north and south of China. The area along the Yangtze River is one of the most developed in terms of the Chinese economy, where the gross domestic product (GDP) growth rate was 7.5%–8.5% from 2000 to 2010 [37]. This area accounted for 43%–45% of the national GDP in 2010, but this growth has led to large-scale environmental pollution [38]. In particular, the middle and lower reaches of the Yangtze River are the main sources of water for the cities along the river, but water environment constraints have begun to emerge, thereby restraining the use of water by these cities. As one of China's megacities, Nanjing located in the lower reaches of the Yangtze River, with a very high population of about 6.43 million (in 2013) and a high level of economic development (GDP of about 129.36 billion dollars in 2013) [39], is chosen as a study area for analyzing the stability of water consumption structure and the driving factors that affect water consumption structure, with a hope that this will provide a useful reference for megacities water resources planning and management.

This study is divided into two parts: First, we analyzed the changing trends in water consumption for the different water use sectors in Nanjing from 1993 to 2014, where we employed information entropy to analyze the stability of water consumption. Grey incidence analysis was then applied to identify the driving factors that might have affected the changes in water consumption. Finally, the driving factors that have affected water consumption changes in Nanjing were determined by analyzing three sectors together.

2. Study Area

Nanjing, covers an area of 6597 km^2 (30°13′39′′ N–32°36′37′′ N and 118°21′28′′ E–119°15′57′′ E) is located in the southwest of Jiangsu Province and close to the Anhui Province, as shown in Figure 1. Nanjing has a subtropical monsoon climate with ample rainfall, with an average annual precipitation of more than 1000 mm. There are 120 rivers in Nanjing, all of which can be categorized according to four main watersheds: the Nanjing branch of the Yangtze River, Chuhe River, Qinhuai River, and Shuiyangjiang River. The annual average rainfall equates to 3 billion m^3 (excluding the passing-through water amount), where the average annual surface water is about 2.4 billion m^3. Nanjing is located in the lower reaches of Yangtze River, Shuiyangjiang River, and Chuhe River, so the average annual amount of passing-through water resources is 898.2 billion m^3, which is nearly 300 times the total amount of local water resources used by Nanjing [39].

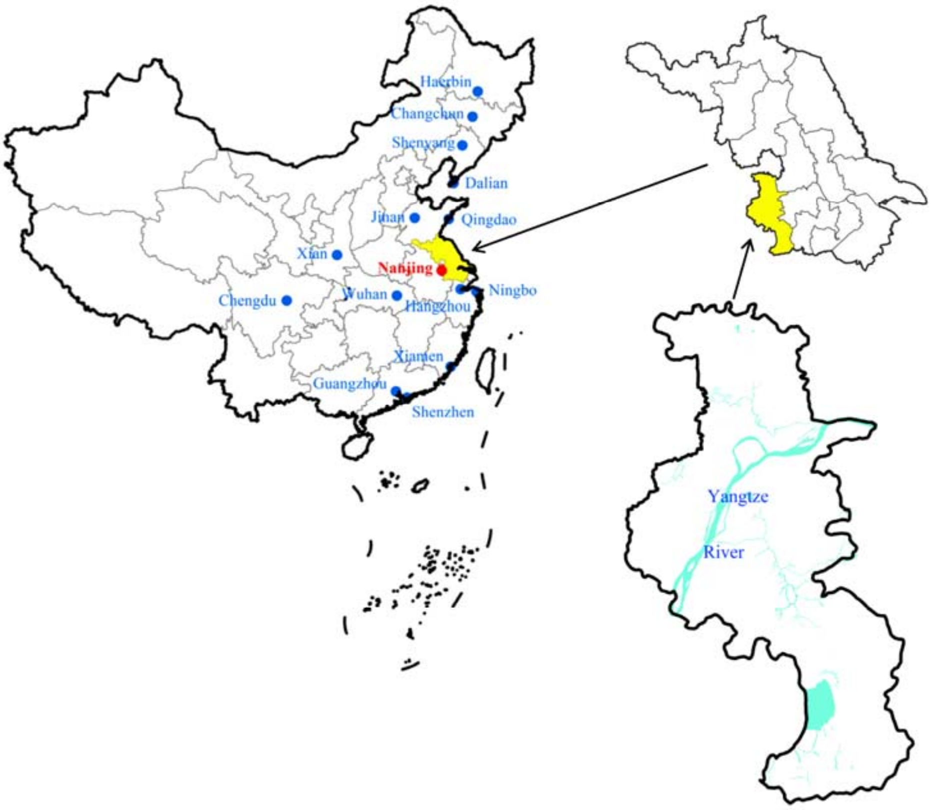


Figure 1. Location of Nanjing city in Jiangsu province, China.

Nanjing is the capital of Jiangsu Province and the central city in the east China region. It is a major industrial city. The GDP of Nanjing in 2014 was 882 billion Yuan (about 135.65 billion dollars), which was ranked 11th in the country with a growth rate of 10.1% [39]. Population growth and economic development in Nanjing during 1993–2014 are shown in Figure 2, which demonstrates that the population and GDP increased by about 26% and 2383%, respectively, in the last 22 years.

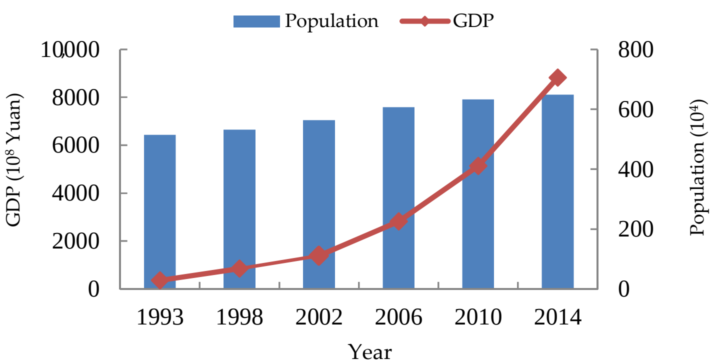


Figure 2. Population growth and economic development in Nanjing during 1993–2014.

Water consumption pattern in Nanjing has changed with population growth and economic development according to four types, namely: AW, IW, DW, and EW consumption. As shown in Figure 3, the total water consumption increased by 575 million m^3 in the last 22 years. In 2011, it reached a maximum of 4.562 billion m^3, but there has been a downward trend in the last three years. Among the different sectors, the most remarkable decrease was AW consumption, whereas there were huge increases in both IW and DW consumption. AW consumption decreased by 335 million m^3 between 1993 and 2014. The proportion of AW consumption relative to the total water consumption decreased from 0.51 in 1993 to 0.36 in 2014. In addition, both IW and DW consumption have increased because of industrial development and population growth. The ratios of IW and DW consumption relative to total water consumption increased by 0.36 and 0.25, respectively, from 1993 to 2014, where the water consumption amounts by the IW and DW sectors increased by 379 million m^3 and 391 million m^3, respectively. However, IW consumption increased after decreasing initially. In order to address severe environmental and ecological problems that have emerged in recent years, EW consumption measures were initiated in 2005, which mainly comprise water consumption by the renewed inner urban landscape rivers and the outer rivers. EW consumption increased from 20 million m^3 in 2005 to 140 million m^3 in 2014.

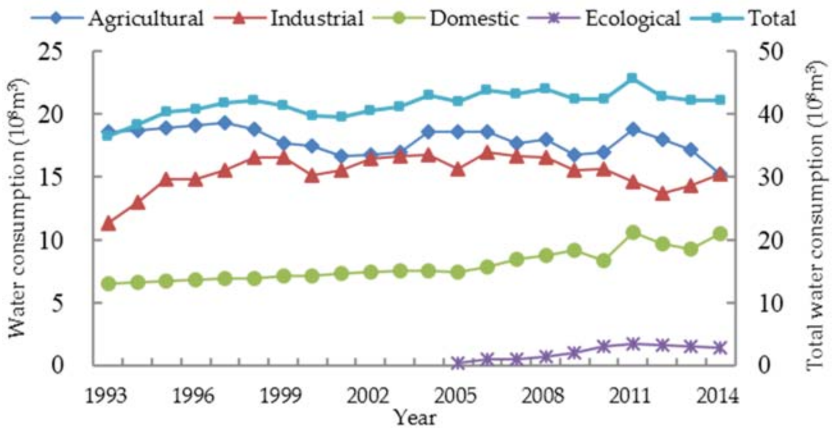


Figure 3. Changes in water consumption by Nanjing city from 1993 to 2014.

3. Data and Methods

3.1. Data and Sources

In the present study, data related to the social economy were collected from Nanjing Statistical Yearbook from 1993 to 2013. The index data for water resources were collected from Water Resources Bulletin of Nanjing from 2002 to 2013, and the data for the other years were collected from Water Resources Management Center of Nanjing [40].

3.2. Methods

3.2.1. Information Entropy

Information entropy describes the confusion or disorder degree of a system. Therefore, it was used in this study to assess the distribution of water consumptions by different sectors and to describe the trends in system structural evolution. A higher value of information entropy indicates more equality in the distribution of water consumption and vice versa [18,28–32]. The proportion of water consumption by different sectors is denoted by p_i, where i represents different sectors. The information entropy H of a water consumption system is as follows.

$$H = -\sum_{i=1}^{n} p_i \times \ln p_i \quad (1)$$

If there is only one water-consuming sector, the water system is in an extremely simple condition i.e., $H_{min} = 0$. If each sector consumes the same amount of water, i.e., $p_1 = p_2 = \ldots\ldots = p_n = 1/n$, the water system is the most highly ordered and H_{max} = ln(n). However, this situation is impossible in the real world, and thus the information entropy of water consumption always satisfies the criterion: $H_{min} \leqslant H \leqslant H_{max}$.

The lack of a common measure of the information entropy for a water consumption system when using different values of n at various time scales must be considered. Therefore, it is necessary to incorporate the balance degree J, which represents the ratio between the information entropy H and the maximum information entropy H_{max}.

$$J = H/H_{max} \tag{2}$$

A higher value of J indicates less dominance by a single water user and the structure of the water system is more complex, thereby indicating greater balance and a more stable water system [18].

3.2.2. Grey Incidence Analysis

Grey System theory [34] focuses on the study of problems involving small samples and poor information. It can deal the problems of uncertainty and missing or partial information through extracting useful information from available data. In the natural world, most of the systems are uncertain with insufficient information. Therefore, the grey system has gained popularity in a wide range of scientific fields. The grey incidence analysis is one of the major components of the grey systems theory. Grey incidence analysis can be employed for the quantitative analysis of the dynamics of a developing system to measure the correlations among the factors in the system [23–26]. If the reference sequence is set as $X_0 = \{x_0(1), x_0(2), \ldots, x_0(n)\}$ and the comparison sequence is set as $X_i = \{x_i(1), x_i(2), \ldots, x_i(n)\}$, the grey incidence coefficient of point $\gamma(\mathrm{x_0}(\mathrm{k}), \mathrm{x_i}(\mathrm{k}))$ is calculated as [41],

$$\gamma(x_0(k), x_i(k)) = \frac{\underset{i}{min}\,\underset{k}{min}\,|x_0(k) - x_i(k)| + \rho\,\underset{i}{max}\,\underset{k}{max}\,|x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho\,\underset{i}{max}\,\underset{k}{max}\,|x_0(k) - x_i(k)|} \tag{3}$$

where k = 1, 2, . . . , n, ρ is the distinguishing coefficient and its value follows the principle of minimum information $\rho \in (0,1)$.

The degree of grey incidence $\gamma(\mathrm{X_0}, \mathrm{X_i})$ between X_i and X_0 is written as follows [41].

$$\gamma(X_0, X_i) = \frac{1}{n}\sum_{k=1}^{n}\gamma(x_0(k), x_i(k)) \tag{4}$$

A larger degree of grey incidence indicates that the reference sequence has more effect on the comparison sequence, and vice versa.

However, in the case of dimensionless data, the differences in the incidence degrees can be found. Therefore, the grey incidence analysis model has prospered [42–44]. The generalized grey incidence analysis model uses two methods to represent the degree of similarity for two geometric shapes and the changing rate of sequences. Combining the incidence degrees obtained by these two methods yields the synthetic degree of incidence.

Dimensionless path 1 is described as follows.

$$x_i^0(k) = x_i(k) - x_i(1),\ k = 1, 2, \ldots, n \tag{5}$$

The absolute degree of incidence ε_{0i} is calculated by the following steps [33,34].

$$|S_0| = \left|\sum_{k=2}^{n-1} x_0^0(k) + \frac{1}{2}x_0^0(n)\right| \tag{6}$$

$$|S_i| = \left| \sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2} x_i^0(n) \right| \tag{7}$$

$$|S_i - S_0| = \left| \sum_{k=2}^{n-1} \left[x_i^0(k) - x_0^0(k) \right] + \frac{1}{2} \left[x_i^0(n) - x_0^0(n) \right] \right| \tag{8}$$

$$\varepsilon_{0i} = \frac{1 + |S_0| + |S_i|}{1 + |S_0| + |S_i| + |S_i - S_0|} \tag{9}$$

The absolute degree of incidence ε_{0i} can be used to analyze the relationship between the absolute values of the sequences.

Dimensionless path 2 is described as follows [35].

$$x_i'(k) = \frac{x_i(k)}{x_i(1)},\ k = 1, 2, \ldots, n \tag{10}$$

$x_i^{0\prime}(k)$, $|S_0'|$, $|S_i'|$ and $|S_i' - S_0'|$ are calculated using Equations (5)–(8). The relative degree of incidence π_{0i} is calculated as follows.

$$\pi_{0i} = \frac{1 + |S_0'| + |S_i'|}{1 + |S_0'| + |S_i'| + |S_i' - S_0'|} \tag{11}$$

The relative degree of incidence π_{0i} can be used mainly to analyze the changes in the rate from the sequence to the starting point.

Finally, the synthetic degree of incidence γ_{0i} is obtained by:

$$\gamma_{0i} = \theta\varepsilon_{0i} + (1 - \theta)\,\pi_{0i} \tag{12}$$

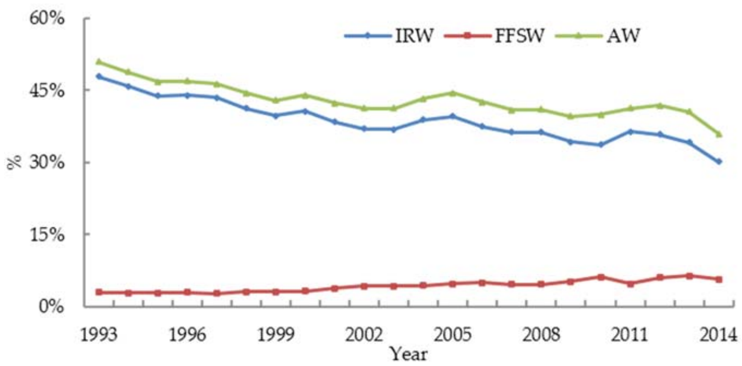
where $\theta \in (0,1)$. The synthetic degree of incidence is an index that describes the nearness relationships of two sequences, and the rates of change of those sequences relative to their initial values. Generally, it is considered that $\theta = 0.5$ [45,46]. If the study is more concerned about the relationship between the relevant absolute quantities, θ may have greater value. Conversely, if the focus is on comparing rates of changes, then θ takes a smaller value. In this study, the value of θ was 0.5. Thus, the geometric shape and rate of change had equal weights in this study. Similar to grey incidence analysis, a high synthetic degree of incidence indicates that the comparison sequence has a great influence on the reference sequence.

4. Results and Discussion

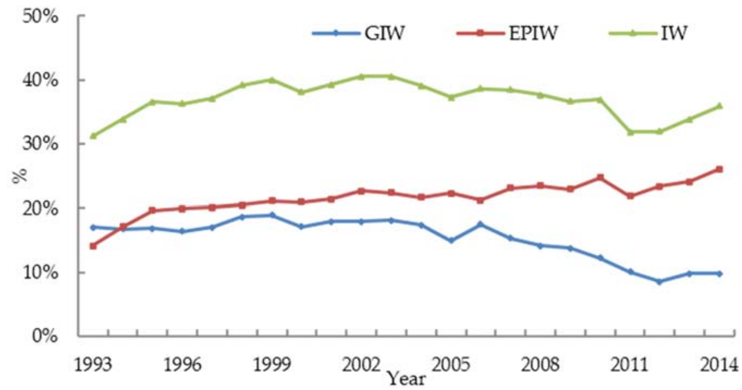
4.1. Analysis of Water Consumption Using Entropy

4.1.1. Changes in the Relative Proportions of Water Consumption Sectors

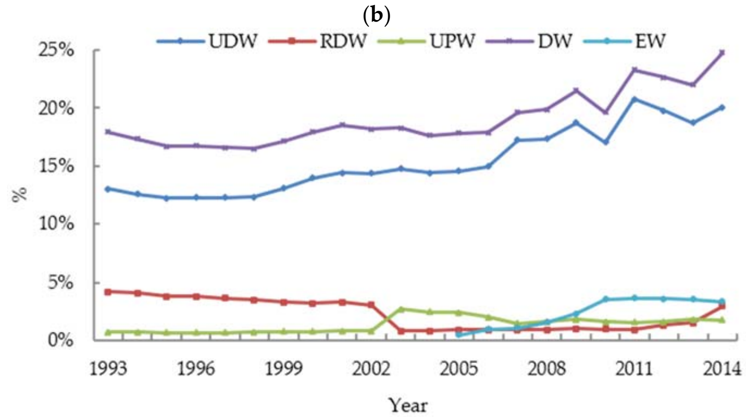
Water consumption was analyzed for four main components introduced in Section 2: AW, IW, DW, and EW consumption. Information entropy was analyzed according to the amount of information in the system. Therefore, coupled with statistical information, four main water consumption components could be subdivided into eight sectors, as follows: AW consumption comprising irrigation water (IRW) and forest, fishing, and stockbreeding water (FFSW) consumption; IW consumption comprising general IW (GIW) and electric power IW (EPIW) consumption; and DW consumption comprising urban DW (UDW), rural DW (RDW), and urban public water (UPW). EW consumption only comprises one sector. The changes in relative proportions of water consumption by different sectors from 1993 to 2014 are shown in Figure 4.



(**a**)



(**b**)



(**c**)

Figure 4. Changes in relative proportions of water consumption by different sectors in Nanjing from 1993 to 2014. (**a**) Changes in relative proportions of water consumption by different agricultural sectors; (**b**) Changes in relative proportions of water consumption by different industrial sectors; (**c**) Changes in relative proportions of domestic water and ecological water consumption.

Figure 4a shows that relative proportion of AW consumption decreased from 50.86% in 1993 to 30.97% in 2014. The major water consumption sector was IRW, which accounted for 80%–95% of AW consumption in 1993. The ratio of IRW water consumption tended to decline relative to total AW consumption with an average annual reduction rate of 2.17%. By contrast, FFSW consumption increased from 2.98% in 1993 to 5.78% in 2014.

Figure 4b shows that the relative proportion of IW consumption tended to increase first before decreasing. However, two components of IW consumption exhibited different trends during the last 22 years. The relative proportion of GIW consumption decreased by 7.23%, whereas the relative proportion of EPIW consumption increased by 11.96% during 1993–2014.

Figure 4c shows the changes in relative proportions of DW and EW consumption. In general, water consumption in both sectors increased during 1993–2014. UDW consumption was the main sector, accounting for 70%–90% of DW consumption increased significantly in the last 22 years. The relative proportions of RDW and UPW consumption accounted for low proportions of DW consumption, which changed from 4.18% and 0.73% to 2.96% and 1.76%, respectively, over the 22-year period.

4.1.2. Information Entropy Analysis for Water Consumption

As shown in Figure 5, the entropy value of water consumption system in Nanjing increased from 1.470 natural units of information (nat) in 1993 to 1.716 nat in 2014. The overall trend showed a clear increase in water consumption. This indicates that water consumption structure in Nanjing became more ordered over time, or the dominance of water consumption by a single water use sector declined, and therefore the balance became more equal. Thus, water consumption system became more stable. Figure 5 also shows that the balance degree increased from 0.755 in 1993 to 0.825 in 2014. This demonstrates that relative proportion of a single water user structure in a water consumption system has decreased gradually; thereby, the utilization of water resources in Nanjing has become rational and diversified.

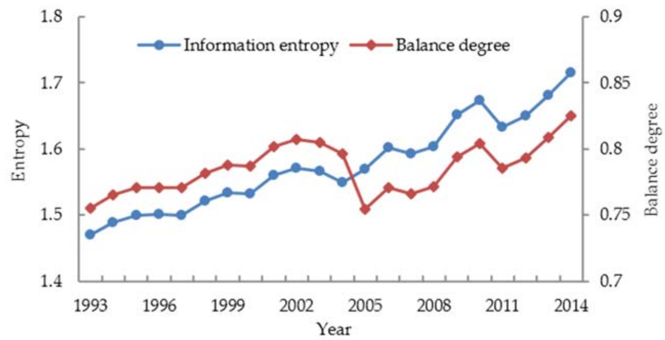


Figure 5. Changes in information entropy and the balance degree for water consumption in Nanjing.

However, there were several large fluctuations in the balance degree. According to the fluctuations of balance degree, changes of water consumption structure in Nanjing could be divided into three stages: 1993–2002, 2003–2010, and 2011–2014.

(1) Growth period (T1) from 1993 to 2002

During this period, the information entropy and balance degree of water consumption structure increased gradually from 1.470 nat and 0.755 to 1.571 nat and 0.807, respectively. In addition, the relative proportion of IRW consumption decreased from 47.88% to 36.89%, whereas the relative proportions of GIW (from 17.08% to 17.91%), EPIW (14.11% to 22.64%), and UDW (13.04% to 14.34%) consumption increased significantly.

(2) Adjustment period (T2) from 2003 to 2010

During this period, the information entropy exhibited a fluctuating increasing trend, whereas the balance degree tended to decrease first to 0.755 in 2005, before increasing to 0.804 in 2010. The relative ratio of EPIW consumption exhibited a similar trend (36.92% in 2003, 39.60% in 2005, and 33.71% in 2010), whereas relative proportion of IRW consumption exhibited the opposite trend (22.37% in 2003, 22.32% in 2005, and 24.70% in 2010). The relative ratio of GIW consumption decreased from 18.14% in 2003 to 12.24% in 2014, and relative proportion of UDW consumption increased from 14.78% to 17.03%.

(3) Growth period (T3) from 2011 to 2014

During this period, the information entropy and balance degree of the water consumption structure increased from 1.633 nat and 0.785 to 1.716 nat and 0.825, respectively. The relative proportions of IRW (from 36.40% to 30.19%), GIW (10.07% to 9.85%), and UDW (20.78% to 20.07%) consumption decreased. By contrast, the relative proportion of EPIW consumption increased significantly (21.81% to 26.70%). This indicates that the water consumption system became more stable.

4.2. Analysis of Driving Forces That Affected Water Consumption

4.2.1. Selection and Calculation of Driving Forces

The information entropy of water consumption structure depends on the relative proportions of water consumption by different sectors. However, different factors could affect relative ratio of water consumption for AW, IW, DW, and EW. Water consumption in different sectors is affected by numerous factors. A through literature review [19] identified 11 factors for agricultural water consumption, 11 factors for industrial water consumption, 13 factors for residential water consumption and one factor for ecological water consumption. However, the selection of factors for a particular region depends on their relevance and measurability. Justification of selection of different factors is given below.

AW consumption includes IW and FFSW consumption, and the relative ratio of IRW consumption usually accounted for over 80% of the total. Therefore, farmland areas, food production, and planting structures were correlated with AW consumption.

IW use involves various sectors, including industrial and mine enterprises, manufacturing, processing, cooling, air conditioning, washing, boiler water, and factory workers using water during industrial production processes. Thus, IW is influenced mainly by industrial output, efficiency of water use, and water reuse rate.

DW refers to human consumption in daily life, which comprises UDW, RDW (including livestock), and UPW (including services, catering, freight, telecommunications, and construction industry). The demand for DW consumption is related to the basic needs of human daily life. Thus, increases in population and per capita living water consumption are the main factors that influence DW consumption.

EW consumption was measured from 2005, where it mainly comprises water consumption due to renewed outer river EW consumption and uses to improve water environment, green space irrigation, and clean sanitation. EW consumption is influenced mainly by the developmental level of a city and green space areas.

Therefore, four factors for each water consumption sector (total 16 factors) were selected in the present study. The estimation procedure of those factors is discussed below.

(1) Factors related to AW consumption

Ratio of agricultural output (%): X_{11} = Agricultural output/ GDP
Ratio of irrigation area (%): X_{12} = Irrigation area/Arable land
Per capita food production (ton/person): X_{13} = Food production/Population
Ratio of grain crops to economic crops (%):

$$X_{14} = \textit{Grain crop planting area}/\textit{Economic crop planting area}$$

Grain crops include wheat, rice, potato, corn, and soybean in Nanjing.

(2) Factors related to IW consumption

Ratio of industrial output (%): X_{21} = Industrial output/GDP
Ratio of high water consumption industry (%):

$$X_{22} = \textit{High water consumption industrial output}/\textit{Industrial output}$$

Reuse ratio for IW (%): $X_{23} = \textit{Reuse water use}/\textit{Industrial water consumption}$
Per ten thousand Yuan industrial output of water consumption (m^3/ten thousand Yuan):

$$X_{24} = \textit{Industrial water consumption}/\textit{Industrial output}$$

High water consumption industries include oil processing industry, chemical products manufacturing, black metal smelting industry, and the electric power industry in Nanjing.

(3) Factors related to DW consumption

Ratio of third industry output (%): $X_{31} = Third\ industry\ output/GDP$
Population density (person/km^2): $X_{32} = Population/City\ land\ area$
Daily water consumption per capita (m^3/person· day):

$$X_{33} = Domestic\ water\ consumption/Urban\ population * Days$$

Natural population growth rate (%): $X_{34} = Birth\ rate - Mortality$

(4) Factors related to EW consumption

Per capita disposable income of urban residents (Yuan):

$$X_{41} = Disposable\ income\ of\ urban\ households/Average\ family\ number$$

GDP growth rate (%): $X_{42} = Change\ of\ GDP/GDP\ of\ last\ year$
Ratio of urban green coverage (%): $X_{43} = Urban\ green\ coverage/Urban\ area$
Per capita park green area (m^2/person): $X_{44} = Park\ green\ area/Urban\ population$

4.2.2. Analysis of Driving Force Factors by Grey Incidence Analysis

According to grey incidence analysis, the synthetic incidence degrees between relative water consumption ratios and 16 factors were calculated as shown in Table 1. The grey relational ranking based on the synthetic incidence degrees of relative water consumption ratios were determined as follows.

Grey relational ranking of AW consumption: $X_{13} > X_{11} > X_{14} > X_{12}$
Grey relational ranking of IW consumption: $X_{22} > X_{23} > X_{21} > X_{24}$
Grey relational ranking of DW consumption: $X_{34} > X_{31} > X_{32} > X_{33}$
Grey relational ranking of EW consumption: $X_{42} > X_{43} > X_{41} > X_{44}$

Table 1. Grey incidence analysis between the relative water consumption ratios and driving forces.

Referenced Sequence	Comparison Sequence	N	Mean	SD	Synthetic Incidence Degree γ
Ratio of AW	X_{11}	22	0.046	0.017	0.7370
	X_{12}	22	0.734	0.080	0.5494
	X_{13}	22	0.228	0.071	0.9085
	X_{14}	22	1.197	0.650	0.6016
Ratio of IW	X_{21}	22	0.471	0.031	0.5571
	X_{22}	22	0.328	0.054	0.8948
	X_{23}	22	0.669	0.138	0.6449
	X_{24}	22	238.863	178.781	0.5073
Ratio of DW	X_{31}	22	0.483	0.046	0.6441
	X_{32}	22	883.201	70.601	0.6374
	X_{33}	22	358.086	100.066	0.5766
	X_{34}	22	0.025	0.011	0.6490
Ratio of EW	X_{41}	10	28,076.2	9474.497	0.5551
	X_{42}	10	0.127	0.019	0.6439
	X_{43}	10	44.756	0.811	0.5629
	X_{44}	10	13.620	0.853	0.5226

(1) Driving forces of AW consumption

Plant production is a high water consumption component of agriculture. Therefore, there is a direct link between food production and AW consumption. During 1993–2014, the relative ratio of AW consumption decreased from 50.86% to 35.97%. Concurrently, food production declined from 1.573 million tons to 1.147 million tons, and per capita food production decreased from 0.306 ton/person to 0.177 ton/person. These changes in food production were due to decreases in the amount of arable land because of the implementation of policies related to the conversion of degraded farm land into forest and grass land, as well as the expansion of urban areas, where the area of arable land decreased from 312.68 thousand hectares in 1993 to 237.19 thousand hectares in 2014. The per capita grain yield and the proportion of AW were highly correlated, and the grey correlation coefficient also reflected this strong correlation. The synthetic incidence degree between the relative ratio of AW consumption and per capita food production (X_{13}) was γ_{13} = 0.9085, which shows the strong correlation.

Agricultural structure adjustment was another important cause of the decline in the relative ratio of AW consumption. The agricultural structure adjustments included adjustments of the rural economic structure and the rural production structure, which can be expressed by the relative ratio of agricultural output (X_{11}) and the relative ratio of grain crops to economic crops (X_{14}), respectively. These two factors had major impacts on the relative proportion of AW consumption (γ_{11} = 0.7370, γ_{13} = 0.6016). The relative ratio of agriculture decreased from 9.78% to 2.43%, which shows the decrease in economic benefits due to agriculture. In the planting structure, the ratio of grain crops to economic crops decreased from 71:29 to 49:51. These changes to the agricultural structure led to reduced AW consumption, especially agricultural IRW consumption.

(2) Driving forces of IW consumption

The relative ratio of IW consumption increased initially from 1993 to 2002, before decreasing from 2003 to 2011, and then increasing again in the last three years. In addition, GIW consumption decreased greatly to 4144 million m^3 from 6215 million m^3. EPIW accounted for a large relative ratio of the IW consumption and it still comprised the majority of IW consumption in Nanjing.

The proportion of high water consumption industries (X_{22}) had a major impact on the relative ratio of IW consumption (γ_{22} = 0.8948). The reuse ratio of IW (X_{23}) represented the production process level and it tended to increase, with a major impact on the relative ratio of IW consumption (γ_{23} = 0.6449), which also led to a decline in IW consumption. The decline in the proportion of industrial output (X_{21}, γ_{21} = 0.5571) and per ten thousand Yuan industrial output of water consumption (X_{24}, γ_{24} = 0.5073) represented industrial structure adjustment and the improvement of industrial efficiency, respectively, which also reflected the changes in IW consumption, although this was not clear in the results.

(3) Driving forces of DW consumption

According to the synthetic incidence degree obtained by the grey incidence analysis, the ratio of third industry output (X_{31}), population density (X_{32}), and natural population growth rate (X_{34}) had major impacts on the ratio of DW consumption (γ_{31} = 0.6441, γ_{32} = 0.6374, γ_{34} = 0.6490). Due to the economic development of Nanjing, DW consumption increased from 6530 million m^3 in 1993 to 10,445 million m^3 in 2014, and its relative ratio increased to 24.79% from 17.95%. This can be explained by population growth and development of the third industry. The population of Nanjing reached 8,187,800 people and the proportion of third industry output accounted for 56.49% of the GDP. The development of third industry sectors such as services and tourism were drivers of increased municipal water consumption, which increased the relative ratio of DW consumption.

(4) Driving forces of EW consumption

The GDP growth rate (X_{42}) had a major impact on the relative ratio of EW consumption (γ_{42} = 0.6439), whereas the per capita disposable income of urban residents (X_{41}), ratio of urban green coverage (X_{43}), and per capita park green area (X_{44}) had low impacts on the relative ratio of EW consumption (γ_{41} = 0.5551, γ_{43} = 0.5629, γ_{44} = 0.5226). The deterioration of the ecosystem influences human life and development, so improving living standards and ecological consciousness will increase the demand for EW consumption. EW consumption mainly comprised water consumption for renewing the inner urban landscape rivers and the outer river EW. In theory, increasing the ratio of urban green coverage (X_{43}) and the per capita park green area (X_{44}) could increase the demand for environmental water in cities. However, this was not clear from the EW consumption results, which were mainly due to inner river water.

5. Conclusions

This study used information entropy to analyze water consumption structure and its changing trends in Nanjing. We also employed the generalized grey incidence analysis from grey system theory to analyze synthetic incidence degree of the factors associated with AW, IW, DW, and EW consumption. We identified the main driving forces that affected these four water use sectors, and we analyzed forces responsible for the changes in water consumptions in Nanjing. Our main conclusions are as follows.

(1) The information entropy and balance degree of water consumption structure in Nanjing showed that the development of the water structure passed through following three stages. (a) A decrease in relative ratio of IRW consumption and increases in GIW, EPIW, and UDW consumption led to increases in information entropy and balance degree; (b) The information entropy exhibited a fluctuating increasing trend, whereas balance degree tended to decrease first before increasing. The relative ratio of EPIW consumption exhibited a similar trend, but relative ratio of IRW consumption had the opposite trend; (c) The information entropy and balance degree of water consumption structure increased. The relative ratio of IRW consumption decreased, whereas the relative ratio of EPIW consumption increased significantly. Thus, water consumption structure became more stable and equilibrated in Nanjing.

(2) The synthetic incidence degree of per capita food production and the ratio of agricultural output relative to AW consumption were 0.9085 and 0.7370, respectively. The synthetic incidence degree for high water consumption industries relative to the ratio of IW consumption was 0.8948. The synthetic incidence degrees for the third industry output, population density, and natural population growth rate relative to the ratio of DW consumption were 0.6441, 0.6374, and 0.6490, respectively. The synthetic incidence degree of the GDP growth rate relative to the ratio of EW consumption was 0.6439. The main factors that affected water consumption structure in Nanjing were adjustments to agricultural and industrial structures, and the level of water saving measures.

With the implementation of a strict water resource management policy in China, the government departments responsible for water management are restricting the total demand of urban water. Thus, determining the changing trends in water consumption and the factors responsible for the changes are important for guiding water consumption control in Nanjing as well as in other first-tier cities in China and other developing countries, where there is a need to control water use and stabilize the water consumption structure. Therefore, the results of this study provide a reference for water resources management and planning in water abundant rivers in other parts of the world.

Acknowledgments: We are grateful to the National Natural Science Foundation of China (No. 51309155, No. 41330854), the National Key Basic Research Program of China (2013CB956503), the Science and Technology Project of Jiangsu Province Water Conservancy (2014007), Special Fund of State Key Laboratory of China (No. Y515023) and Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin China Institute of Water Resources and Hydropower Research (No. IWHR-SKL-201515) for providing financial support for this research. We also thank the anonymous reviewers and editors for their helpful comments and suggestions.

Author Contributions: Hao Wu collected data, did the detailed work and wrote the paper; Xiaojun Wang provided the method and guided the whole study; Shamsuddin Shahid contributed to the Information entropy method and reviewed the draft manuscript; Mao Ye contributed to the Grey incidence analysis method analyzed the data.

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

References

1. Blanc, E.; Strzepek, K.; Schlosser, C.; Jacoby, H.; Gueneau, A.; Fant, C.; Rausch, S.; Reilly, J. *Analysis of US Water Resources under Climate Change*; MIT Joint Program on the Science and Policy of Global Change: Cambridge, MA, USA, 2013.
2. Blignaut, J.; Van Heerden, J. The impact of water scarcity on economic development initiatives. *Water SA* **2009**, *35*, 415–420. [CrossRef]
3. Schlosser, C.A.; Strzepek, K.; Gao, X.; Fant, C.; Blanc, É.; Paltsev, S.; Jacoby, H.; Reilly, J.; Gueneau, A. The future of global water stress: An integrated assessment. *Earth's Future* **2014**, *2*, 341–361. [CrossRef]
4. Gosling, S.N.; Arnell, N.W. A global assessment of the impact of climate change on water scarcity. *Clim. Chang.* **2016**, *134*, 371–385. [CrossRef]
5. Shandas, V.; Lehman, R.; Larson, K.L.; Bunn, J.; Chang, H. Stressors and strategies for managing urban water scarcity: Perspectives from the field. *Water* **2015**, *7*, 6775–6787. [CrossRef]
6. Cheng, H.; Hu, Y.; Zhao, J. Meeting china's water shortage crisis: Current practices and challenges. *Environ. Sci. Technol.* **2009**, *43*, 240–244. [CrossRef] [PubMed]
7. Keskinen, M.; Guillaume, J.H.; Kattelus, M.; Porkka, M.; Räsänen, T.A.; Varis, O. The water-energy-food nexus and the transboundary context: Insights from large asian rivers. *Water* **2016**, *8*, 193. [CrossRef]
8. Vörösmarty, C.J.; Green, P.; Salisbury, J.; Lammers, R.B. Global water resources: Vulnerability from climate change and population growth. *Science* **2000**, *289*, 284–288. [CrossRef] [PubMed]
9. Wang, X.; Zhang, J.; Shahid, S.; Eimahdi, A.; He, R.; Bao, Z.; Ali, M. Water resources management strategy for adaptation to droughts in China. *Mitig. Adapt. Strateg. Glob. Chang.* **2012**, *17*, 923–937.
10. Duarte, R.; Pinilla, V.; Serrano, A. Globalization and natural resources: The expansion of the Spanish agrifood trade and its impact on water consumption, 1965–2010. *Reg. Environ. Chang.* **2016**, *16*, 259–272. [CrossRef]
11. Chen, X.F. Analysis of grey relation degree based on water utilization evolution and driving force of information entropy in xiamen. *J. Water Resour. Water Eng.* **2013**, *24*, 188–191.
12. Yun, Y.; Zou, Z.; Wang, H. A regression model based on the compositional data of Beijing's water consumed structure and industrial structure. *Syst. Eng.* **2008**, *26*, 67–71.
13. Liu, X.; Xie, J. The interactive relationship between water consumption structure and industrial structure of shanxi province. *Syst. Eng.* **2011**, *29*, 45–51.
14. De Paola, F.; Fontana, N.; Galdiero, E.; Giugni, M.; Savic, D.; Degli Uberti, G.S. Automatic multi-objective sectorization of a water distribution network. *Procedia Eng.* **2014**, *89*, 1200–1207. [CrossRef]
15. De Paola, F.; Galdiero, E.; Giugni, M. A jazz-based approach for optimal setting of pressure reducing valves in water distribution networks. *Eng. Optim.* **2016**, *48*, 727–739. [CrossRef]
16. Zheng, A.; Wang, W.; Duan, L. Water consumption structue evolvement and its driving forces for Guanzhong basin. *J. Arid Land Resour. Environ.* **2011**, *9*, 015.
17. Lu, C.-M.; Wu, Z.-N.; Hu, C.-H. Grey relational degree analysis on the major driving forces of water use structure. *Water Sav. Irrig.* **2008**, *2*, 013.
18. Wang, X.-J.; Zhang, J.-Y.; Yang, Z.-F.; Shahid, S.; He, R.-M.; Xia, X.-H.; Liu, H.-W. Historic water consumptions and future management strategies for haihe river basin of northern China. *Mitig. Adapt. Strateg. Glob. Chang.* **2015**, *20*, 371–387. [CrossRef]
19. Zhang, C.; Dong, L.; Liu, Y.; Qiao, H. Analysis on impact factors of water utilization structure in Tianjin, China. *Sustainability* **2016**, *8*, 241. [CrossRef]
20. Ma, L.-H.; Kang, S.-Z.; Su, X.-L. Study on evolution and its driving forces of water utilization structure of shiyang river basin in northwest arid areas. *Agric. Res. Arid Areas* **2008**, *1*, 022.
21. Su, X.; Zhao, C.; Ma, L. Water consumed structure evolvement and its driving forces for guanzhong region in the past 20 years. *J. Irrig. Drain.* **2008**, *5*, 019.
22. Shannon, C.E. Mathematical theory of communication. *Bell Syst. Tech. J.* **1948**, *27*, 379–443. [CrossRef]
23. Doutsoyiannis, K. Uncertainty, entropy, scaling and hydrological statistics. 1. Marginal distributional properties of hydrological processes and state scaling. *Hydrol. Sci. J.* **2005**, *50*, 381–404.
24. Pechlivanidis, I.; Jackson, B.; McMillan, H. The use of entropy as a model diagnostic in rainfall-runoff modelling. In Proceedings of the 2010 International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting, Ottawa, ON, Canada, 5–8 July 2010; Swayne, D.A.,

Yang, W., Voinov, A.A., Rizzoli, A., Filatova, R.T., Eds.; International Environmental Modelling and Software Society (iEMSs): Ottawa, ON, Canada, 2010.

25. Singh, V. The use of entropy in hydrology and water resources. *Hydrol. Process.* **1997**, *11*, 587–626. [CrossRef]
26. Mogheir, Y.; De Lima, J.; Singh, V. Characterizing the spatial variability of groundwater quality using the entropy theory: I. Synthetic data. *Hydrol. Process.* **2004**, *18*, 2165–2179. [CrossRef]
27. Singh, V.P. Hydrologic synthesis using entropy theory: Review. *J. Hydrol. Eng.* **2011**, *16*, 421–433. [CrossRef]
28. Singh, V.P. *Entropy Theory and Its Application in Environmental and Water Engineering*; John Wiley & Sons: Chichester, UK, 2013.
29. Chen, J.; Zhang, Y.; Chen, Z.; Nie, Z. Improving assessment of groundwater sustainability with analytic hierarchy process and information entropy method: A case study of the hohhot plain, china. *Environ. Earth Sci.* **2015**, *73*, 2353–2363. [CrossRef]
30. Kim, S.; Kim, Y.; Kang, N.; Kim, H.S. Application of the entropy method to select calibration sites for hydrological modeling. *Water* **2015**, *7*, 6719–6735. [CrossRef]
31. Da Silva, V.P.R.; Belo Filho, A.F.; Almeida, R.S.R.; de Holanda, R.M.; da Cunha Campos, J.H.B. Shannon information entropy for assessing space–time variability of rainfall and streamflow in semiarid region. *Sci. Total Environ.* **2016**, *544*, 330–338. [CrossRef] [PubMed]
32. Zeng, X.; Wu, J.; Wang, D.; Zhu, X.; Long, Y. Assessing bayesian model averaging uncertainty of groundwater modeling based on information entropy method. *J. Hydrol.* **2016**, *538*, 689–704. [CrossRef]
33. Deng, J. *A Course on Grey System Theory*; Huazhong University of Science and Technology Press: Wuhan, China, 1990.
34. Deng, J.L. Grey control system. *J. Huazhong Univ. Sci. Technol.* **1982**, *3*, 9–18.
35. Liu, S.; Fang, Z.; Lin, Y. A new definition for the degree of grey incidence. *Sci. Inq.* **2006**, *7*, 111–124.
36. UNESCO-WWAP. *Facts and Figures Managing Water Under Uncertainty and Risk*; The United Nations World Water Development Report 4; The United Nations World Water Assessment Programme: Paris, France, 2012.
37. National Bureau of Statistics of China (NBS). *Statistical Communiqué of the People's Republic of China*; National Bureau of Statistics of China: Beijing, China, 2012.
38. Wu, B.; Zhao, D.; Jia, H.; Zhang, Y.; Zhang, X.; Cheng, S. Preliminary risk assessment of trace metal pollution in surface water from Yangtze river in Nanjing section, China. *Bull. Environ. Contam. Toxicol.* **2009**, *82*, 405–409. [CrossRef] [PubMed]
39. Statistical Bureau of Nanjing. *Nanjing Statistical Yearbook*; China Statistics Press: Beijing, China, 2015.
40. Bureau of Nanjing Water Resources. *Water res Bulletin of Nanjing 2002–2013*; Bureau of Nanjing Water Resources: Nanjing, China, 2002–2013.
41. Liu, S.; Lin, Y. *Grey Information: Theory and Practical Applications*; Springer Science & Business Media: Heidelberg, Germany, 2006.
42. Liu, S.; Forrest, J.Y.L. *Grey Systems: Theory and Applications*; Springer: Berlin, Geramny, 2010.
43. Lin, Y.; Liu, S. Solving problems with incomplete information: A grey systems approach. *Adv. Imaging Electron Phys.* **2006**, *141*, 77–174.
44. Lin, Y.; Chen, M.-Y.; Liu, S. Theory of grey systems: Capturing uncertainties of grey information. *Kybernetes* **2004**, *33*, 196–218. [CrossRef]
45. Ingle, V.R.; Ingle, V. An empirical study on degrees of grey incidences to decide maintenance priorities of power transformers. *Int. J. Recent Trends Eng. Technol.* **2014**, *11*, 60–66.
46. Lei, H.; Zhang, X. Analysis on water use structure change and its driving forces during last 10 years in shaanxi province. *J. Water Resour. Water Eng.* **2012**, *4*, 028.