An evaluation index system of water security in China based on macroeconomic data from 2000 to 2012

X S Li1,2,3, Z Y Peng1 and T T Li1

1Economy and Management School, Wuhan University, Wuhan 430072, China
2Water Research Institute, Wuhan University, Wuhan 430072, China
E-mail: xuesong7401@263.net

Abstract. This paper establishes an evaluation index system of water security. The index system employs 5 subsystems (water circulation security, water environment security, water ecology security, water society security and water economy security) and has 39 indicators. Using the AHP method, each indicator is given a relative weight to integrate within the whole system. With macroeconomic data from 2000 to 2012, a model of water security evaluation is applied to assess the state of water security in China. The results show an improving trend in the overall state of China’s water security. In particular, the cycle of water security is at a high and low fluctuation. Water environment security presents an upward trend on the whole; however, this trend is unsteady and has shown a descending tendency in some years. Yet, water ecology security, water society security, and water economy security are basically on the rise. However, the degree of coordination of China’s water security system remains in need of consolidation.

1. Introduction
Water is the source of life and the indispensable material basis of national economic development. Problems that are related to water resources, such as water pollution, floods, and drought can seriously restrict social and economic development. Thus, maintaining water security is the foundation and premise for achieving sustainable development. China has long been faced with serious issues of water security. The population is so large that the volume of water resources per capita is much less than the global average, which has led to a relative water shortage and an uneven distribution. In addition, problems including flooding and water pollution accidents have emerged, which have made the situation even worse. In order to realize comprehensive and sustainable development, it is necessary for China to resolve the problems that threaten water security and alleviate the water resources crisis. As the
foundation of water resource management decisions, water security evaluation is aimed at estimating the state of water security in a country or region. After such evaluations have been conducted, corresponding countermeasures can be developed to reach the goal of sustainably developing the social economy and ecological environment of a country or region [1]. Therefore, a requisite premise in solving water security matters is to evaluate water security objectively and reasonably.

In recent years, many scholars and organizations have constructed evaluation index systems and made comprehensive assessments of the state of water resources in certain areas with a variety of statistical methods. The Policy Research Initiative (PRI) of Canada developed a composite water index, known as the Canadian Water Sustainability Index (CWSI), to evaluate Canadian communities’ water well-being [2]. This model was widely applied to the water resource evaluation of other regions or river basins [3]. Later, the Sustainable Water Resources Roundtable (SWRR) established a water resource evaluation index system, which included 400 indicators that included three aspects: society, the economy, and the environment [4]. Constructing an evaluation index system that employed four criteria, including the economy, society, the environment and maintenance capability, Kang et al. developed a water resource sustainability evaluation model (WRSEM) [5]. In China, there were also many related studies. Han et al took several factors into consideration, such as the safety of drinking water, the contradiction between water’s supply and demand, and the realization of water value, based on a multi-criteria assessment index, which was built and applied to Ningxia city for an empirical analysis [6]. Dai set personal security, economic security, social security and environmental security as four subindices under the synthetic index of water safety to constitute a water security evaluation index system, and Liupanshui City was taken as a case [7]. Generally speaking, in the existing water resource evaluation studies, assessment index systems have usually been established by dividing water security into several aspects including the economy, society, ecology and the environment. Next, corresponding indicators are selected for further calculation. However, the method of synthetic evaluation is diversified, among which the WPI [8], PCA [9] [10], fuzzy evaluation method [11], matter-element evaluation method [12], set pair analysis [13] and AHP [14] [15] have been most commonly used. Nevertheless, in the last few years, a great number of studies on water safety evaluation have attained significant results. Most of these studies have focused on the water safety of a certain region, while countries as a whole have received minimal attention. Furthermore, those studies have been based on short time periods, focusing, for example, on a single year; thus, vertical comparisons have been lacking. In view of these elements and China’s actual water safety situation, this paper develops a comprehensive water security evaluation index system and assesses the state of water security in China from 2000 to 2012 utilizing the AHP method and the water security index formula, which is expected to provide reference and foundation for China to make effective water security preserving policies.

2. Establishing an evaluation index system

2.1. The concept of water security
Since the idea of water security was first put forward, the concept has attracted growing attention, especially in the recent decade. In the early days, the issues that were discussed in terms of water
security varied depending upon context and disciplinary perspective. For example, from a legal perspective, water security has generally been associated with allocation rules that seek to secure entitlements to desired quantities of water [16]. After 2000, water security was generally described in an integrative and interdisciplinary way, which can be sorted into four types with respect to varying priorities [17]. The first type of definition focuses on water availability, whereby water security is defined as a condition in which people have access to sufficient, safe and affordable water to satisfy their basic needs for drinking, washing, and livelihood [18]. The second type places an emphasis on human vulnerability to hazards; specifically, water security involves the protection of vulnerable water systems, protection against water related hazards such as floods and droughts, the sustainable development of water resources, and the safeguard of access to water functions and services [19]. The third type pays more attention to human needs, a representative point being that “water security is a condition where there is a sufficient quantity of water at a quality necessary, at an affordable price, to meet both the short-term and long-term needs to protect the health, safety, welfare, and productive capacity of position (households, communities, neighborhoods or nation) [20]. The last type considers sustainability as the most important element, and water security is defined as a condition in which “every person has access to enough safe water at an affordable cost to lead a clean, healthy, and productive life, while ensuring that the natural environment is protected and enhanced [21]. In China, definitions of water security that have been provided in the literature were similarly derived from the above concepts. For instance, “water security is based on an analysis of the relationship between environmental changes and security issues considering not only the situation of water resources, but the related factors of environment, ecology, society, politics, and economy [22]. Referring to the above definition, in this article, water security, based on the causes of water safety threats, is defined as a state in which the natural hydrologic cycle and human water related activities do not cause water shortages, water pollution, deluge, drought or other problems, and do not hamper the sustainable development of the social economy and the ecological environment.

2.2. The basic framework of the water security evaluation system

Obviously, with its abundant connotations, water security cannot be scaled through a few indicators. Based on the conception that is set forth in this paper, referring to existing studies, a multi-criteria water security evaluation index system is established as shown in table 1, which employs five subsystems, namely water circulation security, water environment security, water ecology security, water society security, and water economy security, which ultimately include 39 indicators.

Representing the degree of water security in the designated areas, the comprehensive water security index provides direct proof for judging the state of water security in that area. As for the five sub-indices, water circulation security is employed to describe the natural phenomena and processes that are related to water resources, mainly involving precipitation, water reserves and water-related natural hazards, recording and reflecting the law of hydrological motion. Water environment security is mainly about the situation of water quality, and it is connected with the straightforward influences that people’s water-related behaviors have on their water environment. In daily life and production, the quality of the water environment is largely affected by actions such as sewage treatment and disposal. Water ecology security represents the ecological factors that affect water security, such as forests and wetlands, which are helpful for water conservation and purification, and thus play a vital role in
maintaining water safety. Water social security stands for the ability to construct water security. A higher level of water security development capability can be achieved by reducing the negative impacts that natural water conditions, and the ecological environment, have on water security. Water economy security is a sub-index regarding the economic efficiency of water usage and the capacity of the economy to support water security construction. Increasingly, the utilization efficiency of water resources and guaranteed economical and sustainable development are important aspects of water security. In turn, the development of the economy can lay a foundation for water security construction.

Table 1. Water security evaluation index system.

| Objective system | Subsystem      | Indicators                                                                 | Units       | Index attributes |
|------------------|----------------|----------------------------------------------------------------------------|-------------|------------------|
|                  | Water circulation security | per capita volume of water resources $C_1$ | $m^3$ per capita | +                |
|                  |                 | mean annual precipitation $C_2$                                             | mm          | +                |
|                  |                 | Groundwater quantity $C_3$                                                  | $10^6 m^3$  | +                |
|                  |                 | Surface water quantity $C_4$                                                | $10^8 m^3$  | +                |
| B1               |                 | The area affected by inundation $C_5$                                       | $10^3$ hectare | -               |
|                  |                 | The area affected by drought $C_6$                                          | $10^3$ hectare | -               |
|                  | Water environment security | Frequency of water pollution accident $C_7$ | times       | -                |
|                  |                 | COD emission load $C_8$                                                     | $10^4$ tons | -                |
|                  |                 | Industrial waste water discharge success rate $C_9$                         | %           | -                |
|                  |                 | Ratio of water quality preceding III among rivers assessed $C_{10}$         | %           | +                |
|                  |                 | Emission load of ammonia and nitrogen $C_{11}$                              | $10^4$ tons | -                |
|                  |                 | Total emission load of effluent $C_{12}$                                    | $10^4$ tons | -                |
|                  |                 | Ratio of investment on dealing with environmental pollution $C_{13}$        | %           | +                |
|                  |                 | Disposing rate of urban sewage $C_{14}$                                     | %           | +                |
|                  |                 | Ratio of forest covering $C_{15}$                                           | %           | +                |
|                  | Water ecology security | Per capita urban public greenbelt area $C_{16}$                            | $m^2$       | +                |
|                  |                 | The proportion natural reserve area accounts for jurisdiction area $C_{17}$ | %           | +                |
|                  |                 | Soil erosion control areas $C_{18}$                                         | $10^3$ hectare | +               |
| B3               |                 | Ratio of ecological water consuming $C_{19}$                              | %           | +                |
|                  |                 | The proportion wetland area accounts for country's total land area $C_{20}$ | %           | +                |
Total amount of water supplied $C_{21}$ & $10^8$ m$^3$ & +
Investment for drainage construction project $C_{22}$ & $10^8$ yuan & +
Year-end length of urban water supply pipe $C_{23}$ & km & +
Water popularizing rate of urban population $C_{24}$ & % & +
Levee protection area $C_{25}$ & $10^3$ hectare & +
The number of industrial wastewater treatment facilities $C_{26}$ & set & +
Effective irrigation area $C_{27}$ & $10^3$ hectare & +
Accumulated benefit rate of rural water reform $C_{28}$ & % & +
Ratio of loss caused by inundation $C_{29}$ & % & -
Ratio of economic crops loss caused by drought $C_{30}$ & % & -
Per capita GDP $C_{31}$ & Yuan & +
Per capita output of grain $C_{32}$ & kg & +
Engel coefficient of urban households $C_{33}$ & % & -
Engel coefficient of rural households $C_{34}$ & % & -
Per capita yearly net income of rural households $C_{35}$ & Yuan & +
Per capita yearly real income of urban households $C_{36}$ & Yuan & +
Water consumption per ten thousand yuan GDP $C_{37}$ & m$^3$ & -
Recycling rate of industrial water $C_{38}$ & % & +
Water consumption per capita $C_{39}$ & m$^3$/capita & -

2.3. Determining relative weights

Water security is a complex multi-objective system, the effects of which vary among indexes. Thus, in water security assessment, it is an important step to determine the relative weights of the indicators. In this article, the AHP method is employed to determine relative weights. With respect to the principle of AHP, by consulting specialists and carrying out a questionnaire survey, a judgment matrix is structured with a scale from 1 to 9, based on a pairwise comparison between two indicators or two sub-indices. Then the relative weight of each indicator and sub-index can be confirmed through a series of calculations. The result of the relative weight determination is shown in table 2, which furnishes water security evaluations with a reliable substratum.
Table 2. Relative weights of indicators and sub-indices in water security evaluation index system.

| Indicators | Weights | Indicator | Weights | Indicator | Weights | Indicator | Weights |
|------------|---------|-----------|---------|-----------|---------|-----------|---------|
| C1         | 0.0750  | C12       | 0.0207  | C23       | 0.0051  | C34       | 0.0050  |
| C2         | 0.0205  | C13       | 0.0369  | C24       | 0.0274  | C35       | 0.0120  |
| C3         | 0.0142  | C14       | 0.0680  | C25       | 0.0137  | C36       | 0.0071  |
| C4         | 0.0518  | C15       | 0.0497  | C26       | 0.0073  | C37       | 0.0262  |
| C5         | 0.0378  | C16       | 0.0101  | C27       | 0.0137  | C38       | 0.0254  |
| C6         | 0.0378  | C17       | 0.0151  | C28       | 0.0218  | C39       | 0.0178  |
| C7         | 0.0100  | C18       | 0.0328  | C29       | 0.0177  | B1        | 0.2372  |
| C8         | 0.0184  | C19       | 0.0084  | C30       | 0.0177  | B2        | 0.3354  |
| C9         | 0.0499  | C20       | 0.0248  | C31       | 0.0155  | B3        | 0.1410  |
| C10        | 0.1116  | C21       | 0.0385  | C32       | 0.0060  | B4        | 0.1677  |
| C11        | 0.0201  | C22       | 0.0050  | C33       | 0.0038  | B5        | 0.1186  |

According to table 2, among the five subsystems, water environment security, that represents the state of water quality, makes the most contribution to water safety at 0.3354, followed by water circulation security and water society security, the weights of which are 0.2372 and 0.1677, respectively. Comparatively, the influences that water ecological security and water economical security exert over water security are less, and their weights are only 0.1677 and 0.1186, respectively. The results of the relative weights determination imply that the quantity and quality of water resources are extremely vital aspects of water security, especially the quality of a water resource. In fact, the quality of a water resource determines the quantity of the available water. Further, a sufficient water supply is the fundamental premise of water security, which cannot be realized under the conditions of a water shortage. What is more, water social security has a relatively great effect on water security, which implies the inferior position of water security, which results from natural and artificial factors, can be improved with intentional corrective measures, which can increase the degree of water security. Specific to the various indicators, in view of their contribution to water security represented by the relative weights, the top ten indicators are: ratio of water quality preceding among rivers assessed, per capita volume of water resources, disposal rate of urban sewage, industrial waste water discharge success rate, surface water quantity, ratio of forest coverage, total amount of water supplied, area affected by inundation, area affected by drought, and ratio of investment in managing environmental pollution.

2.4. Consistency examination
A consistency examination is required to check the reasonableness of the relative weights, which are obtained with a judgment matrix and given a mean random consistency index (RI) that is utilized to
make judgments. If the value of CR is less than 0.1, the relative weights are assigned rationally. As for the above results of the relative weights determination in the water security evaluation index system, the results of the consistency examination are displayed in table 3. Obviously, the relative weights of the indicators and sub-indices, which are attained through the AHP method, are reasonable and can be used to integrate the water security evaluation index system.

Table 3. Results of Consistency Examination.

| System | A   | B1  | B2  | B3  | B4  | B5  |
|--------|-----|-----|-----|-----|-----|-----|
| CR     | 0.0461 | 0.0754 | 0.0412 | 0.0403 | 0.0785 | 0.0680 |
| Comparison with 0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |

3. A comprehensive evaluation of Chinese water security

3.1. Data sources and treatment
In this study, macroeconomic data at the national level from 2000 to 2012 is selected to evaluate the state of water security in China during that period. Data is drawn from the Chinese annual Water Resources Bulletin, China Statistical Yearbook, China Water Conservancy Development Bulletin, China Flood and Drought Disasters Bulletin, China’s Environmental Bulletin, China Environmental Statistics Yearbook, and the CEInet statistics database. To offset the impact of prices, the data of indicators that involve value are converted to that of a level based on 2000. Additionally, some of the missing data is replaced with a linear trend analysis. Further, the range transformation method is utilized to normalize the indicator data to eliminate the differences among the indicator units.

For the positive indicators, the normalization formula is shown below:

\[ D_i = \frac{X_i - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}} \tag{1} \]

For the negative indicators, the normalization formula is given by:

\[ D_i = \frac{X_{\text{max}} - X_i}{X_{\text{max}} - X_{\text{min}}} \tag{2} \]

Where \( D_i \) is the value of the indicators after normalization, \( X_i \) represents the original value of the indicators, and \( X_{\text{max}} \) and \( X_{\text{min}} \) stand for the maximum and minimum values of the indicators, respectively.

3.2. The water security evaluation index formula
To calculate the index’s value of each subsystem in the water security evaluation index system, the following equation is used (GC PRI, 2007; Sullivan, 2001):

\[ B_j = \frac{\sum_{i=1}^{N} w_i X'_j}{\sum_{i=1}^{N} w'_i} \tag{3} \]
Where $B_j$ is the value of the j sub-index, $X_j^i$ is the normalized value of i indicator that is contained in the j sub-index, and $W_j^i$ represents the relative weights of i indicators for the j sub-index.

The comprehensive index value of water security is computed by integrating the sub-indices as follows:

$$WSI = \frac{\sum_{j=1}^{N} w_j B_j}{\sum_{j=1}^{N} w_j}$$  \hspace{1cm} (4)

Where WSI is the comprehensive index of water security, $B_j$ is still the value of the j sub-index and $W_j$ stands for the relative weights of the sub-indices.

Because water security is a complicated system that is composed of several subsystems (water cycling, water environment, water ecology, water society and water economy), which are closely connected and affect each other, it is of great significance in achieving water security to coordinate the development of each subsystem. The following equation is used to scale the sub-index of the coordination degree of the water security evaluation index system [23].

$$CI = 1 - \frac{S}{B}$$  \hspace{1cm} (5)

Where $S$ is the standard deviation of sub-indices, $\bar{B}$ is the mean of sub-indices and CI is the sub-index of the coordination degree of water security evaluation index system. The larger the CI is, the better the coordination of system will be.

3.3. Evaluation results and discussion

3.3.1. Water security evaluation results and analysis. Based on the water security evaluation index system that is established in this article, with the above calculation formulas and normalized data, the results of assessing Chinese water security are displayed in figure 1.

![Figure 1](image-url). Variation of the water security’s integrated index and sub-indices for China from 2000 to 2012.
According to the evaluation results, the water circulation security index (B1) fluctuated greatly during the studied period without fixed law. The highest value is 0.833 for 2010, while the lowest value was only 0.283 for 2011. The reason for such a consequence is that the water-related natural phenomena and the process that is described by water cycling security are often irregular and beyond human control, even though they have a close relationship with water security. The fluctuation of the water cycling security index is the very embodiment of natural hydrologic motion’s randomness.

The water environment security index (B2) declined by a large margin from 0.507 to 0.323, during the period from 2002 to 2004. Moreover, it also had downward trends in the years 2003, 2006, 2009 and 2011 by 11.2%, 3.4%, 11.9% and 9.2%, respectively. A further analysis of the indicators contained in the water environment security subsystem indicates that the increase in ammonia and nitrogen emission load, and the effluent’s total emission load, was accompanied by a descending ratio of water quality preceding among the rivers that were assessed, which lead to the decreases mentioned above. However, as a whole, the water security index was still on the rise from 2000 to 2012. In the last few years, accidents that threaten water security such as water pollution have occurred constantly, for example, the red river incident in Xinxiang of Henan province. As a result, governmental and public environmental awareness has grown. The central and local governments have introduced a series of laws and regulations, such as the Prevention Plan on Water Pollution in Key River Basins from 2011 to 2015, to control the water environment problem, and NGOs have also taken measures to actively protect the water environment. Having benefited from these efforts, there is no doubt that the problems of the water environment have been remitted to some extent, which has caused the water environment security to gradually improve.

The results show a rising trend in the water ecology security index (B3), water society security index (B4) and water economy security index (B5). In detail, the water ecology security index achieved the fastest growth in 2004 with a 69.3% jump, and the growth pace of 2008 was also comparatively large, approximately 29.3%. The water society security index dropped slightly by 11.1% and 2.4% in 2010 and 2012. Meanwhile, the water economic security index continues to steadily rise. The above consequences reflect that the ecological construction of China is in good condition, and the ability to cope with water security problems and economic strength is improving. In China, ecological safety has attracted growing attention. Ecological civilization constructions are placed in a prominent position and contribute to the beautification of China. In recent years, China's economy has been in a state of steady growth. From 2000 to 2012, the per capita GDP has risen by 52.28%. Moreover, water security has been a source of increasing concern, and as a result, investment in water security construction has increased. In 2012, water conservancy investments in fixed assets reached 411.72 billion yuan and made a gain of 19.27%. All of these facts provide support for the rising trends toward a water ecological index, a water social security index, and water economic index.

In general, China’s integrated water security index still shows an overall upward trend. The year 2000 held the lowest water security index value of 0.249, while the highest value of 0.827 occurred in 2012. This period witnessed a growth rate of 232.1%. Slight drops occurred in 2003, 2006, 2009 and 2011, which is in line with the downward trend of the water environment security index. Thus, improving the water environment plays a crucial role in the future promotion of water security.
3.3.2. **The water security system’s coordination evaluation results and analysis.** Calculated with formula (5), the coordination indexes of the Chinese water security system over the years are displayed in Table 4 and figure 2. From 2000 to 2006, the coordination index of the Chinese water security system has steadily increased from -0.049 to 0.867. Nevertheless, in the following years from 2007 to 2012, the values of the coordination index showed a trend of fluctuations, which fell badly especially in 2009 and 2011 by 32% and 28.9%, respectively. These consequences demonstrate that, in the water security system of China, a coordinating development among water circulation, water environment, water ecology, water society, and water economy has basically come to pass. However, this positive tendency has not continued in recent years, which has not had a negative impact on the overall state of water security, but positive action is still required to make the appropriate corrections.

| Year | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| CI   | -0.04| 0.24 | 0.33 | 0.59 | 0.77 | 0.82 | 0.81 | 0.7  | 0.86 | 0.59 | 0.86 | 0.61 | 0.913|
| Growth rate(%) | -61 | 35.0 | 78.4 | 28.6 | 7.3 | -1.1 | -5.6 | 12.2 | -32.0 | 47.1 | -28.0 | 48.1 |

**Figure 2.** Variation of Chinese water security system’s coordination indexes from 2000 to 2012.

4. **Conclusions and Suggestions**

4.1. **Conclusions**

This paper develops a water security model and applies it to evaluate the state of water security in China, with macroeconomic data from 2000 to 2012, and several conclusions are reached, as follows:

- As a reflection of natural hydrological motion laws, the high and low volatility of the water cycling security index reflects the inherent natural attributes as well as the randomness of the
Although most elements of this subsystem are usually beyond human control, it can still be improved by strengthening the capability of monitoring natural incidents, and completing the mechanism of disaster protection to reduce losses and to enhance of the quality of China’s water security.

- In recent years, China’s water environment security has improved gradually. However, deteriorations have emerged in recent years that imply an increasing tendency toward instability. A focus on pollution control and emissions reduction is required, and the water environmental protection measures must be further implemented.

- In response to the growing economy and an increasing government awareness of environmental issues, ecological and water security construction have increased in China. As a result, in China, over the last few years, water ecological security has been well developed; moreover, the ability to preserve water security and economic support have continuously risen.
- Overall, China’s water security has tended to improve, which results in an increase in vigorous regulations in the recent years. However, coordination among natural conditions, the ecology, the environment, society, and the economy still needs further consolidation.

4.2. Countermeasures and suggestions

According to the above study, some countermeasures should be taken to resolve the problems that were revealed in the empirical water security evaluation presented here, to further maintain momentum to improve Chinese water security.

- Enhancing the ability to monitor natural events and perfect the disaster protection mechanism.

  The power of nature should not be underestimated; the losses that are incurred due to natural forces can be enormous. However, such possible losses can be minimized by enhancing the capability of monitoring water-related natural phenomena, and constructing a set of systematic water hazard protection mechanism. Such actions will greatly help to reduce pressures on water security. Governments should provide more support to projects that aim to develop technologies for monitoring water-related natural phenomena, introduce advanced monitoring facilities, make clear the responsibilities of monitoring sites, and release all types of hydrodynamic monitoring information in a timely manner. Moreover, non-governmental organizations that monitor natural events should be encouraged to function at full capacity. In addition, various government departments that are responsible for water security should cooperate closely with each other, construct special platforms for the collection, analysis and sharing of hydrological information, and maintain flood control and drought relief engineering facilities on a regular basis. In this way, high-level water disaster protection mechanisms can be constructed. Finally, an improved system of managing the aftermath of water hazards must be built.

- Improve the institution of water environment protection, and implement various measures to renovate the water environment

  The fact that water environment security plays the most important role in a water security system makes water environment protection the key to maintaining water security. China has taken numerous actions to renovate its water environment, but they have not been fully operative due to insufficient enforcement. To resolve the problems that threaten water security to further improve the institution of
water environment protection and implement various measures to renovate the water environment, the existing laws and regulations to protect the water environment should be adjusted immediately in accordance with the requirements of the socio-economic development stage. In 2014, China passed a revised draft of Environment protection law, which put forward a higher standard of environmental protection. Therefore, corresponding adjustments should be made in the laws and regulations that are related to water resources, to highlight the norms of new environmental water laws. With regard to execution, governments are expected to strengthen the accountability mechanism of water environment protections. Penalties for behaviors that maliciously destroy the water environment should be strengthened, while proper awards should be given to individuals, companies, or organizations that make outstanding contributions to preserving the water environment. In addition, it is imperative to investigate the achievements of governments at all levels of water environment management, on a regular basis, to ensure that measures for water environment protection are being effectively carried out. In terms of supervision, the publicity of water-related laws and regulations should be expanded to strengthen the public’s environmental awareness and cognitive abilities. Further, special feedback channels need to be explored to encourage the public to supervise others’ water-related activities and government management.

- Coordinate natural environment and social economy and achieve sustainable development of water security construction.

Both the elements of the natural environment and social economy subsystems are organic components of the water security system. Achieving coordination of the development between the natural environment and the social economy will optimize the internal structure of the water safety system, which lays the foundation for water safety to achieve sustainable development. First, industrial enterprises that produce significant pollution need to be stopped, or given the option of making changes. Additionally, the agriculture industry should be properly educated in techniques of managing water pollution that result from sources such as chemical fertilizer. At the same time, it is of great significance for an evolving, environmentally friendly economy to support the development of green industries. Second, based on the rapid development of the economy, efforts should be made to intensify support for the construction of water security, bolster the construction of water conservancy projects such as laying urban pipe networks for cities and towns, and promoting the construction of rural drinking water engineering and water conservancy facilities. Third, economic and social development should positively nurture the restoration of the natural environment. Additional funds should be allocated for activities such as water resource exploitations and water environment management. Meanwhile, various modes of support, such as human and material resources, should be provided for water-related natural and environmental programs.

- Promote the innovation of water resources management systems, and consolidate the foundations for water security construction

The state of Chinese water security is affected by numerous factors such as climate, the country’s social, political and economic situation, and industrialization. Moreover, water resource management should guarantee the smooth operation of China’s water resource system, which should include good water security. In order to make the growing need for water security steady and continuous, it is imperative to accelerate the system’s innovation of water resources management. Efforts should be
made to transform the traditional governance model, with control at the core, into a modern one with
good governance as its goal, converting engineering technology control into comprehensive treatment
and establishing new structures and systems of water management. In the process of water resource
management, the relationship among government, market, and society should be reconsidered. This
relationship should be a circular and interactive one, rather than one in which governments take a
one-way, leading, controlling position. Governments should shift from the direct allocation of water
resources to the implementation of water rights management and the formulation of standards for
water security indicators. Moreover, a unified management system of water resources and an efficient
inter-departmental coordination mechanism with clear responsibilities among high authorities should
be established. To improve public awareness, accurate information about water security should be
published. Democratic management and broad participation should be introduced at all levels, and
various online links that relate to water resources should be shared; such information will help to make
decision-making more scientific, democratic, and systematized by involving the general public. As for
the market, its capacity for allocation should fully exploited. It is suggested that a reasonable
mechanism of water price determination should be established that will open the water market
completely and achieve water’s value, capitalization, and industrialization. Finally, water resource
market system construction, and normative order should be completed. Through the above-described
measures of marketization, the required mechanisms of water security can be established.

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Appendix A. Process of using the AHP method to calculate weights
The rationale of the AHP method is to quantize the experiential judgments via comparisons between
comparative importance of different indicators on the same level on the basis of a hierarchical index
system. The concrete steps and calculation processes are as follows:

1. Build judgment matrix
Each level of principles, and its indicators, may have different weights in the measurements.
The relative importance is judged by a couple of industry experts. The method of Seaty1~9 is
adopted to define the judgment matrix A=aji(n*n). The element aij in matrix A is the
comparative importance measurement of indicators on the Row i and Column j.

| Measurement | Meaning                                      |
|-------------|----------------------------------------------|
| 1           | Two elements have the equal importance.      |
| 3           | The former is a little more important than the latter. |
| 5           | The former is obviously more important than the latter. |
| 7           | The former is far more important than the latter. |
| 9           | The former is extremely more important than the latter. |
| 2,4,6,8     | It means the middle value of the neighboring measurements. |
If the relative importance measurement of indicator i and j is $\alpha_{ij}$, then the relative importance measurement of indicator j and I is the reciprocal of $\alpha_{ij}$.

2. Calculation of weights and examination of consistency

- Calculation of weights: to calculate the geometric average of vectors in each row, conduct the normalization and consider the row vector to be the vector of weight.
- Consistency examination: Since the judger may be subjective to a certain degree, examination of consistency should be adopted to change subject one’s into objective descriptions and calculate the consistency indicators.

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$\lambda_{max}$ is the maximum eigenvalue of the judgment matrix. It should be compared with the values in the consistency indicators (recorded as RI) and then the CR(CR=CI/RI) can be figured out. When CR<0.1, is considered the consistency of the judgment matrix can be accepted. Otherwise the value of the judgment matrix has to be moderated.

Table A2. The Value of RI.

| n | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| RI| 0  | 0  | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 | 1.49 | 1.52 | 1.54 | 1.56 | 1.58 | 1.59 |

In this paper, each principle level and weights of indicators have been calculated out according to the AHP method. In the process of building a judgment matrix are seven experts in the research field of water security—Wu Xinmu, Xia Jun, Ning Yuan, Chen Jin, Fu Chun, Wang Shuyi and Wang Xianjia. They were invited to judge the relative importance of each indicator according to the principles of Seatyl~9 measurement and their judgment results are summarized. Eventually, the level of principles and weights of the indicators have been calculated using the previously described AHP method.

Appendix B. Values of water security index and sub-indices of China from 2000 to 2012

Table B1. Values of water security index and sub-indices of China from 2000 to 2012.

| Year | B1 | Growth | B2 | Growth | B3 | Growth | B4 | Growth | B5 | Growth | WSI | Rank | Growth |
|------|----|--------|----|--------|----|--------|----|--------|----|--------|-----|------|--------|
|      |    | (%)    |    | (%)    |    | (%)    |    | (%)    |    | (%)    |     |      | (%)    |
| 2000 | 0.6 | —      | 0.1| —      | 0.1| —      | 0.15| —      | 0.00| —      | 0.24| 13    | —      |
| 0.08 | 83  | 49     | 2  | 0      | 9  | —      | —   | —      | —   | —      | —   | —     | —      |
| 200 | 0.5 | -3.2 | 0.3 | 80.0 | 0.1 | 29.8 | 0.13 | -11.1 | 0.07 | —— | 0.30 | 12 | 21.1 |
|-----|-----|------|-----|------|-----|------|-----|-------|-----|-----|-----|-----|-----|
| 1   | 57  | 29   | 94  | 5    | 0   | 1    |     |       |     |     |     |     |     |
| 200 | 0.7 | 28.9 | 0.5 | 54.2 | 0.2 | 46.9 | 0.20 | 54.7  | 0.11 | 65.8| 0.42 | 9  | 42.7 |
| 2   | 18  | 07   | 85  | 9    | 6   | 9    |     |       |     |     |     |     |     |
| 200 | 0.5 | -29.8| 0.4 | -11.2| 0.3 | 5.3  | 0.25 | 20.1  | 0.18 | 57.9| 0.37 | 11 | -12.3|
| 3   | 04  | 50   | 00  | 1    | 3   | 7    |     |       |     |     |     |     |     |
| 200 | 0.3 | -22.7| 0.3 | -28.4| 0.5 | 69.3 | 0.35 | 41.3  | 0.54 | 197.4| 0.40 | 10 | 7.5  |
| 4   | 90  | 23   | 07  | 5    | 5   | 5    |     |       |     |     |     |     |     |
| 200 | 0.6 | 65.0 | 0.4 | 25.6 | 0.5 | 4.0  | 0.48 | 36.0  | 0.58 | 6.8 | 0.51 | 6  | 27.6 |
| 5   | 44  | 05   | 28  | 3    | 2   | 7    |     |       |     |     |     |     |     |
| 200 | 0.4 | -32.8| 0.3 | -3.4 | 0.5 | -2.1 | 0.47 | -2.4 | 0.62 | 6.8 | 0.46 | 8  | -10.1|
| 6   | 32  | 91   | 17  | 2    | 2   | 4    |     |       |     |     |     |     |     |
| 200 | 0.3 | -19.8| 0.5 | 30.6 | 0.6 | 21.2 | 0.52 | 10.4  | 0.65 | 5.1 | 0.51 | 7  | 10.4 |
| 7   | 47  | 11   | 26  | 1    | 3   | 3    |     |       |     |     |     |     |     |
| 200 | 0.6 | 96.4 | 0.5 | 7.1  | 0.7 | 23.2 | 0.58 | 13.2  | 0.67 | 2.7 | 0.63 | 4  | 24.7 |
| 8   | 81  | 48   | 71  | 9    | 1   | 9    |     |       |     |     |     |     |     |
| 200 | 0.2 | -59.8| 0.4 | -11.9| 0.8 | 9.2  | 0.61 | 4.9   | 0.88 | 32.3| 0.56 | 5  | -11.4|
| 9   | 74  | 82   | 42  | 8    | 7   | 6    |     |       |     |     |     |     |     |
| 201 | 0.8 | 204.2| 0.6 | 42.5 | 0.8 | -1.7 | 0.69 | 12.0  | 0.93 | 5.6 | 0.78 | 2  | 37.9 |
| 0   | 33  | 87   | 28  | 2    | 7   | 1    |     |       |     |     |     |     |     |
| 201 | 0.2 | -66.0| 0.6 | -9.2 | 0.9 | 11.4 | 0.78 | 13.7  | 1.8  | 1.8 | 0.65 | 3  | -15.6|
| 1   | 83  | 24   | 22  | 7    | 4   | 9    |     |       |     |     |     |     |     |
| 201 | 0.8 | 193.5| 0.7 | 22.7 | 0.8 | -11.0| 0.83 | 6.2   | 0.96 | 1.2 | 0.82 | 1  | 25.5 |
| 2   | 31  | 66   | 21  | 6    | 5   | 7    |     |       |     |     |     |     |     |

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