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CONFLICT RESOLUTION IN WATER MANAGEMENT

ANALYSIS OF THE IMPLEMENTATION OF THE TOTAL WATER USE CONTROL IN CHINA'S MOST STRINGENT WATER RESOURCES MANAGEMENT SYSTEM

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ABSTRACT

In view of the problems of water resource shortage and water use conflict, China's "most stringent water resources management system" (MSWRMS) has been implemented since 2012. The evaluation of the effects of the implementation of this MSWRMS, which will form the basis for the establishment of the assessment mechanism, is necessary and urgent. Taking the total water use in the "three red lines" of the most stringent water resources management system as the indicator, this study analyzes the water use of the agricultural, industrial, domestic, and ecological sectors in 30 provinces (cities and autonomous regions) of China in 2014 using anomaly analysis and value added analysis methods. The provinces of Guangdong, Anhui, and Qinghai are selected as representatives of the eastern, central, and western regions of China, respectively. Analysis is conducted based of the total water control management system and relevant measures for the implementation in the typical provinces in 2014. The results show that the most stringent water resources management are implemented well in the three provinces through actively relevant policies. In addition, this study uses the ARIMA (Autoregressive Integrated Moving Average) model in SPSS (Statistical Product and Service Solutions) to build an optimal model of water use in China, and to thereby simulate and predict change trends of the water use volume for the country as a whole as well as for different sectors. The results obtained in this study will provide a reference for the development, adjustment, and further implementation of the objectives of the MSWRMS in China.

Keywords: Most stringent water resources management system; total water use; ARIMA model; water use forecast.

1 INTRODUCTION

With the acceleration of urbanization and industrialization, water resources scarcity is becoming very serious. Although the total amount of water resources in China is relatively high, the per capita possession is small and regional distribution is uneven. Water demand for production and consumption is increasing, resulting in serious shortage of water resources. There is an urgent need to strengthen the management of water resources and promote its sustainable utilization. China adopted the "most stringent water resources management system" (MSWRMS) in 2011 (Wang, 2011). The central document No.1 and central water conservancy work meeting formalized the implementation of the MSWRMS. The system identifies three areas of control, also referred to as the "three red lines", which include the development and utilization of water resources (total water use control), efficiency of water use control, and water pollutant limits in the water function zone (Yang, 2014). In 2012, the State Council officially issued its opinion on the implementation of the MSWRMS, and initiated comprehensive deployment and specific arrangements to enforce this system. In 2013, the State Council issued the implementation of the MSWRMS assessment approach, to assess its implementation in the provinces (municipalities and autonomous regions). Therefore, scientific evaluation of the implementation of the MSWRMS in 2014, that summarizes regional total water use, regulation mechanism, and their success and deficiencies will provide scientific basis and technical support for further stricter management policies, and have important reference value (Ministry of Water Resources, 2014). For purpose of analysis in this study, China was divided into "three zones", namely, eastern, central and western China, and a typical area representative of each zone was selected. The paper analyzes the current situation of water use under the MSWRMS in China in 2014, and briefly discusses the causes of large changes in water use in various provinces.

2 METHODS

2.1 Study area and data

The paper collected China Water Resources Bulletin data (including total water use data and water use data of different sectors) for all 31 provinces of China from 2000–2014 (China Water Resources Bulletin, 2000-2014). The paper also collected 2014 self-inspection reports of the MSWRMS for all provinces excluding the Xinjiang autonomous region, as Xinjiang did not participate in the 2014 assessment. The study's evaluation is mainly based on regional self-examination reports. This paper analyzed the implementation of the total water use index specified in the MSWRMS both at the national and regional levels. In addition, this paper also analyzed the implementation status of the MSWRMS through a detailed literature survey, internet information retrieval, field investigation, and on-the-spot investigation of relevant issues at the grassroots units.

2.2 Anomaly analysis and value-added analysis

Anomaly is the difference between a certain value and the mean value in a series of values. Anomaly analysis method is commonly used in hydrological and meteorological analysis. This paper, based on the water use data of the provincial administrative regions, used the method to analyze water use in 2014 and compared it with the average water use from 2000 to 2014. The formula is as follows:

$$a_{2014} = w_{2014} - \frac{\sum_{i=2000}^{2014} w_i}{15} \qquad [1]$$

where, a_{2014} is the anomaly of water use for a certain province in 2014, w_{2014} is the water use in that province in 2014, the last item is the average value of water use in that province during the 15 years from 2000 to 2014.

Value-added refers to a series of numerical values between two data points, and can be positive or negative. In this paper, the value-added analysis method was used to analyze the change in water use in a certain area in 2014 compared to 2013. The formula is as follows:

$$v_{2014} = w_{2014} - w_{2013} \qquad [2]$$

where, v_{2014} is the increase of water use for a certain province in 2014, w_{2014} is the water use in that province in 2014, w_{2013} is the water use in that province in 2013.

2.3 Autoregressive Integrated Moving Average model

Autoregressive Integrated Moving Average (ARIMA) model, also called Box-Jenkins model is a time series prediction method proposed by Box and Jenkins in the early 1970s. ARIMA model firstly transforms non-stationary time series into stationary time series, and then establishes the model by regression analysis of lagged value of the dependent variable and present value and hysteresis value of random error. The ARIMA for differential autoregressive moving averages is represented as ARIMA (P, D, q), where, P is autoregressive item, D is the differential number when the time series is stationary, and Q is the moving average number.

The expression for the ARIMA model is shown in Eq. [3]:

$$y_t = \varphi_1 y_{t-1} + \varphi_2 y_{t-2} + \cdots + \varphi_p y_{t-p} - \theta_1 \varepsilon_{t-1} - \theta_2 \varepsilon_{t-2} - \cdots - \theta_q \varepsilon_{t-q} + \varepsilon_t \qquad [3]$$

where, y is time series, φ_p is autoregressive moving average coefficient, θ_q is theta epsilon coefficient, ε_t is white noise sequence; p is the autoregressive order number, and q is moving average order.

The ARIMA model is a data sequence that changes over time as a random sequence. Based on the autocorrelation analysis, the mathematical model is used to describe time series. When the model is successful, it can use past values of the time series to predict future values. In the aspect of prediction, ARIMA model not only considers the disturbance of data fluctuation to forecast results, but also considers the dependence of time series. Accuracy is high in short-term predictions. The model is a widely-used forecasting method. This paper uses ARIMA model in statistical software SPSS (Statistical Product and Service Solution) to forecast water demand and water use trends in the future.

3 REGIONAL AND NATIONAL WATER USE ANALYSIS FOR 2014Total amount of water use

According to the 2014 MSWRSM self-inspection reports collected for all the provinces, the total water use was 549.92 billion m^3. Agricultural water use was 331.36 billion m^3, accounting for 60.26% of the total consumption; industrial water use was 134.77 billion m^3, accounting for 24.38% of the total; amount of water for life was 75.37 billion m^3, accounting for 13.70% of the total; and ecological water use was 8.62 billion m^3, accounting for 1.57% of the total.

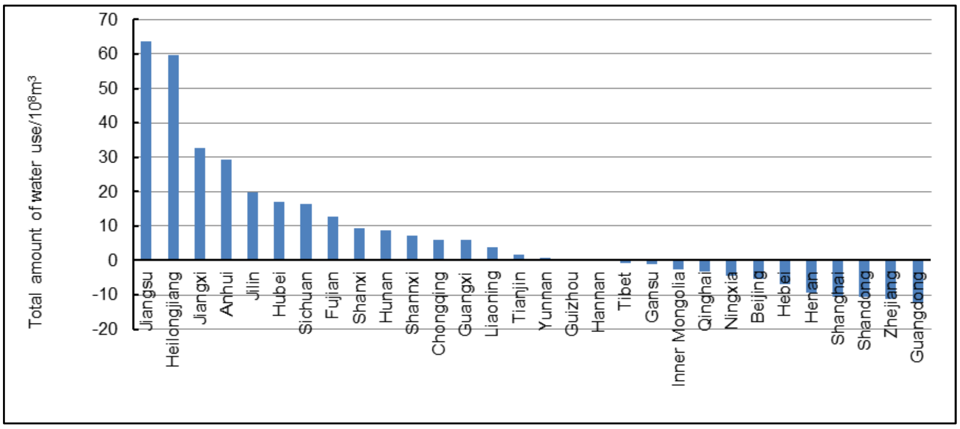

Figure 1. Anomaly map of total water levels in the provinces for 2014.

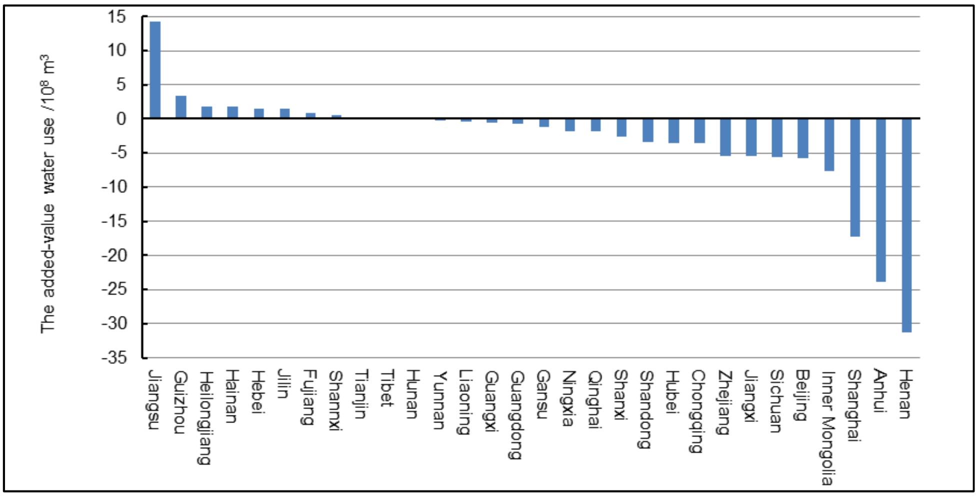

Figure 2. Value-added map for the total amount of water use at the provincial level for 2014.

Anomaly analysis revealed that the total amount of water in 2014 in 18 provinces including Jiangsu, Heilongjiang, and Jiangxi exceeded the average level of previous years (Ayiguli et al., 2015). The remaining 12 provinces recorded lower than average levels (Figure 1). Thus, the analysis highlighted that the MSWRMS results were effective (Figure 2), and water use was reduced by over 500 million m^3 in the provinces of Zhejiang, Jiangxi, Sichuan, Beijing, Inner Mongolia, Shanghai, Anhui, and Henan, indicating that these provincial regions showed significant improvement in water savings in 2014. However, Jiangsu recorded the highest increase in water use in 2014 with more than 1.46 billion m^3.

Figure 3 illustrates the sector-wise proportion of total water use in the provincial regions in 2014. The regions where agricultural water use accounted for more than 70% were: Heilongjiang, Hebei, Inner Mongolia, Gansu, Ningxia, Qinghai, Hainan, and Tibet. Regions with less than 50% were Jiangsu, Zhejiang, Chongqing, Shanghai, and Beijing. In Zhejiang, Jiangsu, Chongqing, and Shanghai, the proportion of industrial water use was much higher than other provinces and cities, accounting for over 40%, Beijing's recorded the larger proportion of domestic water, accounting for more than 50%. However, the ecological water use was average for the provinces (municipalities and autonomous regions).

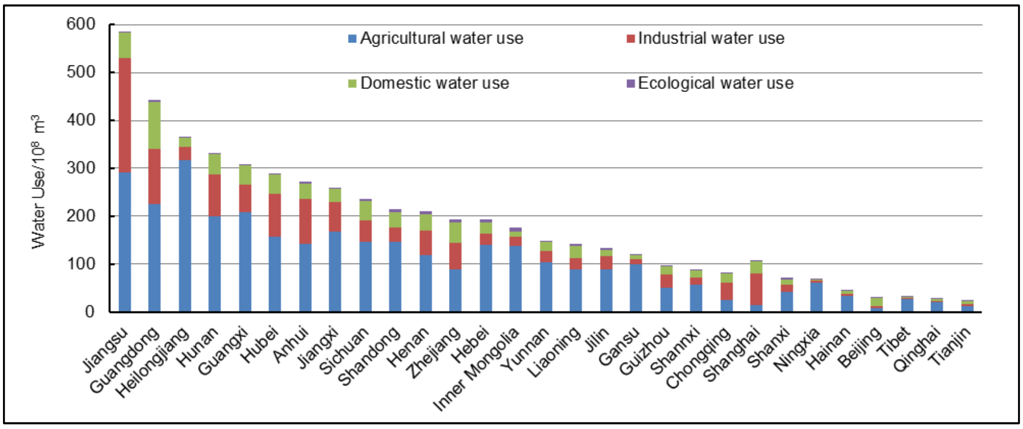

Figure 3. Water composition chart of each province based on 2014 self-examination reports.

2.1.1 Agricultural water use

Agricultural water includes farmland irrigation, forest and grassland irrigation, and fish and livestock water replenishment. Irrigation water use is related to climatic conditions and geographical location and affected by crop planting structure, irrigation methods, irrigation area, management technology, soil conditions, and engineering facilities. The amount of water used by forest, animal husbandry, and fishery mainly depends on the forest area, number of livestock, and scale of fisheries (Zhu, 2009). A comparison of the agricultural water use and water resources bulletin data for 2013 and 2014 reveals that agricultural water use increased in 10 provinces and decreased in 20. There are two main reasons for the change of agricultural water use. Firstly, some areas such as Liaoning, Shandong, Ningxia, Henan, Hubei, and Gansu experienced drought and low precipitation in 2014 and recorded higher consumption of agricultural irrigation water. Additionally, in some areas, such as Shanghai, Zhejiang, Jiangxi, Anhui, and Qinghai agricultural irrigation water is insufficient without supplemental irrigation due to weather conditions. Secondly, the implementation of water-saving irrigation measures in 2014 facilitated the adjustment of agricultural planting structure, development of new agricultural water-saving irrigation areas and facilities, an effective utilization coefficient of irrigation water and irrigation benefit in some provinces such as Tianjin, Jilin, and Gansu and others.

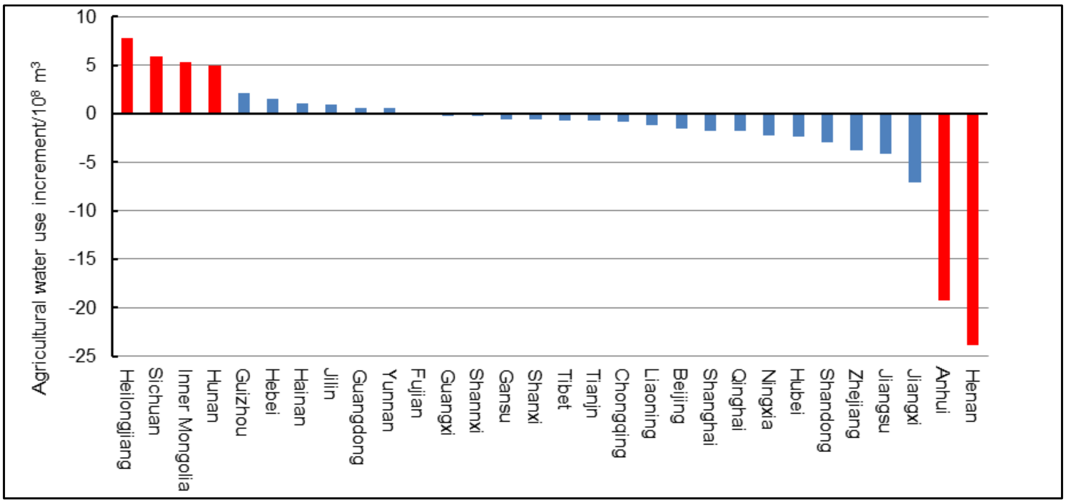

Figure 4. Agricultural water increment map for 2014.

2.1.2 Industrial water used

Industrial water refers to new water intake by industrial and mining enterprises during production processes such as manufacture, processing, cooling, air conditioning, purification, washing, and others, and excludes internal recycling of water (Yang and Cui, 2003). Changes in industrial water use are closely related to national economic development and industrial production structure, level, water resources situation, water management, and water saving. A comparison of the industrial water use and water resources bulletin data for 2013 and 2014 reveals that in 2014 industrial water use had increased in eight provinces and decreased in 22 provinces. There are several reasons for industrial water changes. Firstly, the fire (nuclear) power enterprise underwent several adjustments, such as new sites, closures, and internal unit transformation. Secondly, industrial structure underwent changes as a number of high energy consuming and heavy polluting industrial enterprises closed down. Thirdly, promotion of energy-savings, emission reduction, and clean production; upgrade to water-saving technologies in the enterprise, continuous improvement in industrial water reuse, and reduction in water use also contributed. Lastly, climate change may have played a significant role. In 2014, the local area in the north recorded industrial water use reduction due to abundant precipitation and increase in hydroelectric power generation. Consequently, thermal power output reduced, reducing water use.

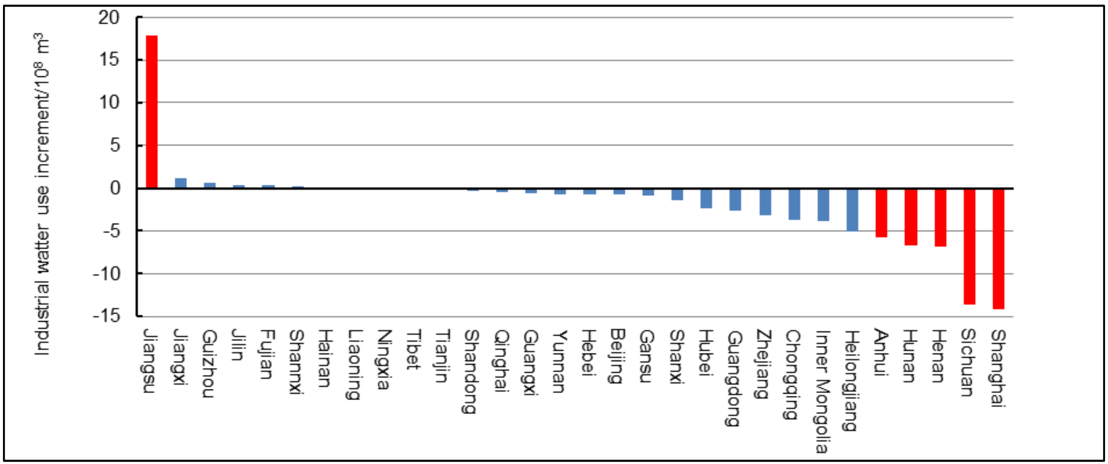

Figure 5. Industrial water use – value-added map for 2014.

2.1.3 Water use for domestic life

Water for living includes urban and rural domestic water, of which urban living water includes water utilized by residents and public water (including third industries, construction, and other water uses). There are many factors affecting urban water use, such as temperature, water resources, population, health conditions, living standards, etc. A comparison of the industrial water use and water resources bulletin data for 2013 and 2014 reveals that water use increased in 24 provinces, and reduced in six. Among them, Yunnan saw a reduction in total water use due to better technology and review of domestic water use; Gansu and Shanxi accounted for one-third of the domestic water use decrease due to migrant workers and other reasons; Water use increased in Shanghai due to high temperature in the summer.

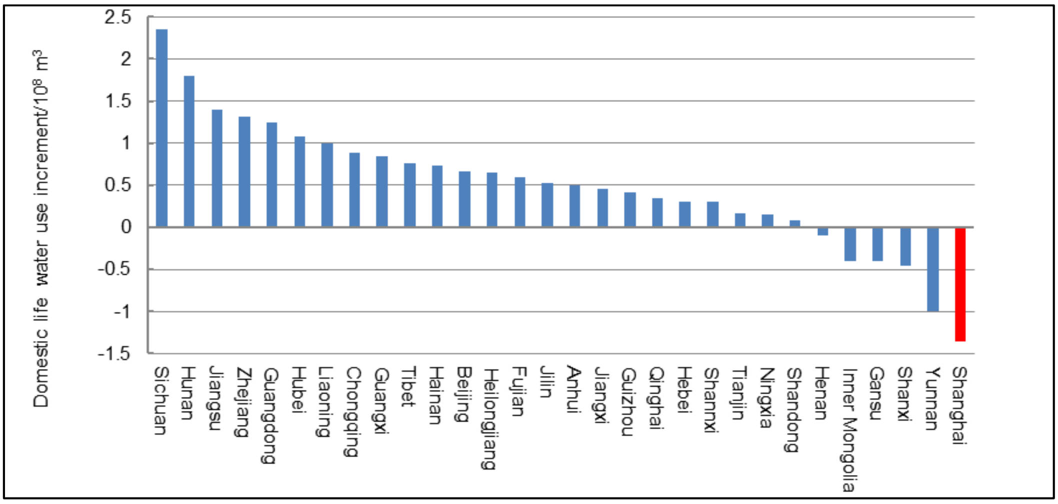

Figure 6. Domestic life water use - value-added map for 2014.

2.1.4 Ecological water use

Ecological environment water includes rivers, lakes, wetland water replenishment, and does not include natural precipitation and runoff water. A comparison of the ecological water use and water resources bulletin data for 2013 and 2014 reveals that ecological water use increased in 15 provinces in 2014, and decreased in 15. Beijing and Inner Mongolia registered notable changes, while other provinces changed little. There are two main reasons for the change in ecological water use. Firstly, climate change played an important role as continuous drought persisted in some areas, while the improvement in water resources in other areas eliminated the need for artificial replenishment. Secondly, in accordance with the Ministry of water resources "project total water statistics (Trial)" (2014), the statistical caliber of ecological environment water use was redefined.

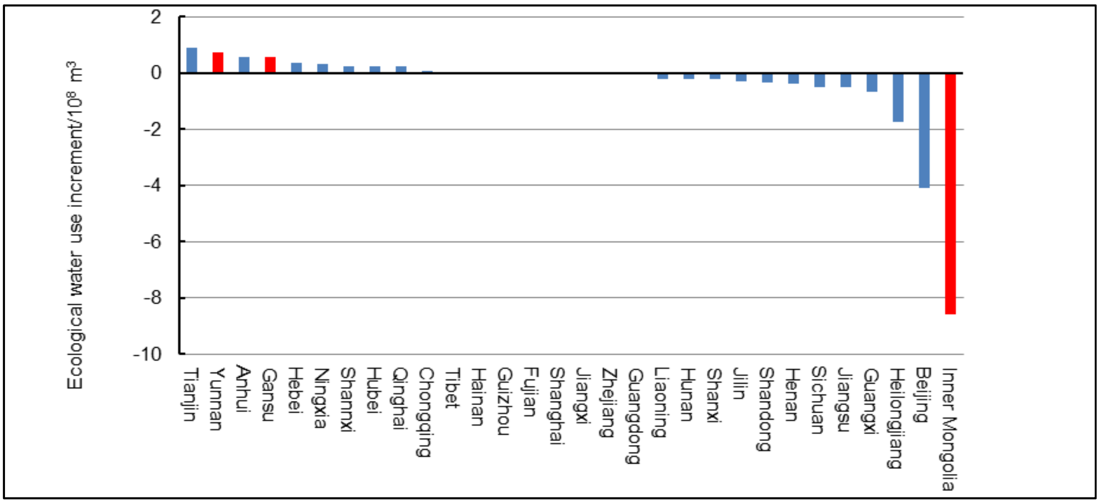

Figure 7. Ecological water use increment map in 2014.

3.2 Regional water use status

China's regional division is very diverse. With the development of economy and policy orientation, economic development is closely related to geographical location. In this paper, the commonly used "three zones" division method, as referred by China's water resources bulletin, was employed to divide the provinces and autonomous regions of the country into eastern, central, and western regions (Table 1).

Table 1. Division of eastern, central, and western zones in China.

Region	Province (Municipalities and Autonomous Regions)
Eastern China	Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan
Central China	Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan
Western China	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunan, Tibet, Shannxi, Gansu, Qinghai, Ningxia, Xinjiang

According to the 2014 report data, available water resources in the east, central, and western regions were 218.67 billion m^3, 192.97 billion m^3, and 13.28 billion m^3, respectively and corresponding total water use ratio was 39.76%, 35.09%, and 25.15%, respectively. From the administrative point of view, the proportion of domestic water was high in the east and low in the central and western regions. The proportion of industrial water was high in the eastern and western regions and low in the central regions. The proportion of agricultural water was low in the eastern region and high in the central and western regions. Ecological environment water was nearly the same in all regions. The total amount of water in the eastern region was significantly higher than the central and western regions, which is closely related to the economic level of the eastern region.

Some representative regions were decided considering the integrity of MSWMRS inspection report, the representativeness of the geographical location and economic situation. The eastern region plays a leading role in Chinese economic development, so Guangdong Province, the economically top-ranked province in China, was selected as one typical area. The central region is located inland, connecting the eastern and western region economically, and Anhui Province was chosen as the typical area for its typical central-region characteristics. The western region is on high elevation with abundant resources, so Qinghai province, which has the reputation of "roof of the world", was chosen as the typical area.

3.2.1 Guangdong

The total water use in Guangdong was 44.25 billion m^3 in 2014, recording a decrease of 70 million m^3 since 2013. The MSWRMS gradually implemented strict planning and management of water resources and demonstration, an organization that deals with planning of water resources, water projects, active assessment of water resources by provinces, active promotion of local water planning, and strict control of total water intake. Acceleration of the main river basin water allocation and coordination of Dongjiang, Beijiang River, and Hanjiang River basin water diversion project was undertaken at the provincial levels. Additionally, county-specific targets for water control, strict implementation of water permits, water intake control indicators, suspension of new water projects, and new water restrictions for approval of construction projects were enforced. Strict compensation for the use of water resources, provincial implementation of a standard unified water resources fee collection, and regulation of the collection of the fees were ensured. Strict implementation of total quantity control of groundwater exploitation, groundwater water as assessment MSWRMS indicator,

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delineation of groundwater overdraft, improved unified scheduling of water resources, implementation of power dispatching, basin water resources compliance, and unified scheduling requirements were also included.

3.2.2 Anhui

The total water use in Anhui was 27.21 billion m^3 in 2014, recording a decrease of 2.39 million m^3 from 2013. The water-saving effect of the MSWRMS was good. In Anhui Province, the MSWRMS measures included strict planning and management of water resources and demonstration, establishment of planning and evaluation system for water resources, market five-year plan with water resources conservation as a key content, and preparation of a special chapter on water resources in industrial park planning and city planning and development zone. Additionally, strict control of the water intake, establishment of total water control index system: deployment of water rights system research, assessment of circulation of water rights, strict implementation of water permit approval, strict approval of water permits, water use to reach or stay within the control index, suspension of approval of new water projects, regulation of total amount of water for control target areas, examination and approval of construction projects, strict limitation of additional water use, water permit renewal based on approval, strengthened supervision, and management of water license according to law were enforced. In terms of compensation for the use of water resources, water resource fee collection standards for hydropower and thermal power generation were improved. Water resource fee collection management was used for the protection, conservation, and management of water resources. Strict implementation of total control of groundwater extraction, management, and protection was conducted in Huaibei, Huainan, Chuzhou, Fuyang, Bengbu, and other cities to actively proceed closing the water well. In the term of strengthening the unified scheduling of water resources, development of a series of water resource scheduling programs and implementation of inter administrative regional water resources unified scheduling were undertaken.

3.2.3 Qinghai

The total water use in Qinghai was 2.63 billion m^3 in 2014, which was a decrease of 190 million m^3 from 2013. The implementation of the MSWRMS was good. In Qinghai Province, the MSWRMS measures included strict planning and management of water resources and demonstration, establishment and gradual improvement of water resource planning system, active planning of water resources assessment, and strict implementation of measures. Strict control of the total water intake at the province, city (state), and county level with "three red lines" control index system, exploration of water rights system, and further improvement of the efficiency and benefits of water resources utilization were undertaken. To ensure strict implementation of water permits, requirements for water permits were clarified, implementation of water license management, municipalities (state) check of water permits, and strengthening of the water permit ledger entry were enforced. Water resources fees were adjusted. Other measures included strict groundwater management and protection, improvement of management of groundwater centralized mining area and self-owned water sources, and promotion of shutdown of self-owned groundwater sources, strengthening the unified scheduling of water resources, development of water resources regulation program, emergency schedule planning, strict implementation of unified water resources management in river basins.

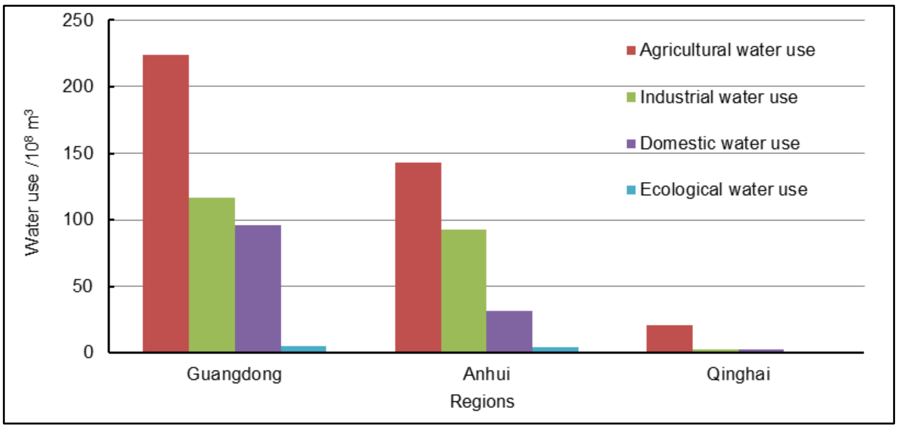

Figure 8. Water use in typical regions.

4 SIMULATIONS AND PREDICTION OF WATER USE USING ARIMA MODEL

Water use was predicted by the ARIMA model in SPSS software using the water use data of China Water Resources Bulletin (2000-2014) (Ji et al., 2008). Based on the existing data, the total amount of water used by various sectors was used to predict water use by 2020; and the ecological water use in the 2003 after the "China water resources bulletin" began to statistics alone, and ecological water use was not used in the total water control index, and therefore it was not used for simulation (Jiang and Fan, 2004).

4.1 Total water use

After adjusting the model, the total water use simulation model was ARIMA (2,2,2). The simulation and prediction results are shown in Figure 9. The simulation results and measured values fit well, and the simulated average relative error is about 1.47%. The difference was high in 2004 but the error was very small for the other years. Especially after 2007, relative errors were less than 1%, which indicated that the model fitting results were reliable and the model can be used to predict total water use trends. After 2004, China's water use significantly increased, but due to the implementation of the MSWRMS total water use in 2014 has declined. It is expected that water use will continue to increase in 2015, and this is closely related to the development of national economy. China's total water use predicted in 2020 would be 6280 billion m^3, which will reach the State Council’s assessment requirement of national total water control target of 6700 billion m^3 by 2020.

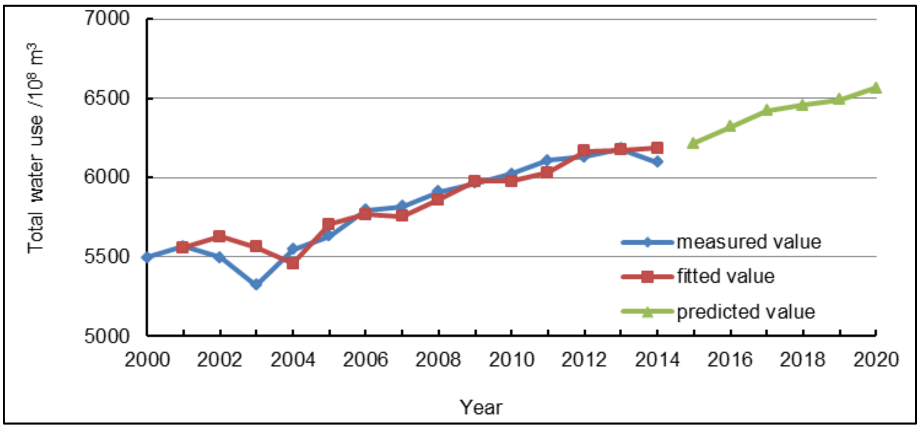

Figure 9. Simulation and prediction of total water use.

4.2 Agricultural water use

After adjusting the model, the model of agricultural water use simulation was ARIMA (2,2,3), and the simulation and prediction results are shown in Figure 10. The simulated and measured values fit well, and the simulated average relative error was about 2.31%. Especially after 2007, the relative error was less than 1%, which indicates that the model fitting is reliable. The effect of bad fitting effect before 2007 was due to poor stability of the data, which affected the prediction accuracy throughout the time series. Therefore, ARIMA (2,2,3) can be used to predict the amount of water used for agriculture. From the simulation and prediction results, steady upward trend of China's agricultural water use is predicted for 2015, and the upward trend will be more obvious. The national agricultural water use will reach 467.2 billion m^3 by 2020.

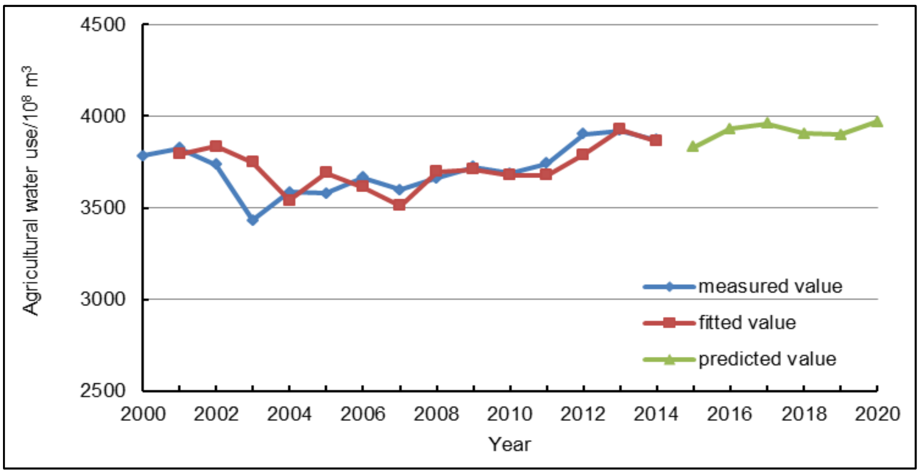

Figure 10. Simulation and prediction of agricultural water use.

4.3 Industrial water use

The industrial water use time series was different. The time series increased stably three times before 2007, with significant fluctuations after 2007. Due to shorter time series, multiple difference branches affected the accuracy of prediction, so d was 3. The final ideal model was ARIMA (3,3,3). The results of simulation and prediction are shown in Figure 11. The average relative error of simulation was about 2.18%, and the fitting effect was good before 2007. Due to the fluctuation of water use after 2007, error precision was reduced. However, the mean of absolute error was still less than 3%, which indicates that the model fitting result was reliable. Therefore, ARIMA (3,3,3) can be used for the prediction of industrial water use (Cao, 2014). From the simulation and prediction results, industrial water use showed a significant upward trend before 2007, and fluctuations before 2020. The national industrial consumption is expected to reach 105.4 billion m^3, showing a rising trend of volatility, in 2020.

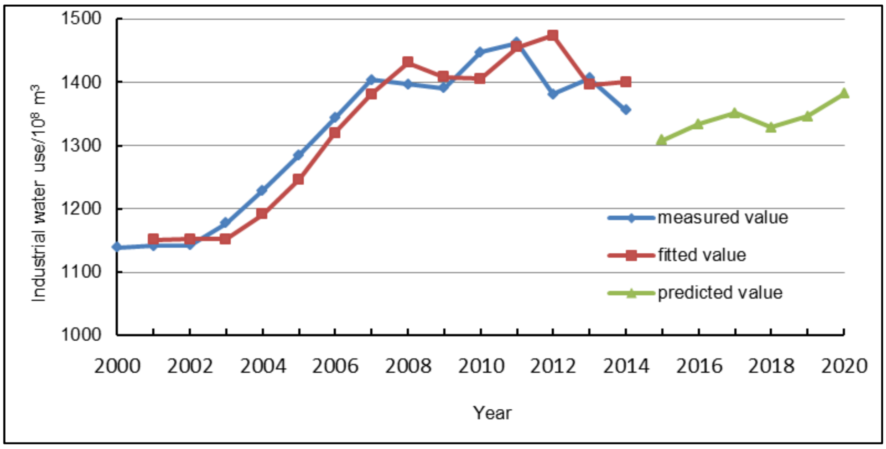

Figure 11. Simulation and prediction of industrial water use.

4.4 Water use for living

After model adjustment, the model of life water use simulation was ARIMA (3,1,1), and the simulation and prediction results are shown in Figure 12. The simulated and measured values fit well. In 2012, the difference was large as daily use of water was larger, affecting the accuracy of the simulation. However, the error was very small in the other years. The fitting error was 1.54%, which indicates that the model fitting is reliable. Therefore, ARIMA (3,1,1) can be used to predict the daily use of water. From the prediction results, in addition to 2012 water use decline, the rest of the years showed a rising trend. Domestic consumption is expected in to reach 88.1 billion m^3 in 2020, showing a clear upward trend. The results show that with the improvement in China's economic level, domestic water use will continue to rise.

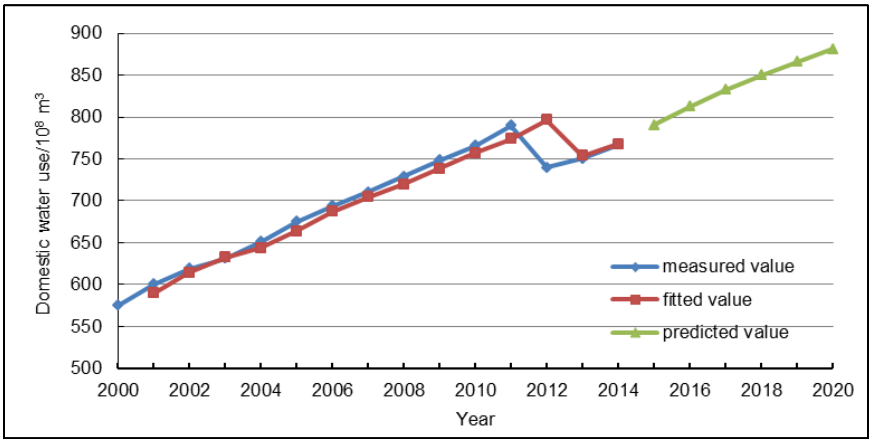

Figure 12. Simulation and prediction of domestic water use.

5 DISCUSSIONS

From the above, we can see that the water consumption in the future will show an upward trend. Agricultural water use will increase along with the irrigation area, but because of the promotion of agricultural water-saving technology, the agricultural water saving prospect is good. Industrial water use will also be in rapid growth with the increase in industrial output value, but due to the extensive application of water-saving measures and water conservation management, the water consumption per unit of industrial added value will gradually decline. In terms of domestic water use, the population is increasing, and the living standard is improving, so the water demand for domestic life is increasing. Although the ecological water is not in the MSWRMS, with more and more attention paid to ecological civilization in the country, the guarantee of ecological environment water use is the need for our own survival and for the sustainable development of economy and the society. Due to the limited data and limited research level, this study has some shortcomings and needs further exploration. For that the MSWRMS inspection schedule limited the availability of water quantity assessment data, whether the statistical caliber is consistent and the authenticity of reported water use data are unclear, and the analyses are still limited to the reported data. ARIMA has generally high prediction accuracy, but there are constraints neglected in this study for limited data, which should be included in future applications.

6 CONCLUSIONS

An assessment of China's MSWMRS effectiveness for total water control was conducted for 2014. Methods included distance average analysis, value-added analysis, provincial totals of control indices of total water use, and total water use by various sectors in 2014. It is evident that the water use sectors basically met the most stringent water management requirements. Using the ARIMA model, China's water use over the past 15 years was simulated, and water use in 2020 is predicted to reach 628 billion m^3. In this paper, the implementation of water quota by the strictest water resources management system was analyzed, which will provide valuable reference for future management programs and research.

ACKNOWLEDGEMENTS

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THE GENERATION POLICY OF HYDROPOWER OF THE BE RIVER BASIN TO MITIGATE THE WATER SHORTAGE

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ABSTRACT

There are four reservoirs in a series located on the Be River of the Dong Nai River Basin in Southern Vietnam. The primary purpose of the three upstream reservoirs is hydropower generation; however, the fourth one plays a vital role in water supply and irrigation. The management of the water resources related to this river to date has been restricted mostly to hydropower. Nevertheless, the increasing water demands for households, industry and agriculture may potentially be met by improved water management policies. This study, therefore recommends a better strategy for hydropower generation to increase the amount of energy that will be generated and to mitigate the water supply shortage. The GWASIM model (Chou and Wu, 2010) is applied in this paper, which is based on Network Flow Programming, to simulate the daily hydropower generation and water resource allocation for the system. Regulation strategies for hydropower generation of cascade reservoirs were evaluated and compared. Strategies and scenarios of different water allocation priorities and rations were also simulated and compared. This study provided a valuable policy to improve the performance of water supply and hydropower generation of the cascade reservoirs of the Be River Basin. When domestic and industrial demand has the first priority access to water, and energy generation comes second, the shortage index of all demands was reduced and the hydropower generation was essentially the same in both strategies. This improved strategy for operating cascade reservoirs can improve energy production from hydropower as well as water supply for domestic demand and irrigated food production.

Keywords: Hydropower; water supply; cascade reservoirs; Be River Basin; simulation.

1 INTRODUCTION

Water is one the most important resources and irreplaceable for the maintenance of life. However, pressures related to overpopulation, urbanization and industrialization have serious impact on water resources. Vietnam is located in the tropical monsoon and faces various disasters. Drought is one of the most frequent natural disasters and which has been becoming more severe due to the impact of climate change. This urgent situation requires national attention toward suitable solutions to protect and develop the sustainability of critical water resources

The Dong Nai River Basin is the largest national river basin and the economic center of the country in southern Vietnam. This river basin ranks second in hydropower potential in the country and in 2000, total installed hydropower capacity reached 1,182 MW (Ringler and Nguyen, 2004). The average density of the river network is about 0.56 km/km2. Figure 1 shows a map of the Be River Basin with four reservoirs which are Thac Mo, Can Don, Srok Phu Mieng and Phuoc Hoa. The Be River Basin has hydropower potential with three hydropower plants. Furthermore, this catchment is an important water resource which provides water for urban water supplies, agriculture, and the industry in not only Be River basin but also Sai Gon River basin. The conflicting objectives lead to significant challenges, so it is necessary to have comprehensive solutions for this river basin. Moreover, the increasing water demands for household, industry and agriculture may be satisfied by improved policy of water management. In order to improve the existing situation, studies on generating strategy of hydropower are needed.

2 LITERATURE REVIEW

Many studies have concerned reservoir problems and also cascade reservoirs problems about planning and operation. It is difficult to give the best solution for water management. A reservoir system is, in general, made to meet many purposes, such as, water supply (domestic, industrial and irrigation), flood control, hydropower production etc (Ko et al., 1992). Studies vary in several ways, including the objective optimized, time horizon for optimization (long- vs. short-term), system size and configuration, and the representation of uncertainty (Olivares, 2008). Some studies concerned about operating rules such as optimal upper and lower rule curves as studied by Rani and Moreira (2010) optimized the decision variables studied as by Fang et al (Fang et al., 2014). Operating rules are always identified using either fitting or simulation-based optimization methods (Rani and Moreira, 2010; Celeste and Billib, 2009). Simulation-based optimization methods are one of the most important and efficient methods of deriving reservoir operating rules within an implicit stochastic optimization framework (Rani and Moreira, 2010; Celeste and Billib, 2009). Deterministic optimization techniques, including linear programming, nonlinear programming and dynamic programming, can be implemented to produce samples for fitting (Rani and Moreira, 2010; Labadie, 2004; Yeh, 1985).

Hydroelectricity is a renewable energy source that has been exploited in many countries, so the scheduling optimal hydropower problem has been studied. To solve the problem of scheduling optimal hydropower, several hydropower optimization techniques have been developed. These techniques can be classified into two main categories. Firstly, mathematical programming techniques, which are applied to quantitative information with well-structured algorithmic processes, such as network flow optimization, linear programming, stochastic linear programming, nonlinear programming and dynamic programming (Fu et al., 2011). The second category is heuristic programming techniques. Moreover, simulation is a modeling technique that is used to approximate the behavior of a system on a computer, representing all the characteristics of the system largely by a mathematical or algebraic description (Yeh, 1985). Some study combined the simulation model and optimization model to get an optimal solution. Chen et al. (2013) proposed a simulation-based optimization model of dynamic control of the flood level water level that made an effective trade-off between the flood control and hydropower generation of the Qingjiang River cascade reservoirs (Chen et al., 2013). In a study by Suiadee and Tingsanchali (2007), combined simulation-Genetic algorithm (GA) model software with graphical interface capability was developed to determine the optimal upper and lower rule curves and to optimal control of water quality, downstream of a reservoir (Dhar and Datta, 2008).

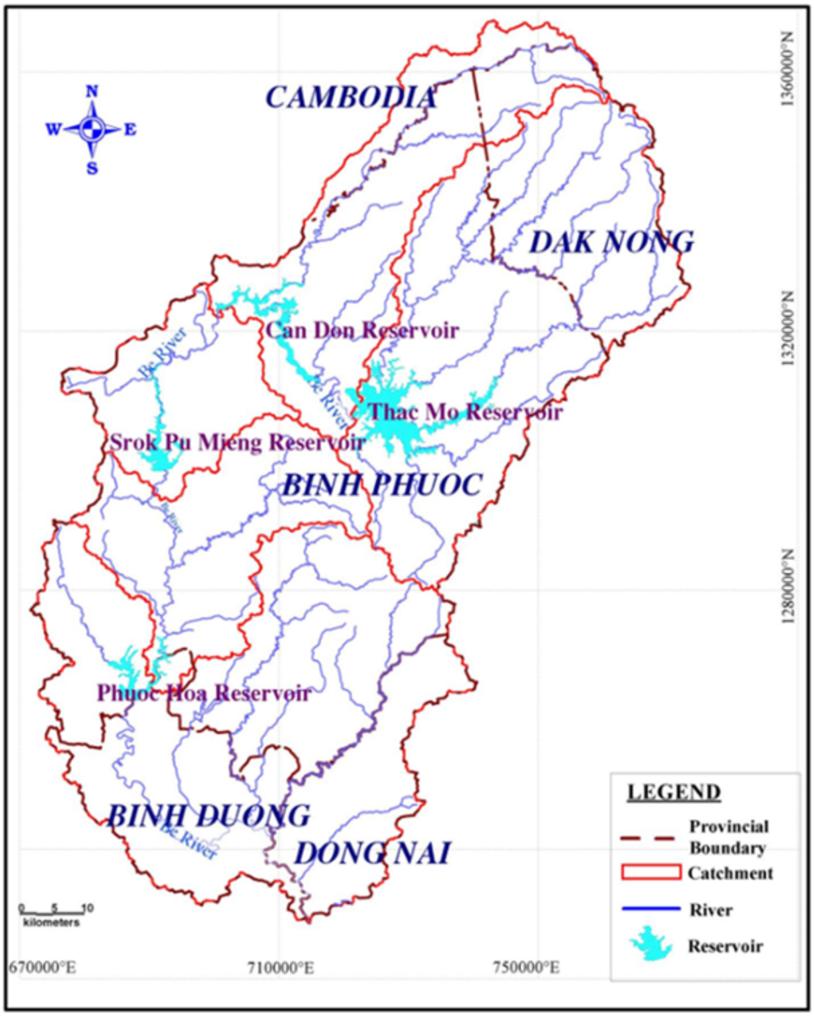

Figure 1. Location map of the Be River Basin.

3 METHODOLOGY

3.1 Generalized water allocation model

The generalized water allocation simulation model (GWASIM) was developed based on Network Flow Programming (NFP). It is a generalized water allocation model, referencing MODSIM of Colorado State University (Labadie, 2004) intended to resolve NFP problems by using the Out-of-Kilter Algorithm (Barr et al., 1974; Fulkerson, 1961). GWASIM sets cost coefficients on the artificial demand and storage arcs in order to guide the water allocation mechanism. The cost of arcs is not referring to the actual value of currency, but

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rather refers to some priority (or weighting factor). The cost of artificial storage or demand arcs in GWASIM is hypothesized as below:

$$c_i = -10000 + 10 \times prior_i \qquad [1]$$

where, ci = Unit shipping cost of artificial arci; priori = Priority of artificial arc i.

In analyzing the reservoir operations, GWASIM precisely simulates the operating rule, non-consumptive demand such as minimum environmental flow or power generation demand, reservoir evaporation and channel losses, as well as reduced yield in treatment plants. Since a regional water supply system can be schematically represented as a capacitated network flow, users can simulate the water allocation with GWASIM by preparing the data files and input hydrologic and demand data only, and without altering any computer code.

A well-designed water-shortage index plays an important role in water-resources planning and management. The GWASIM can simulate the yield of a regional system under specific design criteria, SI, with a simulation time step of 1 day:

$$SI = \frac{100}{N}\sum_{i=1}^{N}\left(\frac{DF_i}{D_i}\right)^2 \qquad [2]$$

where, SI = The shortage index; N = Total years of analysis duration; DFi = The water demand in the i-th year; Di = The shortage in the i-th year.

4 SIMULATION AND RESULTS

4.1 Simulation strategy

This study analyzed two strategies concerned with setting the first priority as hydropower generation, domestic and industrial demand. In strategy 1, water will be delivered to the hydropower plant demand first, and other water users will be satisfied later. This means that the main purpose of the Be River is to generate electricity. This objective has been applied to Be River basin to date. However, domestic demand is a special demand, which is one of the most important for survival of life. Domestic demand will be considered as the first target in the strategy 2. A decision made by the Prime Minister (No. 1590/QD-TTg dated October 9th, 2009) made industrial demand at the same level of priority as domestic demand. The strategies incorporated six different combinations of hydropower generation hours used to generate electricity. In six alternatives, the hydropower hours demand are: The original hour demand, reducing 10 %, 20%, 30%, 40% and 50% of the original hour demand.

4.2 Results

4.2.1 Comparison of priorities of allocating water

Strategy 1 is when the hydropower demand is the main priority, then the domestic and strategy 2 is when industrial demand is the first priority. The performance indices of strategy 1 are listed in Table 1. These tables give the information about shortage index and the potential water supply in severe drought years for all demand sites. In general, the drought for agricultural demand was more serious than it was for other water users and the Upstream, Thac Mo and Can Don demand sites have the largest shortage index. In table 1, the highest shortage index of the downstream area was 0.05 while in upstream areas, it was 7.71.

The obvious difference between the two strategies is the significant reduction in the shortage indexes of domestic and industrial demand in all sub-catchments in strategy 2. The Table 1 shows that the highest domestic and industrial shortage index for the Upstream and Thac Mo were 7.71 and 1.37 while those indexes were only 3.34 and 0.50, as shown in Table 2. As shown in Table 1, the highest water shortage in strategy 1 of the Upstream and Thac Mo demand sites was 12.15 and 4.76 respectively, while the highest indices were 7.34 and 4.28 in strategy 2, as shown Table 2. This was significant with regard to guarantee water supply for the most important water users.

4.2.2 Comparison of different rations

As mentioned before, a strategy has six alternatives which were considered in this study. The difference between the six alternatives is the reducing hour demand for hydropower demand. In general, the drought was less serious when hydropower generation hours were reduced, and the drought for agricultural demand was more serious than it was for other water users. The water supply increased sharply at the Thac Mo and Can Don agricultural demand sites in all scenarios from alternative 6 to alternative 1. For domestic demand, the water shortage decreased from 3.34 to around 0.29 in the Upstream and from 0.5 to 0.14 in Thac Mo (Table 3). For agricultural demand, the shortage index of Upstream and Thac Mo demand sites dropped sharply from near 7.3 and 4.28 4 to 1.42 and 0.78 in Strategy 2 (Table 3).

Table 1. Shortage index and the ratio of ratio of water supply to water demand of strategy 1.

Purpose	Demand sites	SI	The ratio of water supply to water demand in the 1st severe drought year	The ratio of water supply to water demand in 2nd severe drought year	The ratio of water supply to water demand in 3rd severe drought year
Domestic and Industry	Upstream	7.71	0.27	0.48	0.57
	Thac Mo	1.37	0.82	0.83	0.85
	Can Don	1.25	0.83	0.83	0.86
	SRPM	0.00	0.99	0.99	0.99
	Downstream	0.00	0.99	0.99	0.99
Agriculture	Upstream	12.15	0.10	0.52	0.52
	Thac Mo	4.76	0.72	0.72	0.73
	Can Don	2.79	0.74	0.75	0.75
	SRPM	0.05	0.95	0.97	0.97
	Phuoc Hoa	0.01	0.98	0.99	0.99
	Downstream	0.05	0.95	0.97	0.97
Others	Phuoc Hoa environment	0.10	0.93	0.95	0.95
	Water diversion	0.26	0.89	0.90	0.91

Table 2. Shortage index and the ratio of ratio of water supply to water demand of strategy 2.

Purpose	Demand sites	SI	The ratio of water supply to water demand in the 1st severe drought year	The ratio of water supply to water demand in 2nd severe drought year	The ratio of water supply to water demand in 3rd severe drought year
Domestic and Industry	Upstream	3.34	0.62	0.64	0.70
	Thac Mo	0.50	0.90	0.90	0.91
	Can Don	0.46	0.90	0.91	0.92
	SRPM	0.00	0.99	0.99	0.99
	Downstream	0.00	0.99	0.99	0.99
Agriculture	Upstream	7.34	0.46	0.55	0.67
	Thac Mo	4.28	0.73	0.74	0.75
	Can Don	2.65	0.75	0.75	0.77
	SRPM	0.05	0.95	0.95	0.96
	Phuoc Hoa	0.01	0.98	0.98	0.98
	Downstream	0.06	0.95	0.95	0.95
Others	Phuoc Hoa environment	0.11	0.93	0.93	0.94
	Water diversion	0.51	0.88	0.89	0.90

Table 3. Shortage index of each demand site in strategy 2

Purpose	Demand sites	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6
Domestic and Industry	Upstream	3.34	2.25	1.61	0.97	0.56	0.29
	Thac Mo	0.50	0.42	0.37	0.28	0.22	0.14
	Can Don	0.46	0.41	0.34	0.27	0.21	0.13
	SRPM	0.00	0.00	0.00	0.00	0.00	0.00
	Downstream	0.00	0.00	0.00	0.00	0.00	0.00
Agriculture	Upstream	7.34	5.74	4.37	0.00	2.06	1.42
	Thac Mo	4.28	3.44	2.57	3.04	1.04	0.78
	Can Don	2.65	2.01	1.41	0.83	0.51	0.38
	SRPM	0.05	0.05	0.03	0.02	0.02	0.01
	Phuoc Hoa	0.01	0.01	0.00	0.00	0.00	0.00
	Downstream	0.06	0.05	0.04	0.02	0.02	0.03
Others	Phuoc Hoa environment	0.11	0.10	0.07	0.04	0.05	0.16
	Water diversion	0.51	0.63	0.69	0.48	0.35	0.33

5 CONCLUSIONS

This study focused on reducing the water shortage of a cascade reservoir system of the Be River Basin of Vietnam by altering the reservoir operation in different hydropower generation policies. The GWASIM model for simulating water allocation was adopted to evaluate different policies while satisfying the requirement for generated energy. Two strategies, six alternatives were considered. With various generating hours of hydropower in a day, six alternatives were analyzed in each strategy. Under different strategies, the trade-off between water shortage and hydropower generation of this cascade reservoir system was obtained. The results showed that strategy 2 which used different water release rations had a less water shortage compared to strategy 1, which was an actual operation adopted. With respect to hydropower generation, the average annual energy has a stable value in all strategies.

In addition, the results also showed that the alternative of generating hydropower in which hydropower is generated with fewer hours in a day was better than the hydropower generation with original demand hours in terms of water supply and hydropower. The results demonstrated that the model could efficiently simulate the system performance of multipurpose cascade reservoirs and assist in decision-making for the improving of the performance of water supply and hydropower generation of the cascade reservoirs of the Be River Basin. The efficient operation of this system is the most important task of water resources management. In the next phase, optimization of the cascade reservoir operation may be carried out with not only joint rule curves but also the balance curves among the reservoirs.

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SCENARIO ANALYSIS FOR INTEGRATED WATER RESOURCES PLANNING AND MANAGEMENT IN AN URBAN AREA

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ABSTRACT

With the fast urbanization expansion, shortage of water resources and deterioration of water environment have become limiting factors of the social and economy development in some area of China. It is necessary to implement scientific as well as practical water resources planning and management measures to balance the contradiction between water supply and demand, which is crucial for regional aquatic environmental security and is the foundation of sustainable urban development. Water shortage problem of the study area, Linhai city in Zhejiang province, is caused by lack of available water along with inadequate water utilization engineering. The economic booming of the study area in recent decade has resulted in growing water demand in industry and agriculture. The layout of the high-water consumption industries is inconsistent with the distribution of water resources. The variation coefficients of water resources between divisions keep increasing and will reach 0.47 and 0.51 by 2020 and 2030. In addition, increasing pollutants and sewage discharge reduce high-quality water availability and aggravated the contradiction of urban water supply. In this paper, water conservation, rainwater utilization and sewage treatment are considered as a comprehensive water supply system. Evaluation model for water resources allocation is constructed including 17 indexes belonging to four criteria layers as society, economy, ecology and water resources development. Four water planning scenarios were analyzed to explore solutions to coordinate dilemma between water resources management and urban development. TOPSIS method was adopted to grade water resources allocation schemes. The results show that the water transfer engineering is imperative for Linhai city to support social and economy sustainable development. While water saving measures can compensate water shortage crisis, the measures are beneficial to the ecological environment by pollution abatement additionally. The research results could provide valuable perspectives in water resources planning and management for other cities facing the same water problems.

Keywords: Water resources planning; water management; scenario analysis; water supply; demand.

1 INTRODUCTION

Water is valuable resource for social and economic development. The expansion of the city makes the water utilization more concentrated and intensified. The relationship between human and water has become increasingly severe (Cai et al., 2016; Chung and Lee, 2009; Zuo and Chen, 2003). The spatial distribution of water resources usually is inconsistent with urban development layout. The water resources allocation does not match human demands, which has become the bottleneck factor for the sustainable development of regional economy. Urban water resources management is a comprehensive system of overall coordinating interaction between human being and nature (Deng, 2014; Wang et al., 2003). Therefore, a set of management concepts and integrated implementation plans are necessary to balance the contradiction between supply and demand of regional water resources as well as rational use of limited water resources. The overall evaluation of water resources management scenarios in aspects such as water supply and demand, utilization components and water consumption intensity is fundamental. It can help reveal key influential factors of regional water resources management, also improve water planning by assessing various engineering and non-engineering measures.

In recent decades, the sustainable utilization of urban water resources has been research focus, especially when water resources facing water quality deterioration which aggravates water crisis (Shen et al., 2015; Loslovich and Guiman, 2001). Water resources carrying capacity has been gravely overload in more and more cities (Jerson and Rafael, 2002). Water allocation models based on the sustainable development were put forward to determine the water allocation of individual water users (Maqsood et al., 2005; Zhong et al., 2003). Researchers are paying more attention to the interaction between natural water systems and social water systems (Hamid et al., 2016; Carmona et al., 2013). Jia and Wang (2006) put forward the basic structure of "natural-artificial" dualistic water cycle model, thus coupled distributed hydrological model and lumped water resource allocation model based on that concept. In urban area, land planning determines industrial layout and the city expansion. The matching of water resources and land resources confirms whether the city achieves sustainable development (Liu and Zhang, 2006; Zhang et al., 2004). The importance of comprehensive water supply system is also put forward, especially rainwater and reclaimed water utilization (Que et al., 2012).

In this paper, taking Linhai City of Zhejiang Province as study area, four water resources allocation scenarios were set up considering social, economic and water resources situations. The TOPSIS approach was adopted to select optimal water management scenario, aiming to enhance spatial match of water supply and urban growth, which provides scientific support for overall harmony development of economy, resources and environment in Linhai city.

2 MATERIALS AND METHODS

2.1 Study area

Linhai City is located in the southeast coast of Zhejiang Province, China, with an area of 2203km^2. The landforms are influenced by the Tiantai Mountains in the northwest and the Kuangcang Mountains in the southwest, and the main features are the fragmentized hills and mountains which account for 68.4% of the total area. Plain area is 25.1% and water area is 6.5% of the total area. Subtropical monsoon climate zone dominates the Linhai city with characteristics of distinct four seasons and abundant rainfall. According to the city's meteorological and hydrological data, the annual average temperature is 16.5-17.8 °C, and the city's average annual evaporation is 1007.2mm. Average annual rainfall is 1685.5mm, which is mainly concentrated in Mei-Yu season in May and June, along with typhoon season from July to September.

The average annual water resources of Linhai is 2.1 billion m^3. The available water supply is 420 million m^3, accounting for only 20% of local total water resources. 97 percent of water supply is from surface water, mainly relying on water storage projects and water division projects. In addition, there is abundant pass-by water resources in Linhai. Lingjiang, the most important river in Linhai, transfer around 2 billion m^3 transit water in the year of low flow.

The spatial distribution of water supply and demand is inconsistent in Linhai city. Water demand is mainly concentrated in the eastern plain area with dense population and developed economy. The region consumed 72% of the city's water demand. In the near future, its water demand growth rate will be kept high due to the effect of urbanization process and industrial development. Thus, major water supply facilities, i.e. reservoirs, generally constructed in mountainous area. There are 324 reservoirs of different sizes with the total capacity of 400 million m^3 in Linhai. Calculated at comparable prices, the total GDP of the city was 46 billion Yuan in 2015, about 7.2% increase over the previous year. The contribution of agriculture, industry and service business was 8.8: 44.5: 46.7.

2.2 Divisions of water resource calculation and category of water users

The integrity of watershed, water conservancy system and administrative districts were considered to partition water resources calculation units. The spatial correspondence of water supply and demand was examined to reflect geographical conditions and water resources utilization status. Figure 1 shows the four divisions of water resource calculation.

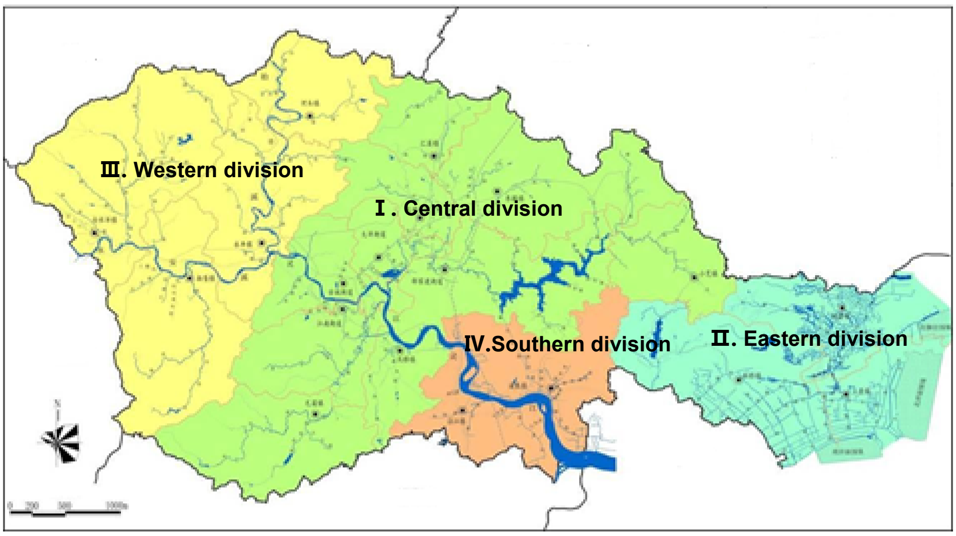

Figure 1. Water resource calculation divisions.

Water users are classified as domestic, production and ecological water supply, which are calculated and predicted respectively. Domestic water users include urban and rural domestic water demand. Production water demand covers agriculture, industry, stock farming, fishery and service business. Ecological water demand is composed of municipal water use and the minimum ecological water requirement.

2.3 Prediction of socioeconomic development and water demand

2.3.1 Social and economic development trend forecast

According to the historical population data in the Yearbook from 2005 to 2013, population growth feature is obtained by the trend analysis method. The population of each division in target years of 2016, 2020 and 2030 are calculated and results are shown in Table 1.

Table 1. Population forecast in target years in Linhai (Unit: 10^4 person).

Target year	Division	Total population	Urban population	Rural population
2016	I. Central	51.06	41.28	9.79
	II. Eastern	41.44	21.48	19.95
	III. Western	20.82	11.14	9.68
	IV. Southern	8.30	2.68	5.62
	Sum	**121.62**	**76.58**	**45.04**
2020	I. Central	64.40	55.74	8.66
	II. Eastern	52.64	39.99	12.65
	III. Western	15.69	8.47	7.22
	IV. Southern	6.27	2.20	4.07
	Sum	**139.00**	**106.40**	**32.60**
2030	I. Central	75.95	69.21	6.74
	II. Eastern	67.29	59.00	8.29
	III. Western	16.15	9.46	6.69
	IV. Southern	5.61	2.33	3.28
	Sum	**165.00**	**140.00**	**25.00**

As stated in related policies and planning, eastern part of Linhai will be the priority area for economic developing in the near future. Industrial parks will be centralized in eastern division, and its economic growth rate will surpass other regions in the city (see Table 2). In contrast, agricultural production size will maintain at the present level and change little.

Table 2. industrial added value forecast of target years in Linhai (Unit: 10^8 Yuan).

Division	2016	2020	2030
I. Central	123.60	156.04	266.54
II. Eastern	83.91	125.10	310.04
III. Western	8.57	9.28	11.31
IV. Southern	17.46	22.04	35.90
Sum	**233.54**	**312.46**	**623.78**

2.3.2 Water demand forecast

(a) Domestic water demand

Domestic water demand is calculated by index rating method and decided by population and water consumption per capita, as in Eq. [1]:

$$W_d = P \times q_d \times 365/1000 \qquad [1]$$

where W_d is annual water demand, $10^4 m^3/a$; P is population, 10^4; q_d is daily water quota per capita, L/p.d.

(b) Industrial water demand

Two parameters, industrial added value and water consumption per 10,000 Yuan of value-added by industry, are used to obtain industrial water demand as in Eq. [2]:

$$W_i = y \times q_i \qquad [2]$$

where W_i is industrial added value, 10^4 Yuan; q_i is water consumption per 10,000 Yuan of value-added by industry, $m^3/10^4$ Yuan.

(c) Agricultural water demand

Agricultural lands include dry farmland and paddy field. According to different irrigation schedule, irrigation quota method is applied to get water demand as in Eq. [3]:

$$W_a = A \times m / \eta \qquad [3]$$

where W_a is gross irrigation water requirement, $10^4 m^3$; A is irrigation area, 10^4mu; m is net irrigation quota, $m^3/10^4$mu; η is utilization coefficient of irrigation water. •

The current utilization coefficient of irrigation water is of 0.55 in Linhai. The coefficient will be enhanced to 0.6 and 0.65 by 2020 and 2030 through on-going water conservancy constructions and application of water saving irrigation techniques. In addition, as stated in Water Quota of Zhejiang Province, combined with field survey, water quotas for different livestock and fishery are defined to determine Animal aquaculture water demand in each division.

(d) Public water demand

Public water needs include construction and service business, which make up 25% of domestic water usage in the present year of 2013. With the expansion of society and economy, as well as adjustment of industrial structure, the public water consumption in 2016, 2020 and 2030 are set to be 27%, 30% and 35% of domestic water amount.

(e) Ecological water requirement

Water resources development and utilization level in Linhai is maintained at a relatively low level either in the current year or in the planned years. According to the estimation, instream ecological water requeirement can fully be sacrified in rivers, lakes and wetlands. Consequently, off-stream ecological water requirement alone is considered in the paper. It refers as virescence and landscape water usage in the city and be calculated by Eq. [4]:

$$W_e = s \times q_e \qquad [4]$$

where W_e is off-stream ecological water requirement, L; s is green coverage area, m^2; q_e is virescence and landscape water usage quota, and value is set to be 1.5 L/m^2•d in the paper.

The forecasted results of water demand in planning years are listed in table 3. The total water demands are 42204, 44071, 47298 and 51239 $10^4 m^3$ in 2013, 2016, 2020 and 2030 respectively. Although the water consumption shows an increasing tendency, the growth rate is decreasing.

Table 3. Forcasted water demands of each division in Linhai Unit: $10^4 m^3$

Year	Division	Urban Living	Rural Living	Public Use	Industry Use	Irrigation Use	Livestock & Fishery	Ecological Use	Sum
2013	I	1634	387	505	5525	7424	1927	163	17566
	II	681	899	395	3269	6799	1100	68	13211
	III	550	265	204	436	5106	1219	55	7835
	IV	138	234	93	770	1527	816	14	3592
	Sum	**3004**	**1785**	**1197**	**10000**	**20856**	**5062**	**300**	**42204**
2016	I	2068	370	658	6427	7040	1872	207	18643
	II	1137	837	533	4363	6447	1075	114	14506
	III	468	230	188	446	4842	1157	47	7377
	IV	122	195	86	908	1448	774	12	3545
	Sum	**3795**	**1632**	**1465**	**12144**	**19778**	**4878**	**379**	**44071**
2020	I	2936	350	986	7022	6806	1805	294	20198
	II	2189	554	823	5630	6232	1046	219	16693
	III	371	184	167	417	4681	1088	37	6945
	IV	104	149	76	992	1400	731	10	3462
	Sum	**5601**	**1237**	**2051**	**14061**	**19118**	**4669**	**560**	**47298**
2030	I	3877	285	1457	7196	6282	1677	388	21162
	II	3230	393	1268	8371	5753	989	323	20328
	III	449	195	225	305	4320	952	45	6492
	IV	119	132	88	969	1292	645	12	3257
	Sum	**7676**	**1005**	**3038**	**16842**	**17648**	**4263**	**768**	**51239**

2.4 Evaluation method of allocation schemes

The TOPSIS model is a sorting method which provide solutions approximating the ideal one. It is suitable for decision analysis of multi-objective complex system (Wang et al., 2012; Hu and Chen, 2000). The distance between positive and negetive ideal solution of each evaluation objective is specified. Then, approximate degrees of objective parameter values to their ideal solutions among allocation scenarios are calculated and sorted from small to large. It is used as the basis for judging performance and selecting better scenario (Zhang et al., 2013). In this paper, the traditional method of TOPSIS is improved in two aspects, weight determination algorithm and distance calculation formula. The operation steps are as follows:

i. Suppose there are M evaluation schemes in total. Each scheme has N evaluation indexes with x_{ij} representing the j^{th} index value in the i^{th} scheme. The decision matrix X is composed of every x_{ij}.
ii. Normalize indexes and obtain the normalization matrix D. Indexes are divided into three types: the larger the better type index, the smaller the better type index and the optimal value type index. Normalizing formulas are listed in Eq. [5] - Eq. [7].

The larger the better type:

$$d_{ij} = x_{ij} \Big/ (\max(x_{ij}) + \min(x_{ij})) \quad i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \qquad [5]$$

The smaller the better type:

$$d_{ij} = 1 - x_{ij} \Big/ \left(\max(x_{ij}) + \min(x_{ij})\right) \quad i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \qquad [6]$$

The optimal value type:

$$d_{ij} = 1 - \left|x_{ij} - x^*\right| \Big/ \left(\max\left\{x_{ij} - x^*\right\} + \min\left\{x_{ij} - x^*\right\}\right) \quad i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \qquad [7]$$

where x^* is the optimal value of the index.

iii. Weights are accessed by variation coefficient method as in Eq. [8]. The standard deviation δ_j and mean value E_j of the index in different scenarios are calculated. The variation coefficient is calculated by δ_j / E_j, which is normalized to get the weight α_j.

$$w_j = \alpha_j \cdot \varphi_j \Big/ \sum_{j=1}^{n} \alpha_j \cdot \varphi_j \qquad [8]$$

The weight for each index to the overall objective constitute the weighted judgment matrix as in Eq. [9]:

$$A = \left(a_{ij}\right)_{M \times N} = \left(w_j d_{ij}\right)_{M \times N} \qquad [9]$$

iv. Determine the positive and negative ideal solutions.
v. Solve the distances to the ideal solutions for allocation scenarios and evaluate scenarios thereby. The original TOPSIS adopts the Euclidean distance formula which makes the optimal solutions sometimes close to the negative side. To avoid this drawback, a revised method of the orthogonal projection formula is selected as in Eq. [10] (Hua and Tan, 2004; Hu, 2002):

$$D_{XY} = \left|\overrightarrow{AB} \bullet \overrightarrow{XY}\right| \Big/ \left\|\overrightarrow{AB}\right\| \qquad [10]$$

where $\| \|$ denotes euclidean destance; $\bullet$ denotes vector product.

3 RESULTS AND DISCUSSIONS

3.1 Components analysis of water demand

Agriculture, industry and living are the three major water use categories in Linhai city. The impact of socio-economic development on the water consumption structure can be seen in Figure 2. Agricultural area maintains similar level in different target years, but its water demand significantly reduces which is mainly benefitted from more investment on effective farm management and water-saving techniques. By 2030, the proportion of agricultural water demand declines from 61.41% to 42.76%. Industrial and domestic water consumption grew steadily, reflecting the trend of urbanization and the enhancement of living standards. Controlled by strict water saving policies in China, water usage per 10^4 Yuan industrial added value decreased gradually, yet the industry still expanding in Linhai, so the industrial water demand is in growth trend.

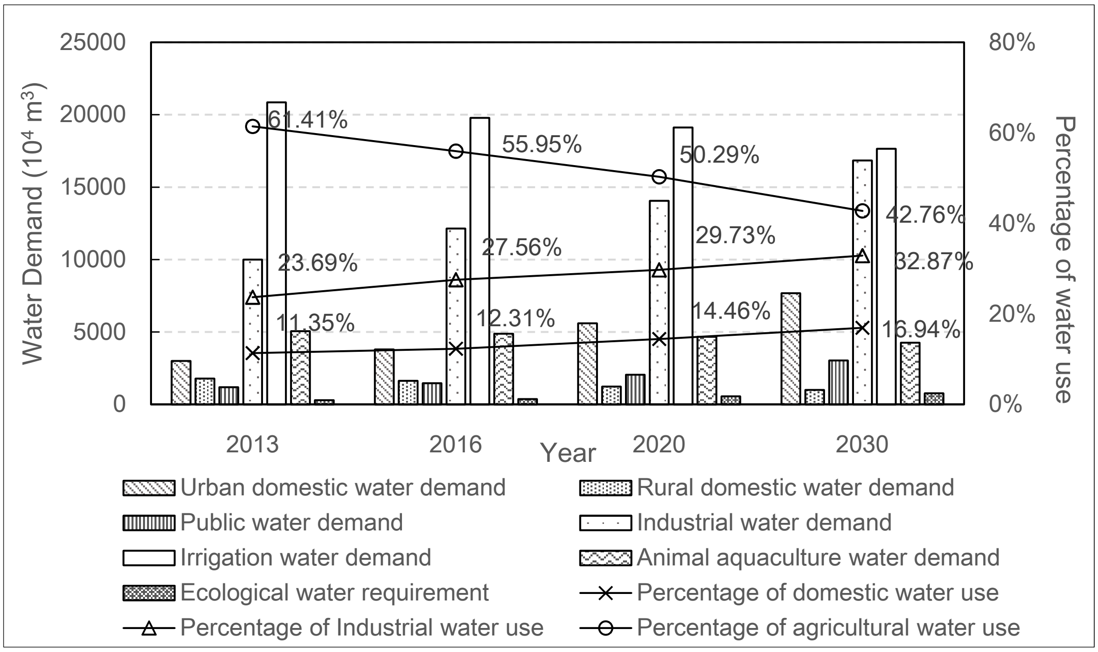

Figure 2. Water demand in different categories of Linhai.

From Figure 3, water consumtion of central and eastern divisions occupies more than 70% of total usage in the city. In particular, the eastern division will be the key area of economy development, even as a deputy city of Linhai City. By 2030, water consumption will be more concentrated in the central and eastern parts of the citty, with a proportion of 82.4% of the water usage. the eastern division have the fastest growing requirement of water, mainly on industrial water needs, with the amount of 3269×10^4 m^3 and 8371×10^4 m^3 in 2013 and 2020, which will exceed the industrial water demand in central division. For this reason, water resouces allocation should pay more attention to water issues in central and eastern area. Especially for the eastern divison, it does not has qualified water sources. The failure of water resources distribution will become the bottleneck of social and economic development in the region.

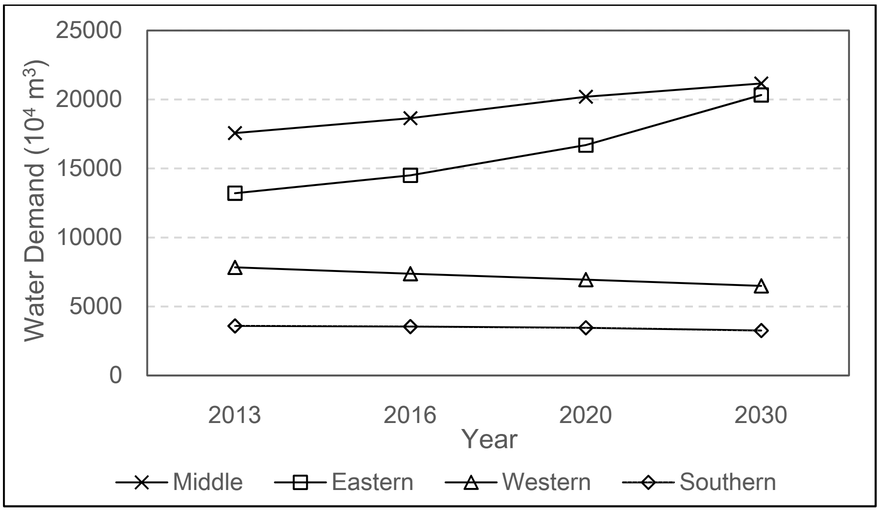

Figure 3. Water demand change of divisions in different year.

3.2 Balance analysis of water supply and demand

3.2.1 Water shortage condition in divisions

The water resources balance analysis can inspect whether the water resources supply meets the regional water demand, which is the basis for the reasonable and scientific water allocation. Linhai city belongs to water-rich area in China, and water resources utilization rate remains at a relatively low level at present. Planned and newly started engineerings for increasing water supply are considered in the water balance calculation to relieve water demand pressure. It can be seen from the figure 4 that the water surplus and deficiency in each division is not uniform. There is surplus water to divert in middle division, and the water shortage is severe in eastern and southern divisions. By 2030, due to the rapid development of eastern industry, the water deficit reaches 10374×10^4 m^3. While there is 9922×10^4 m^3 more water that can be allocated in central region. So the primary task of water resources allocation in Linhai is to coordinate the spatial distribution contradiction of water resources and social-economic development.

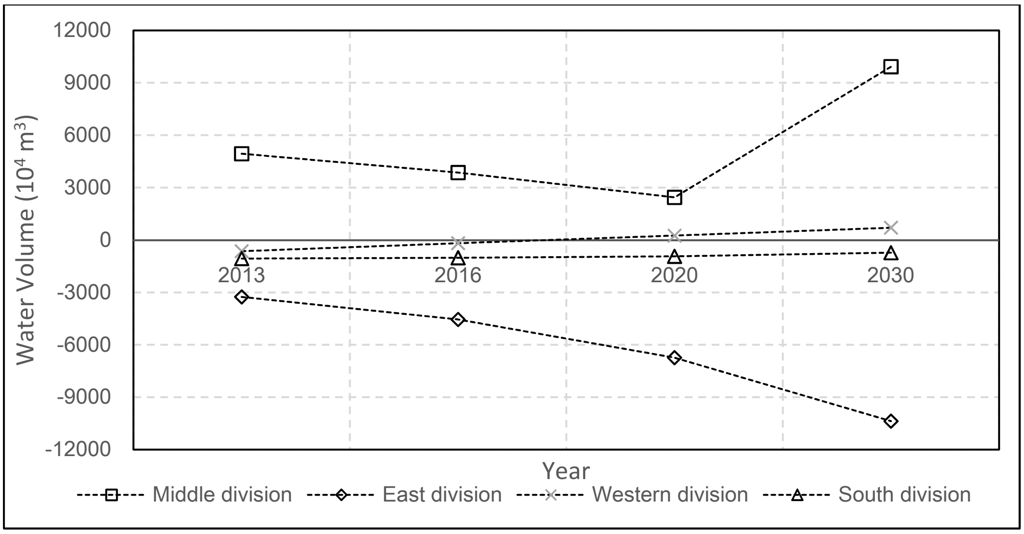

Figure 4. Water surplus and deficiency of divisions in different level year.

3.2.2 Water shortage conditions in divisions

The variation coefficient was used as a statistical index to reflect the variation degree of regional water supply and demand. In this paper, the regional variation coefficients in different level year were computed based on ratios of water supply and water demand. The status of water resources surplus and deficit can be described. The variation coefficient is 0.25 in 2013, and keep unchanged from 2013 to 2016. However, the parameter rises to 0.47 and 0.51 in 2020 and 2030, indicating that the water resources will appear great spatial disparity.

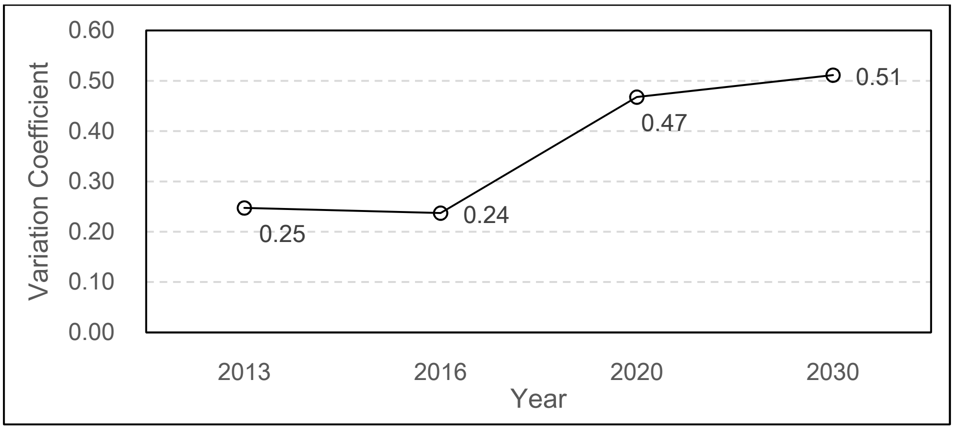

Figure 5. Water resources variation coefficient change**.**

3.3 Water resources allocation scenarios

According to the characteristics of water supply and demand in Linhai City, it is necessary to balance the contradiction between regional water demand, and maintain the sustainable development of water resources. Four water resources allocation scenarios were developed considering water supply projects, water-saving measures, unconventional water resources utilization and ecological requirement.

Scenario 1: enhance irrigation water-saving measures, water efficiency of irrigation increases by 10%; considering the promotion of water-saving facilities, urban domestic water usage decreases by 10%; transfer surplus water from Niutoushan reservoir in central division to eastern division to guarantee the eastern water supply.

Scenario 2: water efficiency of irrigation increases 15%; urban domestic water usage decreases by 15%; build Fangxi reservoir to meet the water demand in west Division and divert water to the central division, and replace more water from Niutoushan reservoir transferring to the eastern part.

Scenario 3: based on scenario 1, enlarge unconventional water resources usage, including flood water and reclaimed water, to replenish ecological water demand.

Scenario 4: based on scenario 2, enlarge unconventional water resources usage, including flood water and reclaimed water, to replenish ecological water demand.

The evaluation system was constructed to access water allocation scenarios, which is composed of 13 indexes covering four aspects of society, economy, ecology and water usage as in Table 4.

Table 4. Evaluation index calculation of water resources allocation scenarios.

Criterion layer	Index layer	Scenario			
		M1	M2	M3	M4
Society B1	Assurance rate of domestic water supply B11	95%	90%	95%	90%
	Water-saving equipment coverage B12	85%	90%	85%	90%
	Comprehensive water consumption per capita (m³) B13	297.19	286.27	316.66	286.27
Economy B2	Annual irrigation water (m³/mu) B21	422	422	422	389
	Water consumption of 10^4 Yuan output value (m³) B22	73	59	73	59
	Industrial water reuse rate B23	65%	75%	65%	75%
Ecology B3	Off-stream ecological water requirement (10^4 m³) B31	400	560	560	400
	Rural domestic sewage treatment rate B32	95%	90%	90%	95%
	Reclaimed water utilization (10^4 m³/d) B33	7.00	7.00	12.00	12.00
	Water supply percentage of high quality water B34	61.5%	61.5%	66.4%	66.4%
Water usage B4	Water efficiency of irrigation B41	0.58	0.6	0.58	0.6
	Utilization ratio of water resources B42	22.98%	27.37%	27.37%	27.37%
	Leakage rate of urban pipe network B43	10%	8%	10%	8%

3.4 Assessment of water resources allocation scenarios

In this paper, the variation coefficient method and analytic hierarchy process were used to calculate weights of indexes, and the results are showed in Table 5. Derived weights passed consistency test with all CRs less than 0.1.

Table 5. The index weights calculated by AHP method.

Criterion layer		Index layer		AHP Weight
Index	Weight	Index	Weight	
Society	0.167	Assurance rate of domestic water supply	0.297	0.050
		Water-saving equipment coverage	0.163	0.027
		Comprehensive water consumption per capita	0.54	0.090
Economy	0.333	Annual irrigation water (m³/mu)	0.311	0.104
		Water consumption of 10^4 Yuan output value	0.493	0.164
		Industrial water reuse rate	0.196	0.065
Ecology	0.333	Off-stream ecological water requirement	0.165	0.055
		Rural domestic sewage treatment rate	0.378	0.126
		Reclaimed water utilization	0.079	0.026
		Water supply percentage of high quality water	0.378	0.126
Water usage	0.167	Water efficiency of irrigation	0.163	0.027
		Utilization ratio of water resources	0.54	0.090
		Leakage rate of urban pipe network	0.297	0.050

Then the weighted judgment matrix A is obtained.

$$A=\begin{pmatrix} 0.01009 & 0.00545 & 0.02778 & 0.02506 & 0.11308 & 0.03135 & 0.05555 & 0.02543 & 0.03666 & 0.03376 & 0.00327 & 0.04489 & 0.03591 \\ 0.00956 & 0.00577 & 0.02877 & 0.02506 & 0.13991 & 0.03618 & 0.07777 & 0.02410 & 0.03666 & 0.03376 & 0.00338 & 0.05669 & 0.04489 \\ 0.01009 & 0.00545 & 0.02601 & 0.02506 & 0.11308 & 0.03135 & 0.07777 & 0.02410 & 0.06285 & 0.03645 & 0.00327 & 0.05669 & 0.03591 \\ 0.00956 & 0.00577 & 0.02877 & 0.02718 & 0.13991 & 0.03618 & 0.05555 & 0.02543 & 0.06285 & 0.03645 & 0.00338 & 0.06848 & 0.04489 \end{pmatrix}$$

Idea solutions and negative idea solutions are as the followings.

$$a_j^+=(0.01009,\ 0.00577,\ 0.02877,\ 0.02718,\ 0.13991,\ 0.03618,\ 0.07777,\ 0.02543,\ 0.06285,\ 0.03645,\ 0.00338,\ 0.06848,\ 0.04489)$$

$$a_j^-=(0.09560,\ 0.00545,\ 0.02601,\ 0.02506,\ 0.11308,\ 0.03135,\ 0.05555,\ 0.02410,\ 0.03666,\ 0.03376,\ 0.00327,\ 0.04489,\ 0.03591)$$

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Distances from idea solutions of four scenarios are listed below.

$$d_i = \left(0.002575, 0.000932, 0.001116, 0.000448\right)$$

Due to the criterion of the smaller the distance the better, the optimal solution is scenario 4.

Four scenarios were proposed based on the actual situation of Linhai. Water sources lies in the central and western region of the city, while water demand is larger in central and eastern regions. If too much reliance is laid on constructing water supply projects and focus on improving water resource development rate in the water resources management schemes, it will need a large amount of budget not only in building new reservoirs but also in water transfer projects. Therefore, in the water resources allocation scenarios, water supplies with separate quality, water saving techniques and unconventional water usage are introduced, so as to alleviate the contradiction between water resources and land planning. Evaluation results prove that opening up new water sources is necessary. Water supply by existing reservoirs cannot satisfy the increasing demand, so the Fangxi reservoir is built as in the scheme. The promotion of water saving and unconventional water use is very crucial as well, which not only can improve water utilization efficiency, but also reduce pollutant output, and is beneficial to the ecological environment in Linhai.

4 CONCLUSIONS

The water resources in Linhai city is characterized as relatively low utilization level, deficiency of surface water supply projects and unemployed transit water. Industry and agriculture are two main pillars, both have promotion space for water conservation. The evaluation results indicate remarkable effect of water saving by improved technology. So, the water saving is the necessary element of rational water allocation.

By comparing the ratio of water supply and water demand in different divisions, the variation coefficient of the ratio keeps rising from 2016 to 2030 and reaches 0.5 in 2030. It suggests that the water supply and demand of each division is highly uneven. Water shortage in some divisions will be getting worse year by year. The spatial distribution of supply and demand is extremely imbalanced, which implies that the water resources are not allocated and utilized in a reasonable way. Water resources will largely restrain the local social and economic development, and also threaten the ecological security potentially.

TOPSIS is an intuitive and flexible method for evaluation, but the selection of the weight algorithm and distance definition will affect the results to a large extent. Therefore, the improvement is considered in the paper aiming at these two aspects. AHP and variation coefficient are combined to get index weight. The orthogonal projection method based on vertical projection distance is used to make the TOPSIS evaluation more scientific and reasonable.

Water resources allocation scenarios are formulated by taking into account water conservation measures, water supply projects and ecological water requirement. Scenario 4 is a combination of high degree of water saving, enlargement of water supply, guarantee of ecological water demand. It shows proper coordination of water resources and meets the needs of urban development in Linhai City.

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PHYTOTOXICITY EVALUATION AND PHYSIOLOGICAL RESPONSES OF *VIGNA RADIATA* SEEDLINGS GROWN IN THE LEAD-DOPED IRRIGATION WATER

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ABSTRACT

Water pollution is the most alarming topic over the past several decades, with the leading cause of diseases and deaths of more than 14,000 people per day. Today, wastewater irrigation has emerged to be a widespread strategy to fulfill the pressing need of non-conventional water resources. These discharges carry appreciable amount of toxic chemicals or trace elements, usually exceeding the maximum allowable limits, suggesting the possible risks to the food chain, water courses, and ecosystem. Heavy metals are among the most carcinogenic, teratogenic, mutagenic, and neurotoxic constituents accumulating in the irrigation water. Lead is one of the most abundant metal contaminant in aquatic and terrestrial ecosystems. Owing to its low solubility, mobility, and freedom from the microbial degradation in soils, it could accumulate in soil, and absorbed by plants to induce physiological and biochemical dysfunctions. Confirming the assertion, this study placed an early attempt to investigate the effects of lead-doped irrigation water on the physical, biochemical, and physiological responses of *Vigna radiata* seedlings. The seed germination, length of roots and shoots, proline accumulation, photosynthetic pigments, and antioxidative responses were elucidated. Results revealed that seed germination was unaffected, but the elongation of roots and shoots were hindered as a function of lead concentrations. Profound reductions were observed in chlorophyll-*a*, chlorophyll-*b*, and carotenoid content in the treated seedlings. The activities of proline, guaiacol peroxidase, catalase, and ascorbate peroxidase were altered, with a pronounce stimulation at 0.55 mM of lead. The current findings shed light on the detrimental implications of wastewater irrigation practice on the physical growth, physiological and biochemical characteristics, and antioxidative systems of *Vigna radiata* seedlings. The health threats, toxicity, and injuries implications could be exacerbated on a larger scale by the indiscriminate application of low quality water resources as a technical solution to the scarcity of clean, fresh irrigation water.

Keywords: Food security; lead; phytotoxicity; vigna radiata; wastewater irrigation.

1 INTRODUCTION

Today, water pollution due to the indiscriminate discharge of industrial waste and unregulated dumping of household effluents is confronted with both developing and developed countries at a global context. Heavy metals, with the cumulative, persistent, and non-degradable nature, are the intrinsic environmental pollutants that have attracted aesthetic concern with respect to the ecological, environmental, and health implications (Nagajyoti et al., 2010). Excessive intake of heavy metals-contaminated food could lead to the depletion of essential nutrients in human body, weakening immunological defenses with intrauterine growth retardation, and higher prevalence of upper gastrointestinal cancer (Hussain et al., 2013).

The terrestrial source of heavy metal contamination could be originated from the atmospheric deposition from the metal smelter, vehicle exhaust, mining effluents wastes, and geological erosion of matrix, and metal processing refineries, coal power plants, petroleum combustion, microelectronics, wood preservation and paper processing plants (Arruti et al., 2010; Pacyna, 1996; Sträter et al., 2010). These trace elements could be bioaccumulated in the surface layer of soil available for the plant uptake to affect the equilibrium (Wang et al., 2004).

Among all, lead (Pb) is the most abundant and ubiquitously distributed metal ions that constitute a sharp threat to the crop yield, development and oxidative stress in plants system. Irrigation with lead enriched water has been associated with the oxidative damages, manifested by the overproduction of reactive oxygen species (ROS) and free radicals (Baisak et al., 1994; Becana et al., 2000; Comba et al., 1998; Malecka et al., 2001), resulting in an unbalanced cellular status. Excess of lead ions uptake could adversely affect the photosynthesis process, evidenced by the distortion of chloroplast ultrastructure, restrained biosynthesis of photosynthetic pigments and carotenoids, perturbation of electron transport, and alteration in stomatal closure (Sharma and Dubey, 2005). Aside from the physiological indices, the macroscopic visual symptoms of plants cultivated with lead-polluted water have been reported (Gohari et al., 2011; Yilmaz and Akinci, 2009).

For years, *Vigna radiata* L. (mung bean) is a popular grain legume food sources in semi-arid and tropical regions. Due to its fast-growing features than other legume plants, mung bean has been recommended to be a potential bio-indicator of the environmental implication of heavy metal doped irrigation practice. With the aforementioned, this present research was envisaged with the objectives: (1) to evaluate the macroscopic visual symptoms of plants; (2) to examine the accumulation of proline content; (3) to investigate the alterations of photosynthetic pigments and carotenoids; and (4) to assess the changes in antioxidant enzyme activities; and (5) to elucidate the possible mechanism and pathway of the lead ions-induced toxicity.

2 MATERIALS AND METHODS

2.1 Plant materials and germination conditions

Seeds of *Vigna radiata* (mung bean) acquired locally were chosen as the experimental material. The seeds were immersed in 75 % (v/v) of ethanol for 5 min, subsequent by 2 % sodium hypochlorite solution for 5 min for sterilization and disinfection purposes. Thereafter, they were rinsed thoroughly with deionized water, and imbibed in distilled water for 4 h. The seeds were sown in plastic cups saturated with distilled water as control and the treatment batches were exposed to Pb (II) at the concentrations of 0.4 mM to 0.7 mM, and placed in the hydroponic setups (Figure 1). The seedlings were uprooted, rinsed under running distilled water and ready for further analyses after 7 days.

Figure 1. Hydroponic setup for plant cultivation.

2.2 Macroscopic symptoms

Length of roots and shoots of *Vigna radiata* seedlings were measured on a daily basis, and expressed in the unit of cm. The root measurement was taken from the root-hypocotyl junction to the root tip, while the shoot length was measured from the plumule grown from the cotyledon to the bottom end of the leave. All measurements were undertaken in triplicates for five replicated seedlings.

2.3 Photosynthetic pigments and carotenoids analysis

For the determination of chlorophyll content, fresh leaves of *Vigna radiata* were grounded with a mortar and pestle. The plant aliquots were extracted in 80 % of acetone and the absorbance was measured at 645 nm, 663 nm, and 470 nm using a uv-spectrophotometer (UV-1800, Shimadzu). The contents of total chlorophyll, chlorophyll-*a*, chlorophyll-*b*, and carotenoid $_{(x + c)}$ (mg/g fresh weight) were determined according to the equations (Lichtenhaler and Wellburn, 1983):

$$\text{Chlorophyll-a} = 12.21A_{663} - 2.81A_{645} \quad [1]$$

$$\text{Chlorophyll-b} = 20.13A_{645} - 5.03A_{663} \quad [2]$$

$$\text{Total chlorophyll} = \text{Chlorophyll-a} + \text{Chlorophyll-b} \quad [3]$$

$$\text{Carotenoid} = \frac{1000A_{470} - 3.27C_a - 104C_b}{229} \quad [4]$$

where A_{663}, A_{645}, and A_{470} are the absorbance at 663 nm, 645 nm and 470 nm; and C_a C_b are denoted to the concentrations of chlorophyll-*a* and chlorophyll-*b*, respectively.

2.4 Proline content

The estimation of free proline content was performed according to the standard procedure of Bates et al. (1973), where the concentration of proline was determined using a uv- spectrophotometer at 520 nm, expressed as μmoles/g fresh weight.

2.5 Determination of antioxidant enzymes

The extraction of antioxidant enzymes was performed by homogenizing 0.2 g of *Vigna radiata* seedlings in 50 mM of cold Na_3PO_4 buffer containing 1 % w/v of polyvinylpyrrolidone and 0.2 mM of ascorbic acid by using a chilled mortar and pestle (Jiang and Huang, 2001). The spectrophotometric analyses of the antioxidant enzymes were conducted using a uv-spectrophotometer.

2.5.1 Guaiacol peroxidase (POD) assay

The activity of POD was measured in accordance to the procedure proposed by Everse et al. (1994), where the absorbance was recorded at 470 nm against the reagent blank. The specific activity was calculated with an extinction coefficient of 26.6 $mM^{-1}cm^{-1}$, and the enzyme activity was defined as the amount of enzyme catalyzing the formation of 1.0 μM of guaiacol dehydrogenation product/min/g fresh weight, calculated by:

$$\text{Specific activity (UA / mg protein)} = \frac{\text{Changes in Abs / min x total volume (mL)}}{\text{Ext. coefficient x Vol. of sample taken (mL) x protein content (mg / g FW)}} \quad [5]$$

2.5.2 Ascorbate peroxidase (APX) assay

The determination of APX was carried out following the method of Nakano and Asada (1981). The reaction was initiated by the addition of H_2O_2 and the variation was measured at 290 nm. The enzymatic activity was expressed as the amount of enzyme required to oxidize 1.0 μM of ascorbate/min/g fresh weight, given by:

$$\text{Specific activity (UA / mg protein)} = \frac{\text{Changes in Abs / min x total volume (mL)}}{\text{Ext. coefficient x Vol. of sample taken (mL) x protein content (mg / g FW)}} \quad [6]$$

with an extinction coefficient value of 2.8 $mM^{-1}cm^{-1}$.

2.5.3 Catalase (CAT) assay

CAT was estimated according to the procedure outlined by Aebi (1984), where the reaction was initiated by the addition of 200 μL of H_2O_2 , and the CAT activity was calculated as the amount of enzyme required to release half of the peroxide oxygen derived as:

$$\text{Specific activity (UA / mg protein)} = \frac{\text{Changes in Abs / min x total volume (mL)}}{\text{Ext. coefficient x Vol. of sample taken (mL) x protein content (mg / g FW)}} \quad [7]$$

with an extinction coefficient 40 $mM^{-1}cm^{-1}$.

2.6 Protein extraction

The protein content was determined according to the method proposed by Bradford (1976), where the absorbance was measured at 595 nm against the reagent blank, expressed in the unit of mg/g fresh weight.

3 RESULTS AND DISCUSSIONS

3.1 Macroscopic symptoms

The macroscopic symptoms in response to the lead concentrations and duration of exposure are depicted in Figure 2. Generally, the seed germination of *Vigna radiata* was unaffected by the treatment of lead ions, and pronounce inhibition was observed in the elongation of roots and shoots, with the reduction from 6.8 to 2.2 cm for roots, and from 2.9 cm to 1.0 cm for shoots as the lead concentration increased from 0.4 to 0.7 mM. The current findings were in agreement with previous researches reported in *Brassica juncea* (John et al., 2009), *Phaseolus aureus* (Kadhim, 2011), and *Brassica napus* (Gohari et al., 2012), with the growth reduction of 0.82 to 96.92 %, and 2.50 to 87.30 % for roots and shoots, respectively (Table 1). Specifically, a marked suppression was observed at the lead ions concentration of 0.55 mM, as compared to 2.5 mM as reported by Kadhim (2011) in *Phaseolus aureus*. The result could be ascribed to the protective role of seed coat against the interference of lead ions during the germination (Munzuroglu and Geckil, 2002). However, during the protrusion of the radicle, root system is the most vulnerable plant part, that is susceptible to the environmental stimuli in the growing medium (Fahr et al., 2013; Siddiqui et al., 2011). This observation was consistent with the proposed hypothesis that root system is a phytotoxicity indicator of the metal pollutants present in the irrigation water. The marked inhibition noticed at 0.55 mM in the root growth might illustrate the threshold level of the lead ions-induced phytotoxicity in *Vigna radiata* seedlings. The growth suppression could be explained by the metabolic pathway: (i) inhibition on the normal cell division and interference on the metabolic processes (Eun et al., 2000; Verma and Dubey, 2003); (ii) perturbation of lead ions in the microfibrils and microtubules to activate the wall-degrading enzymes, leading to the distensions and lesions in the cell wall (Kaur et al., 2013; Liu et al., 2009).

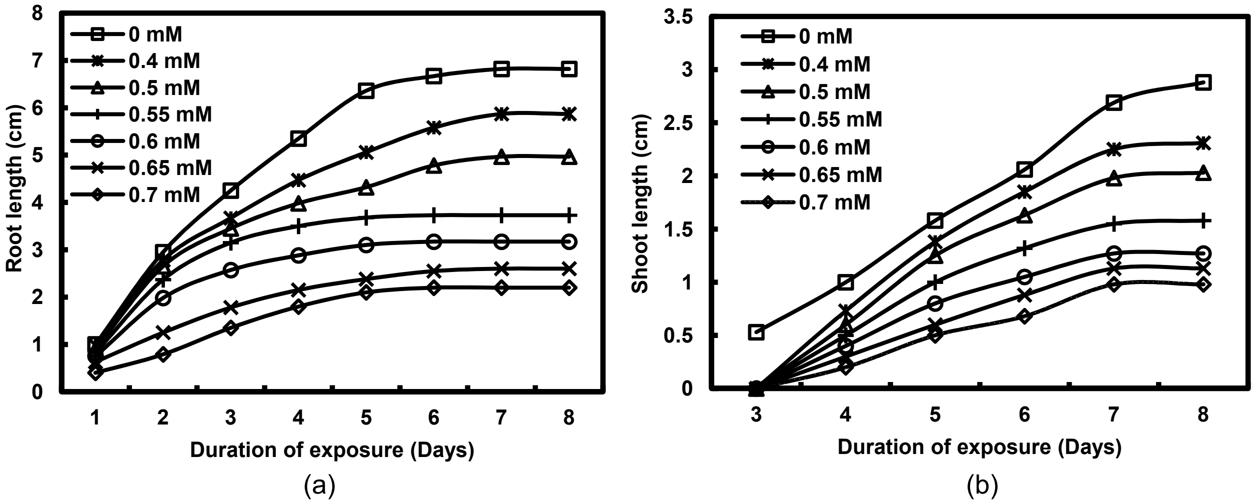

Figure 2. Macroscopic toxicity symptoms of lead ions on the elongation of (a) roots and (b) shoots of *Vigna radiata* seedlings.

3.2 Alterations of photosynthetic pigments

Chlorophylls play a decisive role that is responsible for the control of the photosynthetic process. Chlorophyll-*a*, is the light-harvester that takes part in the redox reaction for the excitation and transportation of electron in the Photosysten I and II (Björn et al., 2009). Chlorophyll-*b* is an accessory chlorophyll presents in the peripheral light-harvesting complexes (Eggink et al., 2001) while carotenoid plays a crucial role to deactivate triplet chlorophyll ($^3Chl^*$) and singlet oxygen ($^1O_2^*$). The alterations of the total chlorophyll, chlorophyll-*a*, chlorophyll-*b*, and carotenoid levels of *Vigna radiata* leaves are illustrated in Figure 3. The control group contained the highest level of total chlorophyll at 11.05 mg/g fresh weight, and it was drastically reduced in a concentration-responsive manner by 12.08 to 38.12 % as the lead concentration was increased from 0.4 to 0.7 mM. A dramatic reduction of the total chlorophyll content was found in black gram (Bibi and Hussain, 2005), eggplant (Yilmaz and Akinci, 2009) and wheat (Lamhamdi et al., 2013) during the exposure to lead ions at the concentrations range of 0.1 to 15 mM, with the reduction within 17.28 to 77.78 % (Table 1). Chlorophyll-*a* showed a similar reduction trend, from 6.66 to 4.66 mg/g fresh weight, while the chlorophyll-*b* was decreased from 4.37 to 2.16 mg/g fresh weight, and the carotenoid was decreased from 1.98 to 1.56 mg/g fresh weight.

These findings were corroborated well with the lead ions irrigation practice on artichoke, wheat, and *Plantago major,* with the inhibition of chlorophyll-*a*, chlorophyll-*b*, and carotenoid content of 0.87 to 36.67 %, 0.15 to 54.34 %, and 24 to 25.33 %, respectively (Karimi et al., 2012; Kosobrukhov et al., 2004; Liu et al., 2010). Lead ions treatment has been reported to inhibit the activities of δ-aminolevulinic acid and dehydratase, with an overall reduction of chlorophyll content (Prasad and Prasad, 1987). Additionally, the presence of lead ions might retard the synthesis of chlorophyll molecules to affect the uptake of essential ions, such as magnesium and iron (Burzynski, 1987). A specific finding to be highlighted in the current study was the higher ratio of chlorophyll-*a* to chlorophyll-*b* of greater than 2.15 after lead treatment, illustrating a greater sensitivity of chlorophyll-*b* to lead ions-induced toxicity than chlorophyll-*a* (Gopal et al., 2002). These findings have verified the lead ions induced oxidative damages on the membraneous structure of chloroplast (Baccouch et al., 1998), with a significant inhibitory impact on the biosynthesis of chlorophyll (Stobart et al., 1985), and activities of functional photosynthetic pigments (Somashekaraiah et al., 1992).

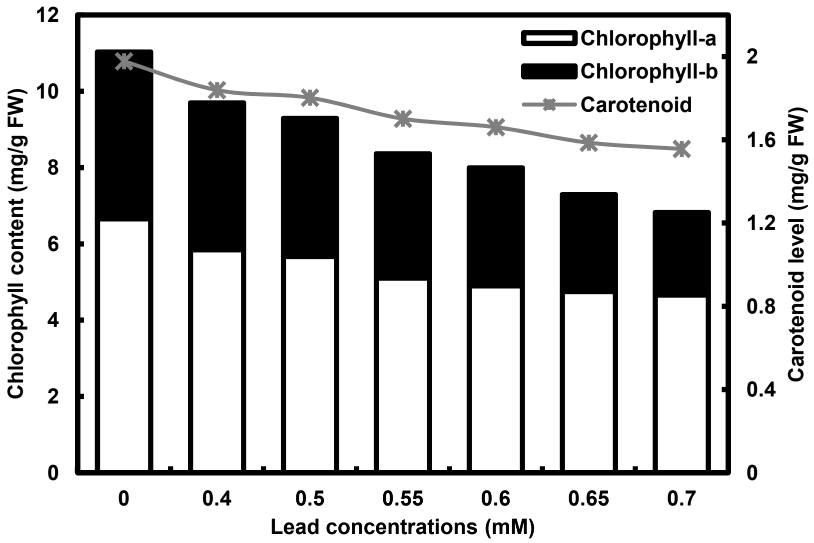

Figure 3. Alterations of photosynthetic pigments: Chlorophyll-*a*, chlorophyll-*b*, and carotenoid levels under lead ions-induced stress.

3.3 Proline level

Lead ions-induced stress has been found to alter the water status in the plant systems, riding to a water deficit conditions. Proline, one of the predominant organic proteinogenic molecules, is known to accumulate in the higher plants under heavy metal-induced stress, to play the protective role in stress resistance and abiotic stressors (Gohari et al., 2012; Nanjo et al., 1999). In this work, the proline content increased gradually from 1.43 to 1.94 µmoles/g fresh weight by increasing the lead concentration from 0.4 to 0.55 mM, and dropped substantially to 0.80 µmoles/g fresh weight at 0.7 mM (Figure 4). These alterations were demonstrated in *Talinum triangulare* and *Phaseolus aureus* (Table 1), as the proline content exhibited an inverted U shape responsive trend, indicating the hormetic impacts against the rising lead concentrations (Kadhim et al., 2011; Kumar et al., 2013). The increase in proline content may be due to de novo synthesis or degradation or both (Kasai et al., 1998) that served as a metal chelator and osmolyte to protect the seedlings against the metal-induced stress. Additionally, proline has been found to combat non-enzymatically against the lead-induced free radicals as the ROS and free radicals scavenger. The reduction of the proline level beyond 0.7 mM could be due to the interruption of excess lead on the biosynthesis enzymes, or a greater proline catabolism at the higher concentration of lead ions (Sharmila and Saradhi, 2002).

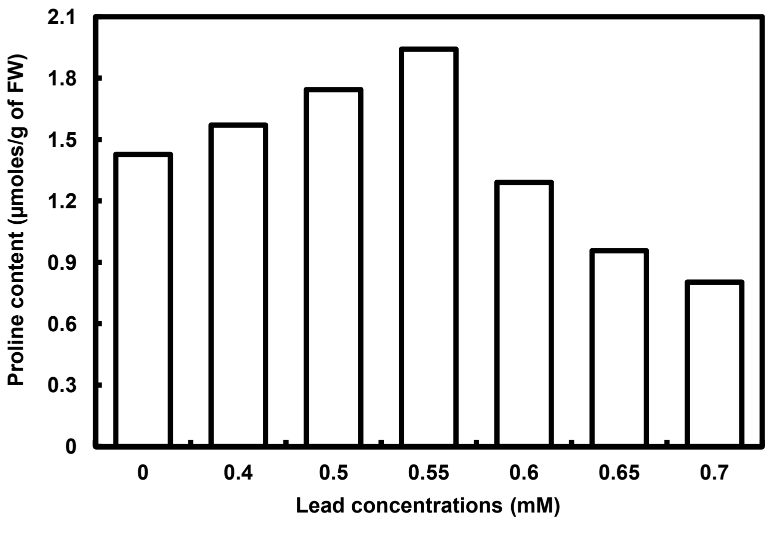

Figure 4. The variation of proline content in *Vigna radiata* seedlings in response to the changing lead ions concentration.

3.4 Antioxidative enzymes

The alteration of CAT, APX, and POD activities in response to the changing lead ions concentration is presented in Figure 5. The APX activity was increased from 18.52 to 37.15unit activity/mg protein by increasing the lead ions concentration from 0.4 to 0.55 mM of lead ions, and beyond the concentration, it steadily decreased to 11.43unit activity/mg protein at 0.7 mM. A similar trend was observed in the CAT activity that increased from 19.32unit activity/mg protein at 0.4 mM to 35.19unit activity/mg protein at 0.55 mM of lead ions and decreased to 8.93unit activity/mg protein at 0.7 mM. However, the POD activity increased progressively from 12.26 to 24.58unit activity/mg protein as the lead concentration was increased from 0.4 to 0.7 mM. The present findings suggested that the presence of lead ion would activate some of the key enzymes in the antioxidant defense system. The enhanced POD activity could be ascribed to the release of POD molecules localized in the cell walls under lead-induced stress (Verma and Dubey, 2003), signaling that this enzyme could play a significant role as the intrinsic defense tool for the protection against lead-induced oxidative damages. The elevation of POD activity was observed in rice plant (Verma and Dubey, 2003; Zeng et al., 2007), that supported that POD is the ROS scavenger when it is subjected to the external metallic stressors. APX, is usually generated during the ascorbate/glutathione cycle in chloroplasts and organelles to specifically degrade H_2O_2 into water and oxygen molecules to preserve the redox condition (Asada, 1992); and CAT, another H_2O_2 quencher in cells shows a lower affinity for the substrate molecules (Willekens et al., 1995), and a lower activity level than APX in the seedlings. Further increase in the lead ions concentration beyond 0.55 mM with a gradually decrease of the activities of CAT and APX indicated the optimum detoxification potential of these enzymes against lead ions to substitute magnesium and iron ions at the surface-active sites (Sharma and Dubey, 2005). The alterations of these antioxidative enzymes activities in *Vigna radiata* were in agreement to the previous work reported on rice (Verma and Dubey, 2003), watercress (Keser and Saygideger, 2010), and *Talinum triangulare* (Kumar et al., 2013) as provided in Table 1.

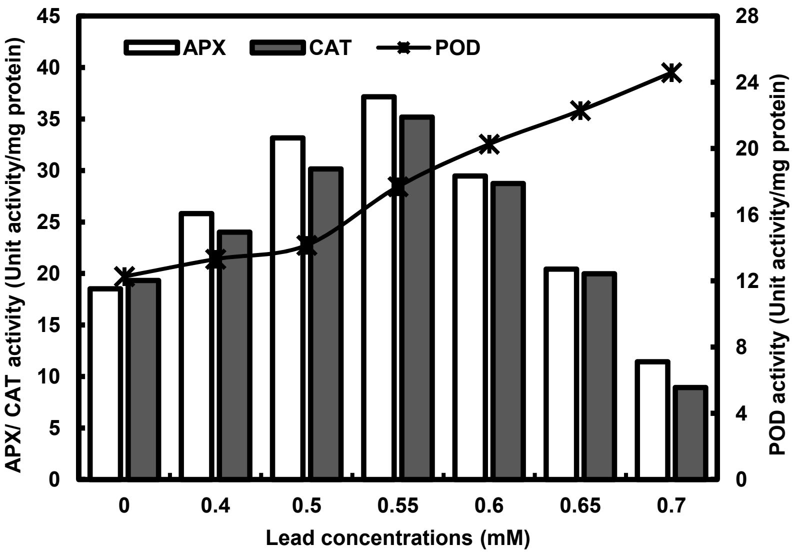

Figure 5. The changing enzymatic activities of guaiacol peroxidase (POD), ascorbate peroxidase (APX), and catalase (CAT) in *Vigna radiata* seedlings in response to the changing lead ions concentration.

Unlike other redox-active metals, lead would induce oxidative stress, leading to the indirect generation of ROS to enhance the pro-oxidant status of plant cells, activate the calcium-dependent systems and disrupt iron-mediated processes (Pinto et al., 2003), resulting in an unbalanced cellular redox status, that could damage the plants cellular machinery (Sharma and Dubey, 2005). The sequential events of ROS production induced by lead ions during the membrane-linked electron transport process, and the associated role of these antioxidative enzymes to maintain the level of ascorbate and glutathione are illustrated in Figure 6 (Sharma and Dubey, 2005).

The present study was a contributory step to a better understanding of the lead-polluted irrigation water practice, and the interconnected effects on the physical indices, physiological parameters and antioxidative responses of the food crops, using *Vigna radiata* as a plant model. The transfer of lead ions from the water-growing medium-plant root system is proposed to be partly via the essential cations transporters, particularly Ca^{2+} and Mg^{2+} gated channel (Kim et al., 2002). Once these ions have penetrated into the root cells, the roots could respond (i) by the synthesis and deposition of callose, to form a barrier against these lead ions; (ii) via the uptake of large quantity of lead ions, and the sequestration in the vacuole, and the alteration in root growth and branching pattern; or (iii) by translocating the lead ions to the aboveground plant parts in hyper-accumulator plants (Fahr et al., 2013). For majority of the plants, 90 % of these lead ions would be accumulated in the roots (Kumar et al., 1995) and localized in the insoluble fraction of cell wall and nuclei, which are responsible for the detoxification mechanism (Piechalak et al., 2002). The overall toxicity effects in plants under lead stress, and the associated pathways of lead-induced alterations in the physical growth, photosynthesis, water regime, and antioxidative enzymes are summarized in Figure 7.

Table 1. A comparison of the lead ions-induced toxicity with respect to the alterations of physical growth, physiological indices, and antioxidative defense system for different plant species.

Plants	Lead ion concentration (mM)	Root length (cm)	Total chlorophyll (mg/g FW)	Proline (µmoles /g FW)	POD (UA/mg protein)	APX (UA/mg protein)	CAT (UA/mg protein)	Reference
Mung bean	0.40 - 0.70	6.80 - 2.20	11.03 - 6.82	0.80 - 1.94	12.26 - 24.58	11.43 - 37.15	9.83 - 35.19	This study
Rice	0.50 - 1.00	13.00 - 8.00	-	-	0.10 - 0.15[a]	-	-	Verma and Dubey (2003)
Black gram	0.10 - 0.24	-	1.91 - 1.42	-	-	-	-	Bibi and Hussain (2005)
B. juncea	0.15 - 1.50	28.20 - 14.00	-	-	-	-	-	John et al. (2009)
Eggplant	0.36 - 1.45	12.20 - 5.90	2.00 - 1.21	-	-	-	-	Yilmaz and Akinci (2009)
Water-cress	0.15 - 1.54	-	-	-	-	4.00 - 13.84[b]	0.50 - 7.00[b]	Keser and Saygideger (2010)
P. aureus	2.50 - 10.00	6.50 - 0.20	1.66 - 0.27	10.00 - 115.70	-	-	-	Kadhim et al. (2011)
Brassica napus	0.10 - 0.40	5.50 - 3.00	-	-	-	-	-	Gohari et al. (2012)
Artichoke	0.10 - 1.50	-	1.54 - 0.82	-	-	-	-	Karimi et al. (2012)
T. triangulare	0.25 - 1.25	-	-	12.00 - 29.00[c]	-	0.12 - 0.37	0.056 - 1.34[a]	Kumar et al. (2013)
Wheat	1.50 - 15.00	-	1.80 - 0.40	-	-	-	-	Lamhamdi et al. (2013)

[a] µmole H_2O_2 reduced/min/mg protein; [b] µmole/min/g fresh weight; [c] mmole/g fresh weight

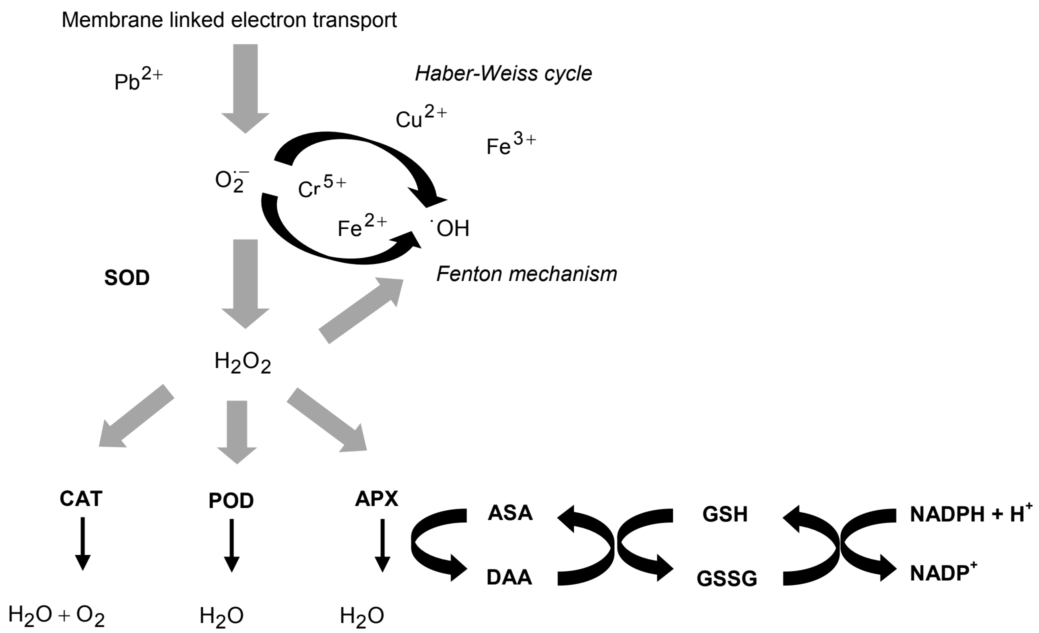

Figure 6. The sequential events of ROS production induced by lead ions during the membrane linked electron transport process.

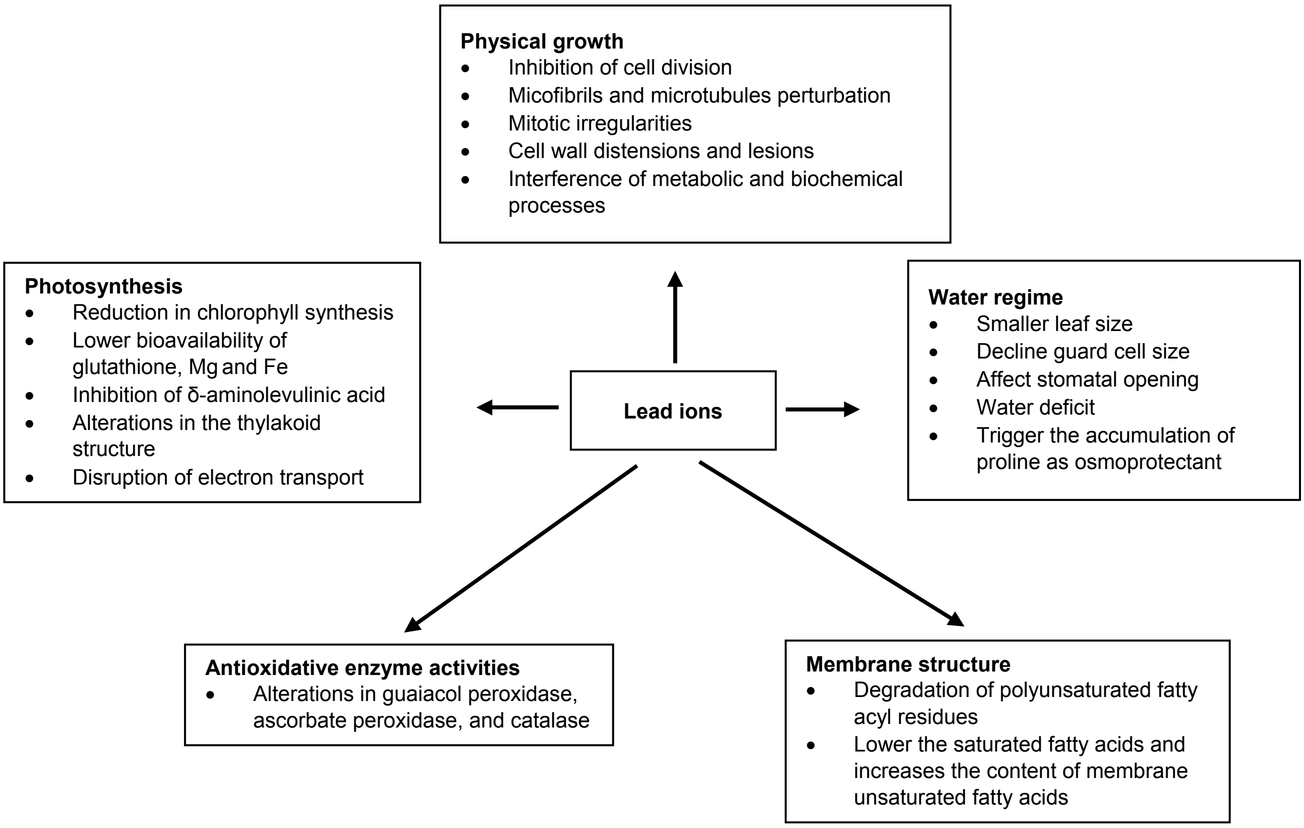

Figure 7. The overall toxicity effects in plants under lead stress, and the associated pathways of lead-induced alterations in the physical growth, photosynthesis, water regime, and antioxidative enzymes.

4 CONCLUSIONS

Lead-doped irrigation water practice has retarded the elongation of roots and shoots of *Vigna radiata*, with the dramatic reduction in total chlorophyll content and carotenoid levels by 38.12 % and 21.30 %, respectively. The contemporaneously increase of proline and alteration of POD, APX, and CAT activities is a signaling pathway to the induction of non-enzymatic and enzymatic defense machinery against the lead ions-induced oxidative damages. These findings have provided a valuable insight into the possible risks of the long term polluted water irrigation on the food crops yield and productivity, food safety, soil suitability for agriculture, and stability of ecosystem.

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DISCUSSION ON URBAN WATER RESOURCES ALLOCATION BASED ON MINIMUM ENERGY CONSUMPTION

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ABSTRACT

Advances in water resources allocation theory has led to significant improvements in the water resources allocation methods. Nowadays, as domestic energy demand increases sharply, it has led to an imbalance between supply and demand of the urban energy. Meanwhile the production, supply, and use of portable water, and wastewater collection, treatment and discharge consume a lot of energy. Hence, water resources allocation methods also need to be revised and improved accordingly. This paper discussed on the ideas and methods of water resources allocation based on the minimum energy consumption principles. It was concluded that the energy value theory will be utilized to analyze the energy consumption of water resource, and construct the energy consumption evaluation function. Moreover, an energy consumption constraint module should be coupled with an existing module, through modeling, in order to reduce the total artificial energy consumption in the process of water resources allocation.

Keywords: Energy consumption evaluation function; energy consumption module; water resources allocation; minimum energy consumption.

1 INTRODUCTION

Every link of social water cycle, including supply, utilization, consumption, drainage, treatment, etc., consumes energy. A research shows that in the U.S. and Saudi Arabia, the electrical energy consumed to satisfy the water resource demand makes up 5%–20% of total electrical energy consumption (Gao, 2012). In China, energy consumption has stepped into a stage of rapid growth since our urbanization rate reached 40.5% in 2003, because energy consumed by urban residents is 2.5 times of that consumed by rural residents (Wenhui et al., 2012). From 2003 to 2011, the urbanization rate rose by 1.35% and energy consumption and per capita energy consumption by 9.5% and 8.5%, in average for every year (China Energy News, September 06, 2012). In cities, the energy supply-demand contradiction is getting worse. China's urbanization stays in a stage of rapid growth, and it will keep developing at high speed in the next 20~30 years. As the country that consumes the most energy in the world, the way to guarantee and save urban energy is a major problem in future urbanization development in China. Reducing the energy consumption in each link of social water cycle will make great contribution to urban energy saving, which has important significance in reality.

This paper summarizes the research progress in recent years, and analyzes the basic ideas of urban water resources allocation based on the minimum energy consumption, and looks forward to the future research direction.

2 RESEARCH PROGRESS

In these years, the structural adjustment of urban water resources and improvement of urban water quality requirements cause the energy consumption of urban water system to increase. European and American countries have paid attention to the energy consumption in water resources utilization. In 2000, Electric Power Research Institute (EPRI) initiated a series of researches into water resources and sustainable development, containing the statistics of public water resources supply and sewage treatment power consumption per user and the prediction of water and power consumption (Goldstein et al., 2002), Kahrl and Roland-Holst (2007) quantified China's energy consumption during water resources utilization with an input-output method and put emphasis on the correlation between capital or economy and water or energy (Kahrl and Roland-Holst, 2007). Siddiqi and Anadon (2011) summarized the water consumption of different kinds of power generation in each link and the power consumption during water resources utilization according to the data provided by several departments of the U.S. (Stillwell et al., 2011) quantified the relationship of water resources with energy sources in Texas, especially the correlation between power generation and water resources; studied the water demand of different kinds of power generation equipment in a typical system throughout the U.S., including Texas; and discussed the energy demand of water supply and sewage treatment systems. Hardy et al. (2012) assessed the current situation of relationship between water and energy in Spain; highlighted Spain's energy consumption in water resources utilization and water consumption in energy utilization; and specially analyzed the energy consumption of agricultural water saving measures.

At present, China's research into energy consumption in water resources utilization is just in the beginning stage. Gao (2012) submitted a dissertation Analysis of Correlation between China's Water Resources Utilization and Power Generation, quantifying the mutual consumption between water resources utilization and power generation and making suggestions on the sustainable development of water resources and energy sources on the basis of water-energy relationship. Wang (2013) submitted a dissertation Study of Energy Saving Control of Urban Water Supply System, analyzing the situation that urban water supply systems are the main power consumer and highlighting that variable-frequency controllers in urban water supply systems can save 5% of electrical energy for water plants. Wen et al. (2014) took the lead in carrying out "analysis of water-energy relationship in urban water resources selection: taking Qingdao as an example", putting emphasis on analyzing the effects of different water resources on the water supply cost, energy consumption, and greenhouse gas emission.

Generally speaking, these scholars carried out exploratory research into the energy consumption in water resources utilization and made progress to a certain extent. Now, analyzing and quantifying the power consumption in such links as supply, utilization, consumption, drainage, and treatment of social water cycle, quantifying the space-time relationship of social water cycle with energy consumption, and quantifying the threshold that energy consumption constrains the water supply capacity of different structures are the difficulties in research.

3 RESEARCH CASE ANALYSIS

3.1 Water supply and energy consumption in the study area

Jinan City is located in the middle of Shandong Province in china, known as the large number of springs, including Urban area, Zhangqiu district, Pingyin district, Jiyang district, and Shanghe district. Taking Jinan City as an example, its situation of power consumption is especially severe, and many large-scale power brownout occurred in recent years. Its biggest power gap in 2008 summer is 900,000~1000,000kW, which goes beyond the load limit of Jinan power grid. According to calculation, that power brownout influences an industrial added value loss of about RMB 90.4 billion, which makes up 8.4% of Jinan industrial added value in that year. The total water demand of the city in 2014 was 16.9 billion m^3, of which surface water supply was 360 million m^3, accounting for 21.3% of the total water supply; groundwater supply was 659 million m^3, accounting for 39.0% of the total water supply; water transfer supply was 595 million m^3, accounting for 35.2% of the total water supply; recycled water and other water supply was 76 million m^3, accounting for 4.5% of the total water supply. The results are shown in Table1.

Table 1. Water supply structure and the energy consumption status quo in the study area.

Administrative Division	Local Surface Water	Ground Water	Unconventional Water Resources	Transferred Water	Total	Energy Consumption
Urban area	1.3	1.7	0.5	3.1	6.6	3.0
Changqing	0.4	0.8	0.0	0.0	1.2	0.2
Zhangqiu	0.4	2.1	0.1	0.5	3.1	0.9
Pingyin	0.3	0.7	0.0	0.2	1.2	0.2
Jiyang	0.2	1.0	0.0	1.7	2.9	0.7
Zhangqiu	1.1	0.3	0.1	0.5	1.9	0.3
Total	**3.6**	**6.6**	**0.8**	**6.0**	**16.9**	**5.3**

unit: billion m3 , billion kWh

By taking the energy consumption by water extraction, treatment, distribution, and disposal processes in 2014 as an example, the ratio of the energy consumption of each part to the total energy consumption associated with water use was analyzed. It can be seen from figure 1 that the energy consumption of water extraction by the four types of water sources (including surface water, groundwater, unconventional water resources, and transferred water) accounts for 58.0% of the total energy consumption, and water treatment and distribution accounts for 27.7% and 14.3%. In the distribution of energy consumption of water extraction by the four types of water sources, because the water supply of Jinan city mainly relies on ground water and transferred water, which accounts for 42.6%. Although it cost a huge energy consumption during the production of unconventional water resources, its actual total energy consumption is the smallest in proportion.

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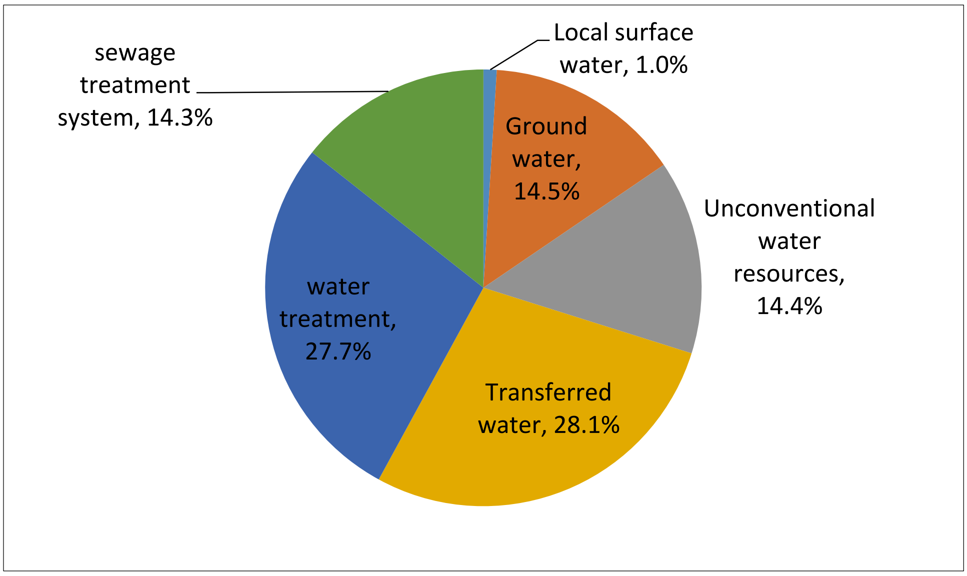

Figure 1. Comparison of Power Consumption in Water Resources Utilization in 2014.

3.2 Water resources supply-demand balance

After the analysis of Water resources supply-demand balance, it shows that the total water demand in Jinan City in 2020 is 20.75 billion m^3, and in 2030, it is 23.39 billion m^3. When P = 75%, the total water supply in Jinan in 2020 is 19.9 billion m^3, including 3.6 billion m^3 of surface water, 6.9 billion m^3 of groundwater, 2.1 billion m^3 of unconventional water resources, 7.4 billion m^3 of transferred water (including the Yellow River tributary water drainage of 0.68 billion m^3), the total water shortage is 85.0 million m^3, and water deficit is 4.1%; the total water supply in Jinan City in 2030 is 22.6 billion m^3, including 3.8 billion m^3 of surface water, 7.6 billion m^3 of groundwater, 3.6 billion m^3 of unconventional water resources, 8.4 billion m^3 of transferred water (including the Yellow River tributary water drainage of 0.68 billion m^3), the total water shortage is 78.6 million m^3, and water deficit is 3.4%. The results are shown in Table 2.

Table 2. Planning the balance of supply and demand of water resources in Jinan City (P = 75%).

Planning Year	Administrative division	Water demand（billion m3）	Water supply（billion m3）Local surface water	Ground water	Unconventional water resources	Transferred water	Total	Water shortage（million m3）	Water deficit（%）
2020	Urban area	8.3	1.2	1.7	1.4	3.7	8.0	34.6	4.2
	Changqing	1.6	0.7	0.7	0.1	0.0	1.6	7.5	4.6
	Zhangqiu	3.8	0.8	2.0	0.3	0.6	3.7	7.0	1.9
	Pingyin	1.3	0.3	0.6	0.1	0.3	1.3	6.5	4.9
	Jiyang	3.5	0.3	1.0	0.1	1.9	3.3	19.5	5.7
	Zhangqiu	2.2	0.2	1.0	0.1	0.8	2.1	9.9	4.4
	Total	20.7	3.6	6.9	2.1	7.4	19.9	85.0	4.1
2030	Urban area	9.8	1.7	1.7	2.3	3.8	9.5	30.9	3.2
	Changqing	1.8	0.5	0.7	0.3	0.4	1.8	7.3	3.9
	Zhangqiu	4.0	0.8	2.0	0.5	0.6	3.9	9.5	2.4
	Pingyin	1.4	0.3	0.6	0.1	0.4	1.4	5.8	4.0
	Jiyang	3.8	0.3	1.0	0.2	2.2	3.6	14.1	3.7
	Zhangqiu	2.5	0.2	1.0	0.2	1.0	2.4	11.0	4.3
	Total	23.4	3.8	6.9	3.6	8.4	22.6	78.6	3.4

3.3 Energy consumption prediction of water supply

By combining the target of energy saving in Jinan city, and based on the former statistical information, and the survey data from Shandong institute of electric power, water supply plant, and wastewater treatment plant, we analyzed and summarized energy consumption in various water supply processes. The energy consumption of water supply is shown in Fig. 2.

According to the forecast of water demand and the analysis of supply and demand balance, using unconventional water resources and transferred water to solve the problem of increasing demand on water resources is feasible considering water conservation. The total water supply in Jinan City increase 6.0 billion m^3, but the consequence of adopting the program is that the energy consumption by water supply of Jinan city in 2030 will be twice of that in 2014. This result shows that under present technical conditions, using unconventional water resources and transferred water to solve water resource problems is to pass the pressure of expanded water shortage to energy production. To reduce the pressure caused by usage of water resources, energy consumption (especially electric consumption) should be taken into full consideration in the selection of water saving technology and the solution to water shortage.

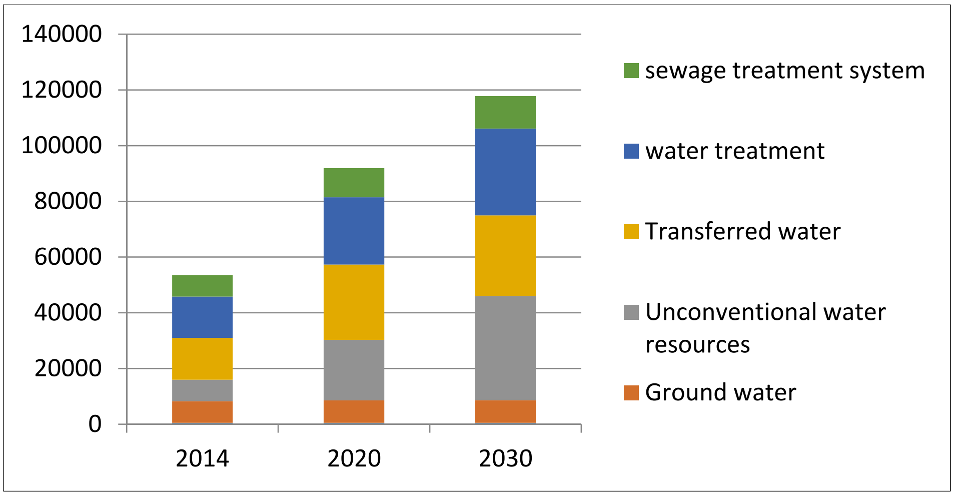

Figure 2. Energy consumption of water supply.

4 FUTURE RESEARCH THINKING

Specific to China's current situation where urban energy supply is short but links such as supply, utilization, consumption, drainage, and treatment of water resources consume a large number of energy, we should perform a quantitative analysis of energy consumption to build an energy consumption evaluation function, which can recognize the advantages and disadvantages of various water resources, on the basis of previous research; and we should also analyze the water supply threshold of various water resources, aimed at minimizing the overall artificial energy consumption.

For urban water resources allocation, basic information, including the available amount of urban water resources, is the basis. We should analyze and determine the available amount of water resources in the study area by sorting out the basic data. On one hand, we should adopt the energy theory and method to quantify the energy consumption in links such as supply, utilization, drainage, and treatment of different water resources and to compare the quantitative values, taking solar energy as the benchmark; comb the energy consumption in water resources utilization; and build an energy consumption evaluation function by using logistic regression model and trend extrapolation. On the other hand, we should start with mathematical modeling to develop an energy consumption constraining module and add the energy consumption threshold to allocation principles in terms of reducing artificial energy consumption and in view of the risk features, supply potential, and energy consumption of various water resources, before we build a lowest energy consumption based water resources allocation model. The coupling between energy consumption module and existing water resources allocation model requires that the physical connotation and physical process of parameters are expressed in unity and also requires harmonious analog spatial and temporal scales. The structure of model is shown in Fig. 3.

5 CONCLUSIONS

Faced with China's current situation where urban energy supply gets more and more intense but water resources utilization consumes a large number of energy, a new thought of water resources allocation is to explore the urban water resources allocation based on energy consumption. The philosophy and principle of water resources allocation are changing with economic development and cognitive progress. In urban water resources allocation, faced with the severe challenge of energy supply during urbanization, considerations of the methods to select water source from surface water, ground water, transferred water, reclaimed water, rainwater, sea water desalination, etc., the methods to make a scientific distribution in time and space among different users, and the methods to save and restrict the energy consumption in supply, utilization, consumption, drainage, treatment, etc. links, as well as more scientific consideration of water supply sources allocation, can provide technical support for building safe and intensive water supply and utilization systems in cities.

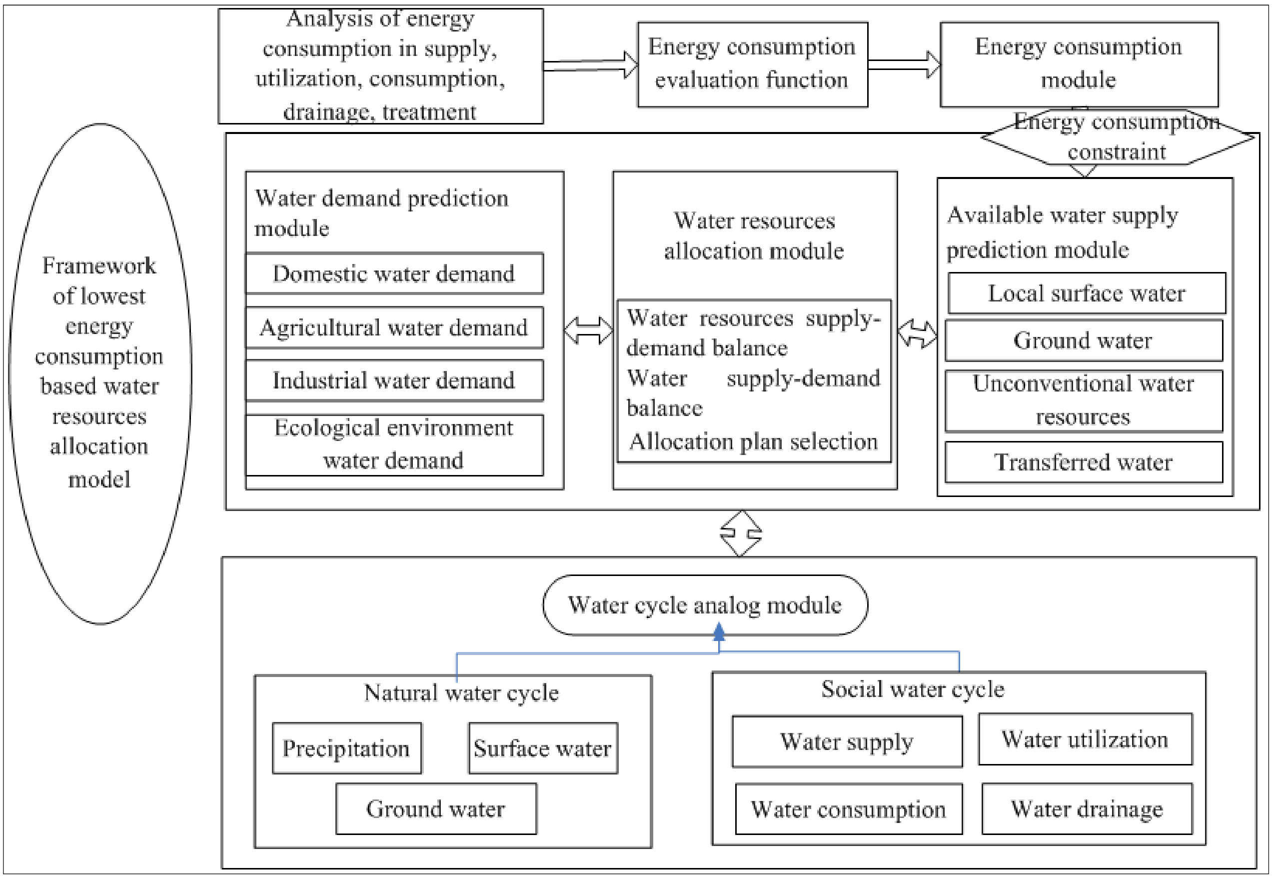

Figure 3. Model framework diagram.

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BALANCING DEVELOPMENT OF COAL-ELECTRICITY POWER WITH AVAILABLE WATER RESOURCES IN MAJOR COAL BASES OF CHINA

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ABSTRACT

The production and distribution of coal are relatively independent. Coal production is concentrated in the northwest region while coal is mostly consumed in the eastern region. The loess plateau in the upper and middle Yellow River valley and northwest inland basin are the main bases of coal resources and heavy chemical industry in China, where are in a shortage of water resources. As the result, expanding the scale of the coal-electricity power will put more pressure on local water resources, and the environmental pollution has become more and more serious. This study analyzes the available water resources and water requirements of coal-electricity power based on development planning of coal bases and the strictest water management measures. Results has shown that the newly increased water demand of coal-electricity power in the fourteen large-scale coal bases will reach 1.9 billion m3 by 2020, and the newly increased available water supply of major coal bases will reach 4.5billion m3, but water resources will become the weak link, restricting the coal-electricity power industry development of coal bases in areas such as Shendong, Eastern Shanxi, Huanglong, and Henan; other coal bases will have water resources to support the development of coal-electricity power by building water supply projects, utilizing unconventional water resources and water right displacement from other regions. The scenario where severe water resources challenge China’s energy development strategies are foreseeable; therefore, the scale of coal-electricity power should be decided by water resources, and it is necessary to begin expanding supply and controlling demand in order to guarantee the water supply required by these coal bases. This paper gives scientific support for coordinated management of water and energy nexus.

Keywords: Water resources; coal-electricity power; newly available water supply; coal bases; water and energy nexus.

1 INTRODUCTION

Coal-electricity power generation is the most important way of generating electricity in China. In order to meet the strong demand of electricity for economic and social development, the output of coal-electricity power is increasing year by year (Cutter et al., 2014). Coal-electricity power, in the development and production process, is inseparable from the consumption of cooling water (Feng et al., 2014). For the arid areas of northwest China, the water supply and demand contradiction has gradually become an important factor in restricting the development of coal-electricity power. With the increasing emphasis on the ecological environment of the country, the coordination of water and energy has become a research hotspot in recent years. China’s energy development strategy is to meet surging energy demand by increasing supply from the main producing areas. According to the energy development strategy action plan (2017-2020) released by the State Council in September 2014, China will build nine 10 GW (Gigawatt) coal-power bases. However, these regions are arid or semi-arid and mainly rely on natural precipitation less than 400mm. The relationship between water resources and the energy system is very complex. Energy conservation and water conservation are not simply identical and not always consistent. In some cases, energy conservation can produce water savings, but in some cases, entails more water consumption.

China is rich in coal resources, accounting for 96% of China's petrochemical energy reserves, coal-electricity power generation scale still has a larger room for growth (Che et al., 2013). By the end of 2013, China's coal-electricity power generation capacity reached 4,221.6 billion kWh, with a year-on-year increase of 7.54% (Jiang and Wang, 2010). According to the national and provincial medium and long-term energy development plan, coal-electricity power installed capacity will reach 4.548 trillion kWh in 2020, far more than hydropower, nuclear power, wind power and other clean energy (Geng et al., 2003). The rapid development of coal-electricity power along with the rapid growth of water consumption, accounted for 40% of the national total industrial water intake (Xiang and Jia, 2016). With the development of society and economy, the competition of water use between various departments are becoming more and more intense, and the local water resource endowment has difficulties to support the huge energy (Chen et al., 2011; Chen et al., 2012). Although the state encourages new and expanded coal-electricity power plant project to adopt new technologies to reduce water consumption, such as supercritical units and air-cooled power generation, water shortage has gradually become one of the biggest bottlenecks restricting energy development (Sun et al., 2015). According to the "12th Five-Year Plan" for the development of coal industry, China has planned 14 large-scale coal bases (northeast, north and southwest, including Shendong, Shanxi, Jindong, Mengdong, Huangzhong, Jizhong, Ningdong, northern Shaanxi and Xinjiang coal bases) to develop coal, coal and coal chemical industry (Jiang et al., 2012). China's coal-rich areas and water-rich regions have the reverse distribution, a total of 10 large-scale coal bases are distributed in the annual precipitation less than 400mm, with prominent contradictions between supply and demand of water resources (Zhang et al., 2015; Zheng and Wei, 2012). Based on the development plan of 14 large coal bases, the paper calculates the water consumption of new coal-electricity power generation in 2020, and analyzes the contradiction between the strong demand of water resources and the lack of water resources support to put forward water and energy development proposals.

2 OVERVIEW OF THE STUDY AREA

The 14 coal bases are located in China's 15 provinces (autonomous regions) (Figure 1). The coal production of those coal bases in 2013 was 3.36 billion t, accounting for 91% of total the production in China. The coal bases in Shendong, Jinbei, Jinzhong, Jindong and Northern Shaanxi are in Central China and Western China, mainly supplying coal to the areas of East China, North China and Northeast China. Jizhong, Henan, Luxi, Lianghuai bases are responsible for suppling coal to the Beijing-Tianjin-Hebei, Central and South East. Mengdong base supplies coal to the three northeastern provinces and the eastern part of Inner Mongolia. Yunnan-Guizhou base was responsible for the southwest, central and southern regions of coal supply. Huanglong base, Ningdong base bear the coal supply to the northwest, east, central and southern regions.

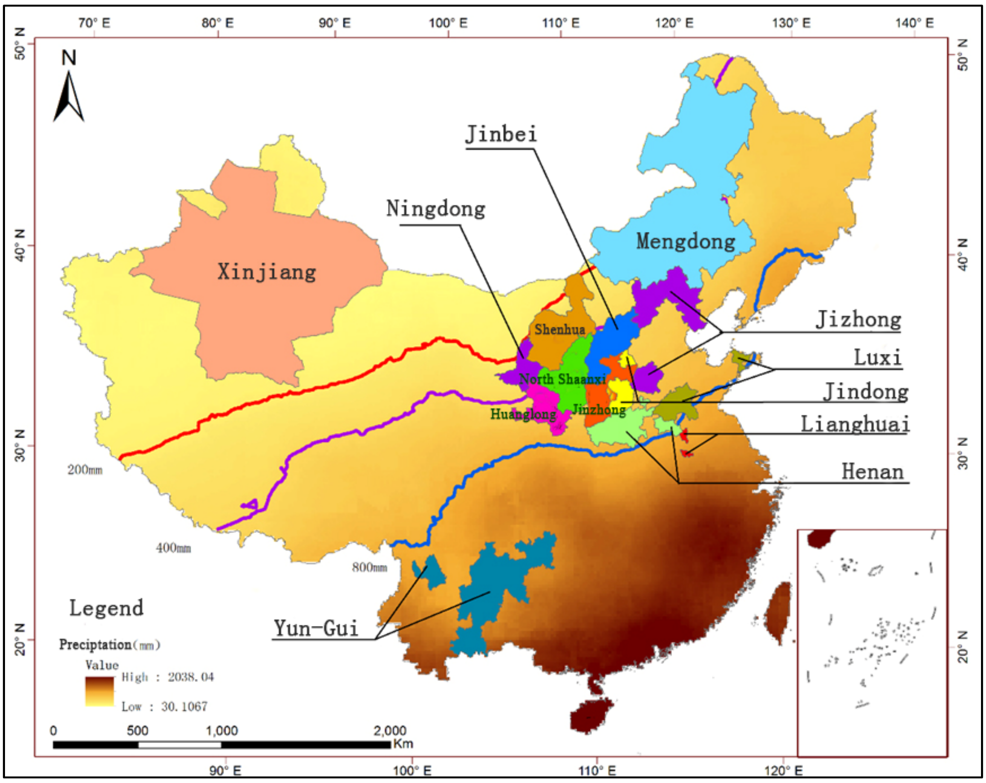

Figure 1. The Location of main Coal Base in China.

3 DATA AND METHOD

3.1 Data sources

(1) Water quota: Industrial water quotas are the amount of water required to provide a unit quantity of industrial products, including water withdrawal and reuse (Cao et al., 2003). Table 1 is the 14 coal-electricity power plants in the province with the standard fixed water situation.

Table 1. Quota standard for coal-electricity power generation in the provinces under the jurisdiction of large coal bases.

Base name	Province	Water quota of coal-electricity power (m^3/Mw.h)					
		Once-through cooling		Circulating cooling		Air cooling	
		≤300MW	>300MW	≤300MW	>300MW	≤300MW	>300MW
Shendong Mengdong	Inner Mongolia	1.2	0.72	4.8	3.84	0.8	
Ningdong	Ningxia			4.8	3.84		
northern Shanxi							0.432
Jinzhong	Shanxi					0.54	
Eastern Shanxi							
Northern Shaanxi	Shanxi			3.2	2.75	0.95	0.63
Huanlong	Gansu	1.2	0.72	4.8	3.84		
	Shanxi			3.2	2.75	0.95	0.63
Xinjiang	Xinjiang			3.889			
Jizhong	Hebei	1.2	0.72	3	2.39	1.2	2.15
Henan	Henan	1.2	0.72	4.8	3.84		
Lianghuai	Anhui	100-120	60-100	3.2	2.75		
Lusi	Shandong	1	0.5	3	3.5		
Yungui	Guizhou			3.6	2.9		
	Yunnan	0.79	0.54	3.2	2.75	0.95	0.63

(2) Water supply and water consumption: The supply and consumption data of water resources in 14 coal bases are mainly based on the 2012 Water Resources Bulletin and the integrated water resources planning in 15 provinces. The red line control target for water resources in 2020 is mainly based on the most stringent water resources management system.

(3) Coal-electricity power production and consumption: The data of coal-based electricity production, consumption, are mainly based on the 2012 China Power Yearbook. The development of power generation in 2020 is mainly based on the 12th Five-Year Plan for Energy Development, the 12th Five-Year Development Plan for Electricity, the Medium and Long-term Energy Development Plan (2004-2020) and the Energy Development Strategy Action Plan (2014-2020).

3.2 Research methods

According to the strictest water resources management system, firstly, the availability of local water resources and the rationality of water abstraction were analyzed; secondly, the local water supply capacity was analyzed to confirm the reliability of water supply; finally, the water consumption of coal-electricity power generation was estimated that whether it is more than the red line control target value.

(1) The amount of new water resources available for coal bases

Firstly, in this paper, we set 2012 as the base year, and calculated new water resources available in 14 coal bases from 2012 to 2020. According to the most stringent water management system, the water resources were allocated to 14 coal bases in 2020 (PWA_{2020}), and subtracted by the amount of water resources used for each coal base in 2012(CWC_{2012}), is allowed to increase the amount of water available (IncPWA), the unit is $10^8 m^3$.

$$IncPWA = PWA_{2020} - CWC_{2012} \qquad [1]$$

Secondly, according to the integrated water resources planning of 14 provinces, the available water resources (WSC_{2020}) of all water conservancy projects in 2020 were calculated, and subtracted by the amount of available water resources (WSC_{2012}) in 2012, the difference is the engineering increase Water resources (IncWSC).

$$IncWSC = WSC_{2020} - WSC_{2012} \qquad [2]$$

Thirdly, in 2020, the local maximum available water supply increment was determined by the relatively small value of the regional engineering water supply capacity (IncPWA) and Incapable Water Resources (IncWSC), and the lowest value is the new water supply capacity (Inc) of the coal base.

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$$Inc=min（IncPWA，IncWSC） \quad [3]$$

Finally, this paper considers that some provinces (such as Inner Mongolia and Ningxia) have begun to implement water right transfer (WRD), with industry to feed agriculture and transfer agricultural water savings to industry. Therefore, the amount of available water resources (AWSI) for coal bases is:

$$AWSI= Inc+ WRD \quad [4]$$

(2) The increase amount of coal water resources available

This paper assumes that the proportion of water use by industry in 2020 is similar to that in 2012. The ratio of coal-electricity power water consumption to coal-based water consumption is ratio2012, so the amount of new water resources available for coal-electricity power is:

$$WS=AWSI×ratio2012 \quad [5]$$

(3) The amount of water for coal-electricity power generation

In 2020, for the 14 coal-electricity power plants in the strict implementation of the provinces where the coal-electricity power water demand quota, the water consumption is:

$$Wi=Ei×quotai \quad [6]$$

4 RESULTS

4.1 Coal-electricity power water consumption in bases

Those 14 major coal bases involved in the 66 administrative regions had the total water consumption of 100.9 billion m3 in 2012, which the industrial water consumption was 15.49 billion m3. The 14 coal bases in the total water consumption of 4.415 billion m3, accounting for 4.4% of the total socio-economic water use, and accounting for 28.5% of the total industrial water. As shown in Figure 2, the proportion of water use in the total industrial water consumption was significantly different. Among them, Shendong, Northern Shaanxi and Huainan Huai, the three major coal bases accounted for more than 50% of the total industrial water consumption. Xinjiang and Jizhong, the two-major coal-base water consumption accounted for the lowest proportion of local industrial water at 11%, and the remaining major coal-base ratios were between 20% and 45%. In Huanglong, Henan, LiangHuai, Luxi, Yunnan-Guizhou and other five coal bases, coal-electricity power generation water accounted for more than 60% of the total base water.

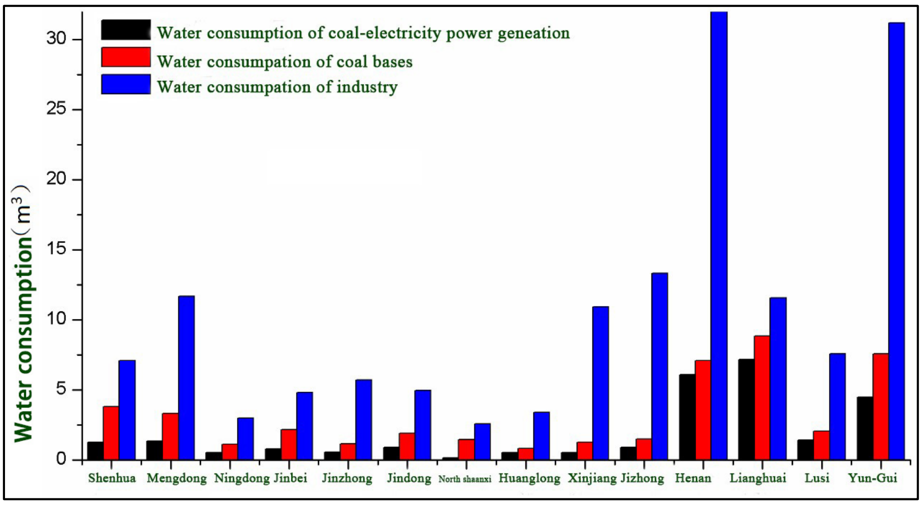

Figure 2. Water consumption in 14 coal-electricity power generation bases.

4.2 The water resources in coal bases

According to Table 2, in 2012, the total amount of water resources in 66 administrative regions of 14 major coal bases was 231.8 billion m3. Several energy bases in Ningxia, Shanxi, Shaanxi, Hebei, Henan and Shandong provinces mainly rely on local water resources. In 2020, the total amount of water used in 14 large coal bases is 113.6 billion m3, of which the current water consumption of Xinjiang coal base area has exceeded the total water consumption control target of 2020, and the other coal bases have 16.7 billion m3. The water consumptions of Shendong, Ningdong, Jindong, Lianghuai, Xinjiang and other coal bases are close to the red line, and the exploitation of water resources and the seeking of the supply of water resources outside the region will be the main way to ensure the water demand of energy base. For other coal bases, the main ways to increase water supply in the future include the construction of new water source projects in the areas with potential development of water resources, as well as the reuse of reclaimed water, mine water and brackish water through the tapping and potential optimization of existing engineering facilities. A variety of measures to protect the energy base for the development of water supply.

Table 2. 14 large coal – electricity based water resources utilization.

coal – electricity based	Annual precipitation （mm）	Total Water resource （$10^8 m^3$）	Water consumption in 2012（$10^8 m^3$）	“the red line” in 2020（$10^8 m^3$）	Available space （$10^8 m^3$）
Shenhau	168-286	37.43	29.15	30.18	1.03
Mengdong	265-442	473.82	82.42	109.46	27.04
Ningdong	196-255	1.85	42.84	43.51	0.67
Jinbei	406-498	48.15	23.69	30.63	6.94
Jinzhong	467-574	46.64	36.68	48.50	11.82
Jinbei	526-630	28.99	13.01	13.87	0.86
North Shaanxi	394-534	40.35	9.96	16.15	6.19
Huanglong	468-610	38.29	17.45	23.60	6.15
Xinjiang	47-220	441.13	353.7	313.38	-40.32
Jizhong	391-576	105.83	84.53	96.58	12.05
Henan	546-821	127.00	112.33	130.84	18.51
Lianghuai	851-887	18.30	22.91	24.52	1.61
Luxi	665-802	134.97	75.98	90.96	14.98
Yun-Gui	983-1396	775.64	104.52	163.77	59.25
Total	**168-1396**	**2318.39**	**1009.17**	**1135.95**	**126.78**

4.3 Analysis on supply and demand match of water resources in coal bases in 2020

According to national and local "Twelfth Five-Year plan", long-term development planning, we plotted the new coal-electricity power installed capacity of the 14 coal bases in 2020 (Figure 3). The five major energy bases of Mengdong, Shendong, Xinjiang, Ningdong and Shannxi are the fastest growing areas in the future. In 2020, the installed capacity will reach 86,700 MW, 52,900 MW, 52,800 MW, 45,700 MW, 3.91 million MW respectively, accounting for 61% of the total installed capacity.

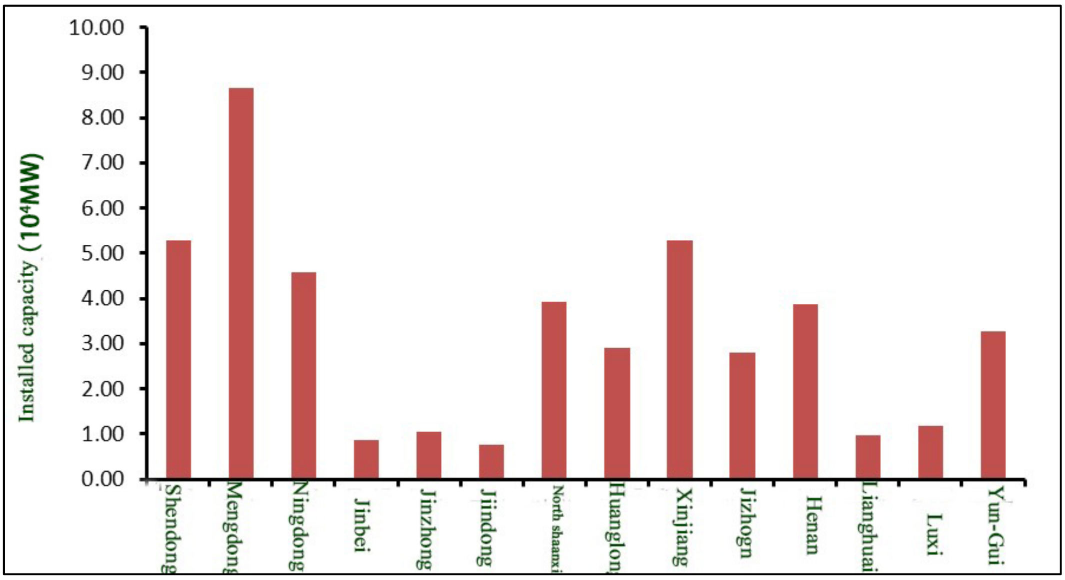

Figure 3. China’s 14 major coal bases additional installed capacity in 2020.

Assuming the water efficiency of existing coal-electricity power maintain the same, and the new coal-electricity power installed capacity are all air-cooled units, the predicted major energy bases of the new water demand is about 1.93 billion m3 under the water quota limit. As shown in Figure 4, the newly installed capacity of Mengdong, Shendong, Ningdong and Xinjiang in 2020 is more than 200 million m3, which is the area where power generation is concentrated. By contrasting and analyzing the new coal demand water quantity of 14 coal bases in 2020 and the newly increased water supply capacity in 2020, it can be found that the new water supply capacity of the four coal bases of Shendong, Jindong, Huanglong and Henan cannot meet the new

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requirements. Mengdong, Ningdong, northern Shaanxi and other three coal bases of the new water supply capacity meet the new coal-electricity power demand for water, but the new coal-electricity power water demand for new coal-based water supply capacity. Jinbei, Jinzhong, Xinjiang, Jizhong, Lianghuai, Luxi and Yunnan-Guizhou can meet the future water demand of base coal by constructing new water source project and developing very water resources and regional water volume replacement.

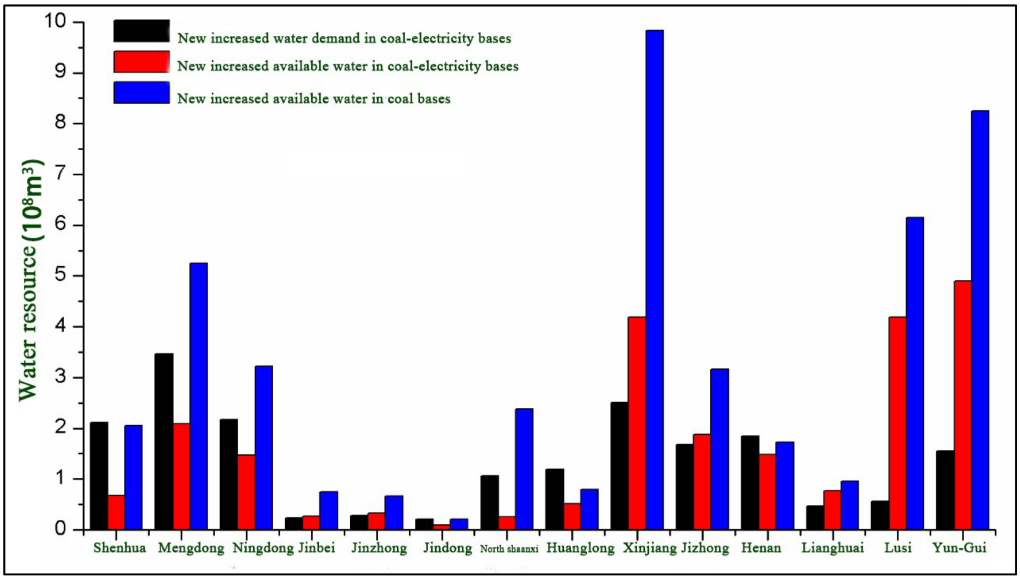

Figure 4. Analysis on Supply and Demand Match of Water Resources in Coal

5 DISCUSSIONS

5.1 Water resources become the main limiting factor of developing coal-electricity bases

The future water supply of coal base is mainly restricted by "The Three Red Line" in the most stringent water management system. By contrast, in 2020, the new water demand of Shendong, Jindong, Huanglong, Henan and other four coal-electricity coal base will not be guaranteed. At the same time, the water use efficiency of these four coal bases is already very high. Most of them use circulating cooling or air-cooling to generate electricity (Shang et al., 2016), so the water-saving potential is limited. The four major coal bases are also agricultural provinces, and more than 70% of the water resource is used in agriculture. For the protection of food security, the feedback of agricultural water into the industrial space is very small. The four coal bases need rational planning of the local water resources and coal power development scale.

5.2 The impact of West-East electricity transmission project on water use

In order to reduce the pressure on the middle and eastern coastal areas and reduce the pressure of coal-electricity transportation, the coal-electricity in the northeast, northwest and southwest are transformed into electric power resources and transported to the eastern coastal areas where electricity is scarce, we call this as "West-East electricity transmission project" (Wang et al., 2015). By the end of 2013, 12 provinces in the central and eastern electricity receiving areas, and the total transport scale reached up to 90 million kW. According to the basic structure from west to east and from north to south, the electric power energy of Beijing, Tianjin and Shandong mainly come from Shenhua, Ningdong, Shanxi and northern Shaanxi coal-electricity bases; the electrical power energy of East China regional mainly come from Sichuan hydropower, as well as Xinjiang, Huang Long, and Ningdong coal-electricity power. The coal-electricity power transmission from Shenhua Coal Base to Beijing-Tianjin-Hebei region is about 107 billion kWh, which is equivalent to 121 million m3 of water resources, according to the water resources consumed by the production units. From Jinbei, Jintong to Hebei, Shandong, accompanied by the transmission of coal-electricity power is 0.73 million m3 of water; the power transported from the Huanglong coal base to the central region associates with the virtual water of 13 million m3. This shows that the West-to-East power transmission not only transforms the abundant coal resources into electricity in the northwest region, but also causes the shortage of water resources in the northwest region to the eastern region, which aggravates the pressure of water resources in the power transmission area.

6 CONCLUSIONS

By 2020, the new coal demand water volume will reach 1.9 billion m3; the new water supply capacity of the 14 coal-electricity bases is 4.5 billion m3, of which, 2.3 billion m3 water resource can be used for coal-electricity power. The new supply capacity of Shendong, Jindong, Huanglong, Henan and other four coal bases cannot meet the demand of new coal-electricity electricity, and the restraint effect of water resources is more obvious; other coal bases can be constructed by new water source project.

Water use efficiency of Northwest China Coal Base has been very high, and most of the coal-electricity power generation used circulating cooling or air-cooled, so water-saving potential is limited. In addition, the problems of water resources and ecological environment in Northwest China are becoming more and more prominent, such as over-exploitation of groundwater, reduction of biodiversity, serious water pollution and so on. The development of large-scale coal-based electricity bases will aggravate the water shortage pressure in Northwest China.

West-to-East power transmission is a strategic measure to optimize the allocation of power resources in China, but the Northwest power transmission area is concentrated in the middle and upper reaches of the Yellow River and the inland river basin in Northwest China. By 2020, the increase of water use in coal-electricity power generation will be beyond the local most stringent water management system. The economic and policy-oriented transmission of electricity from west to east is based on the demand side for electricity production, which will increase the pressure on water resources in the northwest region. In the current planning, water and energy planning are independent of each other, not in accordance with the coordinated development of the two-unified planning, which cannot promote synergies between water and energy sustainable development. The future development of power needs to be considered from the supply side to limit the scale of coal power development in Northwest China.

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STUDY ON WATER QUANTITY REGULATION TECHNOLOGY BASED ON HIERARCHICAL WATER USE AND ECO-ENVIRONMENTAL FLOW

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ABSTRACT

The traditional single-hierarchy of water use priority (Domestic water use - Irrigation water use - Industrial water use - Ecological water use) for water resources allocation is not compatible with practical requirement in water deficient and highly competitive areas; allocation results cannot guide practice. To realize the reasonable water resources allocation and guarantee the dispatching implementation of eco-environmental flow, the concept of hierarchical water use is put forward, which distinguishes water users into different levels. The thought of water quantity regulation based on hierarchical water use and eco-environmental flow was proposed. A water quantity regulation model was constructed for regulating calculation of ecological water. To evaluate the applicability of the proposed model, the method was applied to a case study in the water-stressed Weihe River Basin, China. The balance of water demand-supply and flow processes for key sections under different scenarios can be obtained. Compared with the three-level management targets of eco-environmental flow, the guarantee rate of ecological water for each section is discussed. Although further study is desired, the results are believed to be an important referential value to sustainable development in the basin.

Keywords: Hierarchical water use; water demand level; eco-environmental flow; water quantity regulation model; Weihe River Basin.

1 INTRODUCTION

Water is an essential and irreplaceable resources for human beings and their development. With the rapid development of the economy and society, water resources management is now facing various problems, such as the contradiction between water supply and demand, water pollution and water ecosystem degradation (Jenerette and Larsen, 2006; Sahrawat, 2010; Hirt et al., 2012). The rational allocation of water resources is the main regulation measure to achieve fair and effective distribution of water resources among different regions and water users (Tayyebi et al., 2014; 2015; 2016). The way to effectively coordinate the relationship among society, economy and ecology and realize the benign development among them has become key issues (Fang et al., 2003; Liu et al., 2009; Meanwhile, 2015).

Since the 1950s, the development of computer technology has been introduced to the research of rational water resources allocation (Li and Huang, 2008; Guo et al., 2009). Gradually, studies on rational allocation of water resources have shifted from optimal operation of reservoirs (Teegavarapu and Simonovic, 2002) to water resources planning and management (Jowett, 1997; Orr et al., 2007), water resources exploitation and utilization (Jaarsma et al., 1999), risk assessment of drought and flood disasters (Zhang et al., 2012) and watershed environment management (Xiang et al., 2014). With the increasing development and utilization of water resources, ecological water was taken by industrial and domestic water consumption, which led to a disquieting decline of the riverine ecosystem. Since the 1990s, researches on reasonable water resources allocation have gradually evolved from demand-decided mode into macroeconomic-oriented and ecological-oriented mode (Lind and Davalos-Lind, 2002) and from pursuing maximum economic benefits into pursuing maximum comprehensive benefits of society, economy and ecology (Liu, 2010; Han et al., 2011; Anderson et al., 2012; Nouiri, 2014). The concept of rational allocation of water resources based on ecosystem has been introduced (Wang et al., 2005; Huang et al., 2008; Deng et al., 2013). As can be seen, current researches have taken the eco-environment protection of river channels into account. However, traditional single-hierarchy of water use priority for water resources allocation is not compatible with practical requirement in the water-stressed basin, allocation results cannot guide practice. In order to realize the reasonable water resources allocation and guarantee the dispatching implementation of eco-environmental flow, a new method should be proposed.

The water resources system is a complex system with multiple projects, multiple users, and multiple water sources. As one of the important elements, water demand grades determine the competitive relationship among water users for public water resources. Aiming at realizing sustainable development of socio-economy and eco-environment in the basin, this paper proposes the concept of hierarchical water use, which distinguishes water users into different levels. The connotation of water quantity regulation based on hierarchical water use and eco-environmental flow is introduced. The water quantity regulation model is constructed. The method is applied to a case study in the Weihe River Basin, so as to evaluate the applicability of the newly suggested method.

2 WATER QUANTITY REGULATION BASED ON HIERARCHICALWATER USE AND ECO-ENVIRONMENTAL FLOW

2.1 Connotation of hierarchical water use

Article 21 of the Water Law explicitly states that exploitation and utilization of water resources should firstly satisfy the domestic water use, followed by irrigation, industry, eco-environmental water use, and lastly navigation water use, and eco-environmental water demand should be fully considered especially in arid areas and semi-arid areas. This article reflects the thought of giving priority to the basic requirement for water users and protecting the eco-environment. However, with the rapid development of the economy and society, the water resources situation in water-stressed basin is more serious than ever before. Many rivers have been suffering from various problems, such as water resources insufficiency, water pollution and water channel blockage. The priority sequence for water users is defined roughly, and lack of maneuverability (Yao et al., 2005). The eco-environment water is taken by industrial and domestic water uses, which leads to a disquieting decline in riverine ecologic functioning. Thus, it is necessary to distinguish water users into different levels and rebuild a priority sequence for different water users. Jia et al. (2014) put forward the concept of hierarchical water use based on the cost-benefit theory, which describes the relationship among water use, cost and benefit. The sensitivity between cost and benefit in the water use process are time-varying. To achieve the maximum potential productivity with limited water resources, it is necessary to divide water demand process for each water user into three levels, minimum water demand, appropriate water demand and maximum water demand. Different levels have different guarantee rates.

The relationship among water use, cost and benefit is shown in Figure 1. Among them, $F_c(x)$ is the cost function, which represents the relationship between water use and cost. $F_b(x)$ is the benefit function, which represents the relationship between water use and benefit. W_0 represents the marginal water use with no benefit. W_{min} and W_{exc} are the two points where the total benefit equals the total cost, and the water use between them always brings positive benefit. W_{max} represents the water use with the maximum total benefit. W_{eff} between W_{min} and W_{max} represents the water use where the net benefit reaches the maximum, and the marginal benefit of W_{eff} equals its marginal cost. W_{cap} refers to the design water supply capacity of the system.

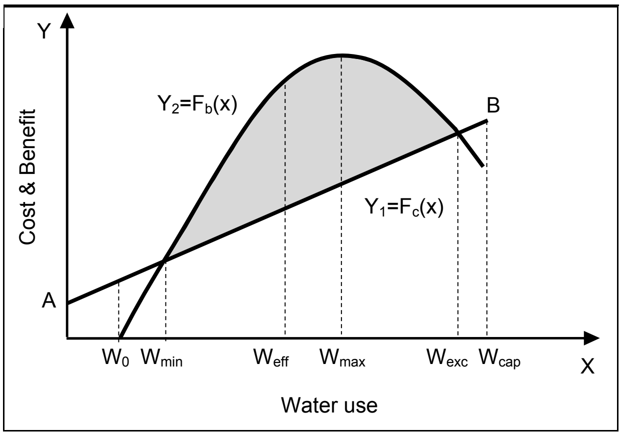

Figure 1. Relationship between cost function and benefit function of water use (English, 1990).

Take irrigation water use for example, in the $F_c(x)$, there are three characteristic values. Firstly, the lower limit, point A, means the fixed cost of the crops, such as fertilizer and cultivation. Secondly, the slope of $F_c(x)$ means the marginal variable cost of the crops, which reflects the relationship between water use and various other factors affecting crop growth, such as fertilizer amount and labor force. Thirdly, the upper limit, point B, means the design water supply capacity (W_{cap}) of the system. As can be seen, the cost function and the benefit function has different sensitivity to water in different stages. When irrigation water use is less than or equal to W_0, the total benefit equals 0. Once it exceeds W_0, the benefit increases with water use. When the irrigation water increases to W_{min}, the total benefit equals the total cost for the first time. Then, the irrigation water continues to increase until W_{max}, the total benefit reaches the maximum. It is noteworthy that the maximum net benefit is attained by W_{eff} between W_{min} and W_{max}, which is consistent with the optimal equilibrium principle of market in economics (Li and Zhang, 2011). Along with the increase of irrigation water, the total benefit begins to decrease until it reaches equilibrium with the total cost again. At the moment, the irrigation water is W_{exc}. It is suggested that water more than W_{max} supplied may reduce the benefit. As shown in the shaded area, when the irrigation water is between W_{min} and W_{exc}, the net benefit is positive. When the irrigation water continues to increase, the total benefit still reduces until it reaches W_{cap} (Solomon, 1985).

It can be seen that optimization for water use process can affect water productivity to a large extent because of various characteristics of sensitivity to water in different stages. Thus, the paper distinguishes water users into three levels: minimum water demand, appropriate water demand, and maximum water demand. Among them, the minimum water demand is the water use when the total benefit equals the total cost for the first time, named W_{min}. The appropriate water demand is the water use when the net benefit reaches the largest, named W_{eff}. And the maximum water demand is the water use when the total benefit reaches the maximum, named W_{max}.

2.2 Division of water demand levels

(1) Domestic water use

Domestic water use includes urban and rural domestic water use. The urban domestic water use includes water use for urban residents and public facilities. The rural domestic water use includes water use for rural residents and drinking water for livestock. In this study, the domestic water use is divided into two levels: minimum water demand and appropriate water demand. The minimum water demand gives priority to water use for urban and rural residents, urban public facilities and some livestock drinking water, which must be ensured. Because it directly relates to the survival of human. The appropriate water demand not only satisfies the minimum domestic water demand, but also meets the water demand in the normal development plan.

(2) Industrial and tertiary industrial water use

Industrial and tertiary industrial water use is called industrial water use for short, including industrial water use and tertiary industrial water use. Among them, the industrial water use includes thermal power water use, nuclear power water use, general industrial water use, and construction water use. The division for industrial water demand levels take many factors into account, such as economic efficiency, social equity and little environmental pollution. In this study, the industrial water use is divided into three levels: minimum water demand, appropriate water demand and maximum water demand. Among them, the minimum water demand gives priority to water use with high economic efficiency, less environmental pollution, and great significance. By contrast, the appropriate water demand, on the premise of satisfying the minimum water demand, refers to water use with low economic efficiency, moderate environmental pollution, and less significance. The maximum water demand refers to water use in the normal development plan.

(3) Irrigation water use

Irrigation water use includes farmland, orchard, grassland and fishery water. The water demand levels for irrigation water are divided through analysis of crop species, water demand characteristics and irrigation system. In this study, the irrigation water use is divided into three levels: minimum water demand, appropriate water demand and maximum water demand. Among them, the minimum water demand, on the basis of determining the critical growth period for various crops, refers to water use in the critical growth period, which should be first guaranteed in order to prevent the total crop failure. For the rest growth periods, the crops mainly rely on natural precipitation. The appropriate water demand firstly meets water use in the critical growth period, combined with the local water diversion conditions, then basically satisfies water use in other growth periods so as to achieve the goal of high yield. The maximum water demand, based on the normal development plan, refers to water use for full irrigation.

(4) Eco-environmental water use

Eco-environmental water use includes the eco-environmental water use outside river and eco-environmental water use inside river. The eco-environmental water use outside river includes forestry water, lakes and urban green land water. Among them, for the forestry water, the minimum water demand refers to water use for natural ecological protection, which must be ensured. The appropriate water demand is the water use for natural ecological restoration. The maximum water demand refers to the forestry construction water according to the normal development plan. For the lakes, the minimum water demand refers to water use for maintaining the most basic water conditions of lakes, which must be first guaranteed so as to ensure the survival of lakes. The appropriate water demand refers to water use for protecting the biodiversity and integrity of lakes. There is no maximum water demand for lakes. For the urban green land water, the appropriate water demand refers to water use for the ecological protection of urban center and national important cultural sights. The maximum water demand mainly refers to water use for urban green land, including the productive green space, suburban landscape green space and suburban ecological green space. The water requirement for the ecological protection of general cultural sights is also included. There is no minimum water demand for urban green land.

The eco-environmental water demand inside the river is determined by ecological basic flow for fish existence, sediment transport, water environmental protection and water landscape project. In order to guarantee the implementation of water quantity regulation, the eco-environmental water demand inside the river is divided into three levels: minimum water demand, appropriate water demand and maximum water demand, which correspond to the three-level management targets of eco-environmental flow in the river. Among them, the minimum water demand guarantees the fish existence for parts of the river, and allows the shrinking of living space for fish in dry seasons. The water demand for wetlands, river evaporation and landscape construction are also taken into account. The appropriate water demand, on the basis of the minimum water demand, meets the fish existence for the vast majority of the river. The maximum water demand refers to water use for the stability of ecosystem and growth of species, which is similar to the natural ecological status.

2.3 Thought of water quantity regulation based on hierarchical water use and eco-environmental flow

To realize the rational water resources allocation and guarantee the dispatching implementation of eco-environmental flow. This study plans to divide the water quantity regulation into two layers. The first layer is introduced to control the total water use based on hierarchical water use. On the purpose of coordinating water uses of socio-economy and ecosystems and realizing the benign development of the riverine eco-environment, hierarchical water use for various water users is adopted to distinguish the water demand of each water user into minimum part, appropriate part, and maximum part. The second layer is proposed to realize the hierarchical regulation of eco-environmental flow. Based on the division of water demand levels for all water users, the three-level management targets of eco-environmental flow for key sections are set, so as to analyze the flow process and guarantee rate of key sections under different scenarios.

By adopting the hierarchical water use, water use process for water users can be classified into three stages. The priority sequence for each stage should be first determined. The minimum water demand for water users should be guaranteed in the first stage. For the water-stressed basin, the priority sequence in principle is as follows: minimum domestic water demand, followed by minimum eco-environment water demand, then minimum irrigation water demand, and lastly minimum industrial water demand. For the second stage, the priority sequence is as follows: appropriate domestic water demand, appropriate irrigation water demand, appropriate industrial water demand, and lastly appropriate eco-environment water demand. The priority sequence for the third stage is as follows: maximum industrial water demand, followed by maximum irrigation water demand, and lastly maximum eco-environment water demand. Generally speaking, in view of the regional economic and social development level, as well as the government policies, the priority sequence for water users in different regions may be adjusted.

3 WATER QUANTITY REGULATION MODEL BASED ON HIERARCHICAL WATER USE

The water quantity regulation model was established based on the rules based object-oriented water allocation simulation model (ROWAS) (You et al., 2005). The ROWAS model is a system simulation model, which is built upon the macroscopic physical mechanism of water transport and transformation. For the complex water resources system with multiple projects, multiple users, and multiple water sources, the model can give the water resources rational allocation schemes through setting various engineering constraints and regulation rules. Meanwhile, the flow process for key sections under different water demand and engineering dispatching scenarios can be obtained. Based on the system generalization, the model can simplify the real water resources system by decomposing system and programming using object-oriented technology. The model nests the water resources regions and administrative districts as calculating unit, which is the key link of the system simulation. Each calculating unit contains several water users. The water demand process for each water user can be described by the parameters of calculating unit.

The model divides water demand into water demand inside river and water demand outside river. The water demand outside river is classified into six categories: urban domestic water use, rural domestic water use, industry water use, irrigation water use, urban ecology and rural ecology water use. The water demand inside river contains power generation, navigation and eco-environmental water use. Based on the above theory and analysis, the water quantity regulation schemes are set as follows: the maximum water demand scheme, named A; the appropriate water demand scheme, named B; and the minimum water demand scheme, named C.

4 CASE ANALYSIS

4.1 Model construction

The Weihe River is the biggest tributary of the Yellow River with total catchment area of 135000km^2 and mainstream of 818km. The River originates from the Niaoshu Mountain of Weiyuan County, Gansu Province and flows into the Yellow River in Tongguan County of Shaanxi Province, which passes through several important cities in Shaanxi Province and plays an important role in the regional economic and social development. The annual average water resources in the Weihe River is 11.07 billion m^3, with surface water resources of 9.25 billion m^3 and the unrepeated water resources of 1.82 billion m^3. With the rapid development of the economy and society along the river, the river has been suffering from various problems, including water resources insufficiency, water pollution, severe water channel blockage and frequent flooding.

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In order to analyze the influence of hierarchical water use on the total water use in the Weihe River, the water quantity regulation model was established. In view of the basin characteristics and the system generalization rules, by nesting the third-level water resources regions and administrative districts, the whole basin is divided into 27 calculating units, including 50 water conservancy projects and about 300 water transmission lines. Figure 2 shows the sketch map of water resources system in the Weihe River Basin. The paper selects 2012 as status quo year and 2020 as planning year. The water supply outside river and flow process for key sections inside river can be obtained with the 1956~2010 series of data for the Weihe River Basin, as noted in section "Results" later in this paper.

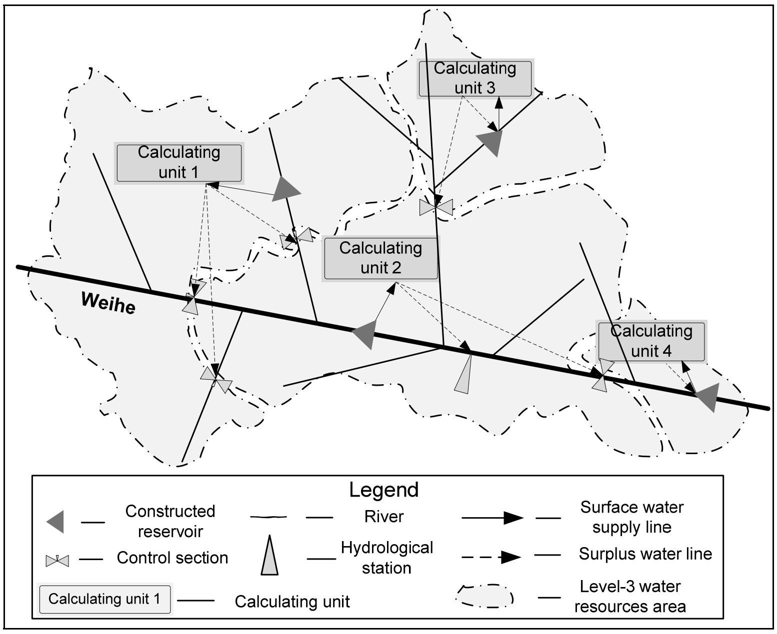

Figure 2. Sketch map of water resources system in the Weihe River Basin.

The annual average irrigation water use in the Weihe River Basin accounts for about 66.9% of the total water use, which occupies an important position in the economic and social system. Therefore, the study mainly analyzes the effects of hierarchical water use for irrigation and eco-environmental water use inside the river on the overall water in the basin.

4.2 Water demand analysis

Figure 3 selects part of calculating units to analyze the agricultural water demand in typical years with different hydrologic frequencies (50%, 75%, and 90%). As in the typical year of 50%, in 2020 the agricultural water demand for scheme A (20) under traditional hierarchy-single water use is the largest, about 4.19 billion m³. Due to adopting the hierarchical water use, the agricultural water demand for scheme B (20) is 1.01 billion m³ lower than scheme A (20). The agricultural water demand for scheme C (20) is the smallest, about 2.51 billion m³ lower than scheme A (20). In the typical year of 90%, the agricultural water demand for different schemes is larger than that in other typical years as a result of less precipitation.

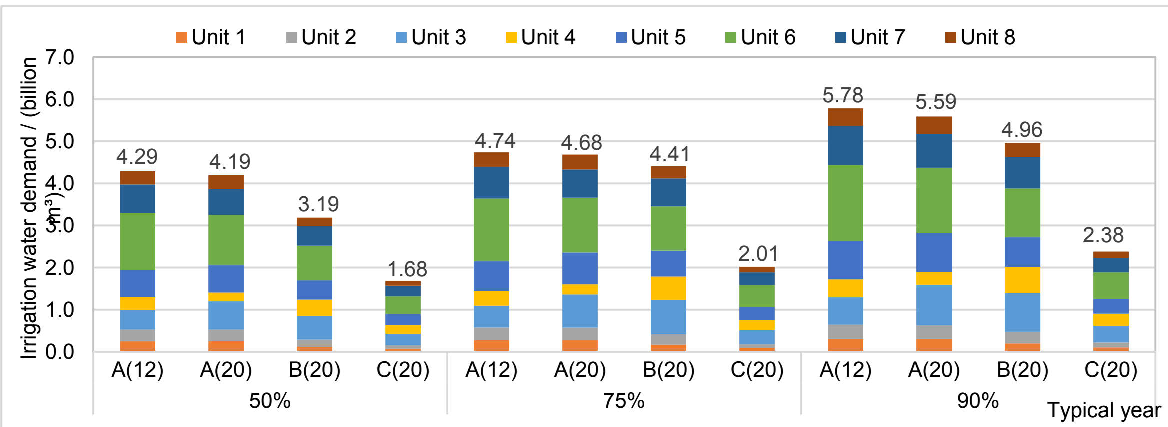

Figure 3. Irrigation water demand of computing units in typical years.

Table 1 shows the prediction of water demand for various water users. Among them, the agriculture water demand is the annual average water demand. As can be seen, in 2020 the total water demand for scheme A(20) is about 9.91 billion m³, with agricultural water demand of 5.59 billion m³. After adopting hierarchical water use, the water demand for scheme B(20) is 1.31 billion m³ lower than scheme A(20), with agriculture water demand reduces by 1.11 billion m³. The water demand for scheme C(20) is 3.59 billion m³ lower than scheme A(20), with agriculture water demand reduces by 3.38 billion m³.

Table 1. Prediction of water demand for schemes (billion m^3).

Level Year	Scheme Number	Total Water Demand	Urban Life	Rural Life	Industry	Agriculture	Urban Ecology	Rural Ecology
2012	A(12)	8.53	0.63	0.43	1.72	5.70	0.06	0.00
2020	A(20)	9.91	0.91	0.45	2.86	5.59	0.10	0.00
	B(20)	8.60	0.88	0.45	2.68	4.48	0.10	0.00
	C(20)	6.32	0.88	0.45	2.68	2.21	0.10	0.00

Aiming to realize the eco-environmental protection targets in the Weihe River Basin, the mainstream of the river was divided into 14 function zones, with 24 ecological control sections. The minimum, appropriate and maximum eco-environmental flow (EEF) of 24 control sections was put forward, corresponding to the three-level management targets of EEF. This paper selects five key sections to analyze the influence of different water quantity regulation schemes on flow process. The eco-environmental protection targets and three-level management targets of EEF for key sections are shown in Table 2.

Table 2. Eco-environmental protection targets and three-level management targets of EEF (m^3/s).

Number	Key Sections	Eco-environmental Protection Targets	Max-EEF	Appr-EEF	Min-EEF
#1	Linjiacun	Ecological base flow, river stability, power generation, and water landscape	12.8	8.6	5.4
#2	Fengjiashan	Ecological base flow, river stability, and water landscape	13.6	8.6	5.4
#3	Shitouhe	Ecological base flow, river stability, and water landscape	21.2	10.1	6.9
#4	Weijiabu	Ecological base flow, river stability, power generation, and water landscape	23.5	11.6	8.4
#5	Yangmaowan	Ecological base flow, river stability, and water landscape	26.2	11.1	8.4

Note: Max-EEF, Appr-EEF and Min-EEF represent maximum, appropriate and minimum eco-environmental flow, respectively.

4.3 Results

(1) Balance of water supply and demand

Table 3 shows the balance of water supply and demand and supply structure for each scheme. As can be seen, in 2020, the water shortage for scheme A(20) under traditional hierarchy-single water use is the largest, about 1.67 billion m³, and the water shortage rate is 17%. After adopting the hierarchical water use, the balance of water supply and demand is greatly improved. The water shortage for scheme B (20) and scheme C (20) is between 0.62 and 1.00 billion m³, and the water shortage rate is about 11%. As can be seen, there is a significant reduction for agricultural water shortage.

Table 3. Water supply and demand balance for schemes (billion m^3).

Level Year	Scheme Number	Water Demand		Water Supply				Water Shortage	
		Total	Agriculture	Total	Surface Water	Ground Water	Others	Total	Agriculture
2012	A(12)	8.53	5.70	6.85	4.40	2.33	0.13	1.68	0.10
2020	A(20)	9.91	5.59	8.24	5.51	2.53	0.21	1.67	0.08
	B(20)	8.60	4.48	7.60	4.80	2.54	0.26	1.00	0.03
	C(20)	6.32	2.21	5.70	3.36	2.06	0.29	0.62	0.01

(2) Monthly guarantee rate

Table 4 shows the monthly guarantee rate of eco-environmental flow for key sections. As can be seen, after adopting hierarchical water use, the monthly guarantee rate for scheme B(20) and scheme C(20) is larger than that for the traditional single water use scheme A(20). For the same scheme, the monthly guarantee rate for the minimum eco-environmental flow is the largest. In general, the guarantee rate for key sections is relatively low, it is necessary to take the relevant water quantity regulation measures and security mechanism to improve the guarantee degree.

Table 4. Monthly guarantee rate of eco-environmental flow (%).

Key Sections	2012			2020								
	A(12)			A(20)			B(20)			C(20)		
	Max-EEF	Appr-EEF	Min-EEF	Max-EEF	Appr-EEF	Min-EEF	Max-EEF	Appr-EEF	Min-EEF	Max-EEF	Appr-EEF	Min-EEF
#1	47.6	52.7	56.1	39.4	46.8	51.4	45.9	51.8	58.2	49.4	57.1	62.1
#2	51.4	57.1	61.7	45.8	53.5	61.2	48.2	57.3	64.7	55.0	63.8	70.0
#3	48.9	70.2	80.5	43.6	61.4	69.1	45.0	65.2	73.9	51.7	69.1	78.0
#4	29.8	41.1	43.6	29.5	36.8	40.5	31.5	40.6	43.8	34.7	46.2	49.1
#5	79.7	95.8	98.2	87.1	96.7	98.8	81.5	95.5	97.4	96.8	99.8	100.0

5 CONCLUSIONS

(1) The new concept of hierarchical water use has been proposed. The priority sequence for different scenarios has been determined. The new concept and approach can effectively control the total water use and coordinate water uses of socio-economy and ecosystems in water-stressed region, and provides a scientific methodology for rational allocation and efficient utilization of water resources;

(2) The thought of water quantity regulation based on hierarchical water use and eco-environmental flow has been put forward, and the water quantity regulation model based on the ROWAS has been introduced. Through applying the model, we compared the water allocation results under the traditional hierarchy-single water use and those of the newly suggested approach. The results showed that the new method is feasible to alleviate the contradiction of water demand and supply and improve the guarantee rate of the eco-environmental flow in the river channel;

(3) The case study analyzes the influence of hierarchical water use for irrigation and eco-environment inside the river on the overall water in the Weihe River Basin. The results are believed to be an important referential value to sustainable development in the basin. Thus, it is necessary to further analyze the hierarchical water use for other water users in the basin.

ACKNOWLEDGEMENTS

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ECONOMIC VALUE OF WATER IN THE ACONCAGUA RIVER BASIN, A COMPARISON BETWEEN AGRICULTURE AND MINING SECTORS

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ABSTRACT

The Aconcagua River Basin (ARB) is one of the most important rivers of the central zone in Chile, providing water for agriculture activities, mining sector, and human consumption. During the last five years, social and economic development have been undermined in ARB, mainly due to a decreasing water supply (drought and climate change), increasing water consumption (population growth and new water requirements from mining and agriculture sectors), low-efficiency irrigation systems, and limitations of the water market for managing water and fostering competition fairly. Likewise, the lack of knowledge about the value of water (social, environmental and economic values) is an obstacle for understanding and communicating on the impact of these issues and how they may be managed by new approaches for allocating water. In this context, the Ecosystem Service Approach was conducted to improve the current understanding of water values in Chile, to assess the possibility to apply an economic methodology and to estimate the total economic value (TEV) of water in ARB. Likewise, the market price methodology was used as a necessary starting point for the TEV approach and for understanding the water market in Chile. The main results show that the average price of water in ARB during 2005-2014, which is about 125 UF/LS (approximately 160,000 US dollars per Gigalitres in a year), principally in agriculture and mining sectors. Additionally, the most important drivers that control the water price are the location, the type of water users (quantity, power, interests, and willingness to pay) and the type of water rights (permanents or conditional).

Keywords: Water value; trade-market; water economics; water management.

1 INTRODUCTION

The Aconcagua River Basin (ARB) is one of the most important rivers of the central zone in Chile, supporting agricultural, industrial and mining activities and supplying water to approximately 550,000 people. The ARB is located at 130 km to the north of Santiago, and it covers a surface of roughly 7,300 km2.

During the last five years, in the ARB, social and economic development has been undermined, mainly due to the decreasing water supply (drought and climate change), increasing water consumption (population growth and new water requirements from mining and agriculture sectors), low-efficiency irrigation systems, and limitations of the water market for managing water and fostering competition fairly.

Likewise, the lack of knowledge about the value of water (social, environmental and economic values) is an obstacle for understanding and communicating on the impact of these issues and how they may be managed by new approaches for allocating water.

By considering all of the above, this study is conducted to support an Ecosystem Services Approach, specifically through the Total Economic Value concept, to quantify the value of water in the ARB and comparable basins in Chile. While ultimately the Total Economic Value approach would include social value assessments (equity), environmental requirements and economics benefits, which are under an Integrated Water Resources Management (IWRM) perspective, this project focusses on understanding the economics of water use in the ARB.

Also, the following objectives have been specifically developed:

- Analyse the water trading data to understand the economic value of water for different user groups, and which factors control the value of water.
- Estimate water supply and demand curves for the main water users.
- Conclude on the applicability of TEV in ARB and recommendations for further work.

2 DESCRIPTION OF ACONCAGUA RIVER BASIN

2.1 Overview

The Aconcagua River begins in the Andes Mountains (a glacier source) at 5,400 masl, where the Juncal River joins with the Blanco River, then it flows through the central valley up to its final discharge in the Pacific Ocean.

The ARB has been separated into five administrative divisions. Four of them cover the Aconcagua River, and the fifth one covers the Putaendo River (see Figure 1).

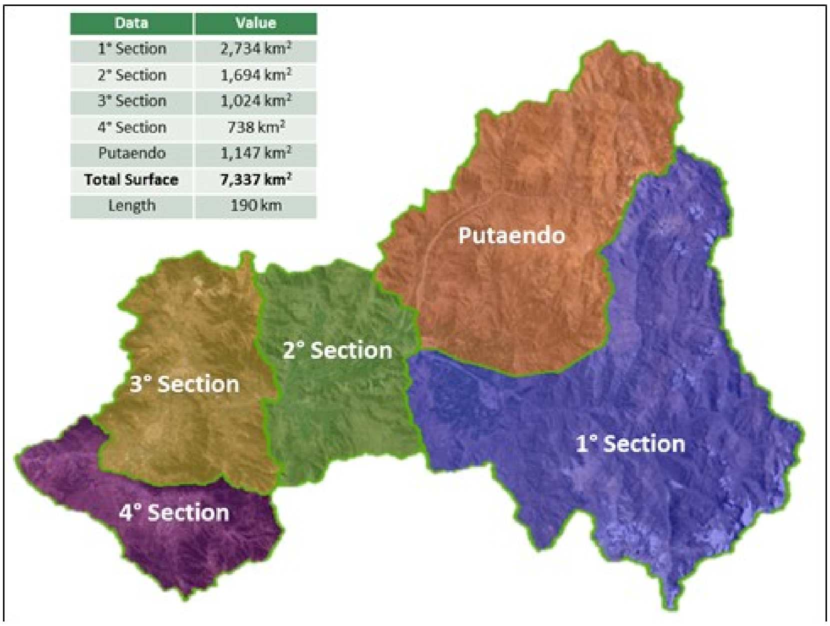


Figure 1. Aconcagua River Basin – Administrative Divisions (Figueroa San Martin, 2016).

2.2 Hydrology

About surface water, although rainfall in upper ARB occurs principally in the winter season (June-August), the peak of water flows happens during the summer season (November-February), due to water flow depending on snow and glaciers melting. Higher temperatures mean higher water flows. Average annual flows in the Aconcagua River are higher in upstream than downstream, mainly because there is a series of water canals in downstream, that uses the water principally in agricultural activities.

The aquifer (groundwater) in ARB is directly linked with surface water, and it moves in the same direction of the Aconcagua River. The depth of water table is between 5.0 m-15.0 m on average (DGA, 2015).

2.3 Water users

Main water users in ARB are represented by agriculture activities, sanitary sector (human consumption), industrial and mining activities. The agriculture sector is the most important water user, reaching the 80% of the total water requirements. On the other hand, mining activity uses roughly the 4% of the total water requirements (see Figure 2).

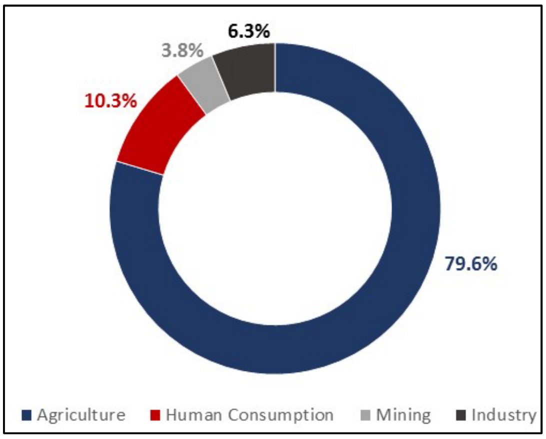


Figure 2. Distribution of Water Consumption by Sector (Cade Idepe Consultores, 2004).

2.4 Water governance

The Water Code (WC) of 1981 is the main regulatory policy that regulates water allocation in Chile; it was developed during a strong neoliberal period. The WC establishes that water resources are a “national property for public use,” but grants permanent, transferable water use rights to individuals to reach an efficient allocation of the resource through market transactions of water user rights (Donoso, 2011). Thus, water rights are traded, inherited, and subjected to the same rules of real estate (Bitrán *et al*, 2011). This allocation mechanism is known as Water Market.

The main public body that manages the Water Code is the Directorate General of Water (DGA). It is part of the Ministry of Public Works of Chile, and it is responsible for monitoring and enforcing the water user rights. Nevertheless, the DGA has maintained a limited role, imposed by the paradigm of limited state interference.

2.5 Key challenges and water issues on Aconcagua river basin

During the last five years, social and economic development has been undermined. This is mainly due to decreasing water supply (drought and climate change), increasing water consumption (population growth and new water requirements from mining and agriculture sectors), low efficiency irrigation systems, poor water quality, and limitations of the water market in managing water and fostering competition fairly. Main issues in ARB related to these effects are:

- Interruption of copper production in the mining sector (water scarcity)
- Decline of crops farming in the agriculture sector (water scarcity, low efficiency irrigation systems)
- Increase of algae concentration in Aconcagua river (poor water quality)
- Water shortage in rural villages (water scarcity and water competition)
- High tension between water users (water competition)

3 THEORETICAL FRAMEWORKS

The theoretical frameworks used to develop the methodology are:

- Integrated Water Resources Management
- Water Allocation Systems
- Ecosystems Services Approach
- Total Economic Value

3.1 Integrated water resources management (IWRM)

Global Water Partnership (GWP) describes IWRM as a process to promote a coordinated development and management of water, land, and its related resources, with the aim of maximizing the economic and social welfare, by an equitable manner assuring the sustainability of vital ecosystems (GWP, 2000).

3.2 Water allocation mechanisms / water market

In order to understand how to implement IWRM principles, it is necessary to know where these principles will be applied. The water market allocation mechanism is referred to as an exchange of the water-use rights of a given quantity of water between users (Dinar *et al*, 1997). Water market mechanism plays a preponderant role in allocating water between users, distributing water to where it is most valued, and fostering an efficient use of water (Department of Environment, 2016). As mentioned before, in Chile, a water market mechanism has been established.

3.3 Ecosystem services approach

The ecosystem service approach is defined as a strategy for the integrated management of land, water, and living resources that encourage the conservation and the sustainable use in an equitable way (Convention on Biological Diversity, 2016).

The ecosystem services approach links underlying science to environmental valuation and policy development, aiming to account for the full range of ecosystem service types (provisioning, regulating, cultural, and supporting) in policy appraisal and the decision-making process. This approach is appropriate for defining the links between different socioeconomic values and changes in the ecosystem, such as river hydrology (Pascual and Muradian, 2010).

3.4 Total economic value (TEV)

Total economic value is intended to estimate the use (direct contact or encounter with water resources) and non-use (no direct contact or encounter with water resources) value of water. Total economic value refers to the total gain in wellbeing from a policy/program/project measured by the net sum of social willingness to pay or the willingness to accept that policy/program/project. Thus, it is possible to estimate the costs and benefits of using, protecting, or developing water resources depending on social, economic, and environmental requirements (Defra 2007). The TEV concept is presented in Figure 3.

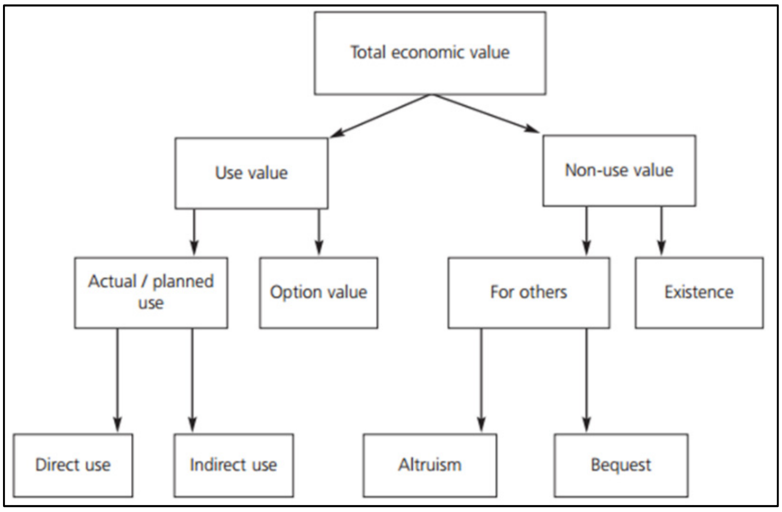


Figure 3. Total Economic Value Approach (Defra, 2007)

4 RESEARCH METHODOLOGY

The research methodology is divided into three analysis:

i. Water price analysis
ii. Market Prices Method
iii. Drivers analysis

4.1 Water price analysis

Considering the public data of water transactions in ARB, the econometrics assessment was developed through a spatial (prices of water volume by administrative sections) and water user analysis (buyer and seller prices paid or accepted by each water user).

4.2 Market price method

To estimate the demand and supply curves, it is necessary to gather the results of the water price analysis by water user, and by sellers and buyers.

4.3 Drivers analysis

A regression model analysis was developed to determine the most important drivers of water price. Through a panel data regressions, it is possible to deal with time effects and cross-sectional effects. In this case, a fixed effects regression analysis was developed.

Fixed-effects regression analyses the relationship between predictor and outcome variables within an entity. It assumes that the entity and its variables may or may not influence the predictor variables (Torres-Reyna, 2007).

5 DATA ANALYSIS AND RESULTS

5.1 Data management

In order to organize the data by administrative divisions (sections), the following codification is presented:

Table 1. Administrative Divisions – Section Codification.

ID Code	Division Name
S1	First Section
S2	Second Section
S3	Third Section
S4	Fourth Section
S5	Putaendo Section

In relation to water analysis the following measurements will be used:

- UF: Indexation Unit (Chile). 1UF = 40.64 US dollars (15/01/2017)
- LS: litters per second (water volume). 1 LS = 0.032 GL/year = 86.4 m3/day
- UF/LS: water price in water market. 1 UFLS = 1,280 US/GL/year = 0.47 US/m3/day

5..2 Water price analysis results

From the results of the economic analysis, the average price of water in ARB during 2005-2014 is about 125 UF/LS (approximately 160,000 US dollars per Gigalitres in a year). The value of the water differs by section, going from 75 UF/LS in the Third Section to 260 UF/LS in the Fourth Section (see Table 2).

Table 2: Water price by section - analysis data, Figueroa San Martín (2016).

Administrative Section	No of water trades	Average Water Price [UF/LS]
S1	183	195
S2	421	108
S3	480	75
S4	27	260
S5	735	146
Total	1,846	125

The results of the data analysed by sellers and buyers of each water users are presented in the tables below.

Table 3. Average price by seller users in each section [2005-2014] [UF/LS], Figueroa San Martín (2016).

Seller Users	No. of transactions	Section 1	Section 2	Section 3	Section 4	Section 5	Total
Agriculture	187	166	94	81	-	70	97
Bank	15	69	107	120	-	-	111
Real State	40	49	113	37	250	80	59
Investment	28	8	312	32	163	108	157
Mining	5	-	-	-	-	17	17
Other	50	62	58	103	-	52	71
Private Individuals	1,528	208	106	76	265	151	132
Sanitary	2	-	-	20	-	-	20
Total	**1,855**	**195**	**108**	**75**	**260**	**144**	**125**

Table 4. Average Price by Buyer Users in each section [2005-2014] [UF/LS], Figueroa San Martín (2016).

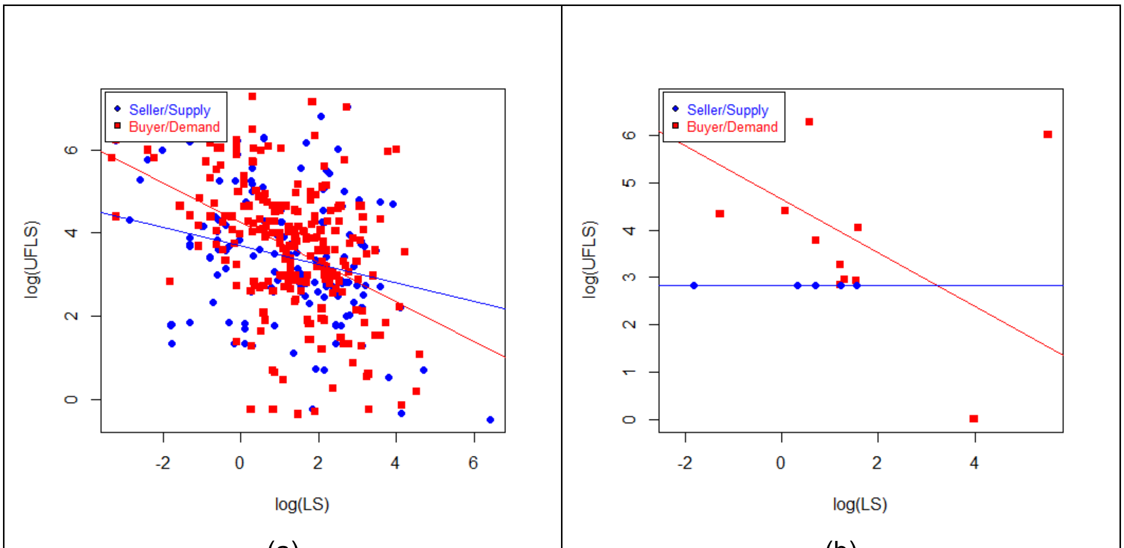
Buyer Users	No. of transactions	Section 1	Section 2	Section 3	Section 4	Section 5	Total
Agriculture	244	158	92	106	3	131	114
Bank	13	28	152	133	-	55	88
Hydroelectric	2	-	33	-	-	-	33
Real State	42	193	86	25	-	279	101
Investment	78	332	83	25	318	147	115
Mining	21	-	159	-	-	312	261
Other	63	436	133	64	109	144	149
Private Individuals	1,391	189	112	72	249	141	125
Sanitary	1	-	68	-	-	-	68
Total	**1,855**	**195**	**108**	**75**	**260**	**144**	**125**

From the above tables emerged are the following conclusions:

- Agriculture sector prefers to buy water on S1, S2 and S5 sections (Upper Basin), but they are not interested in section S4.
- The mining sector is willing to pay more than any other sector per one unit of water volume.
- All water users are interested in buy water rights in section S2, but they are not interested in section S4

5.3 Market price method results

The results of demand and supply curves are presented in Figure 4.



(a) (b)

Figure 4. Demand and Supply curves in ARB in Log-scale – (a) Agriculture Sector - (b) Mining Sector, Figueroa San Martín (2016).

5.3.1 Regression model results (Driver Analysis)

The regression model has been implemented in Agriculture sector because it is the only one sector that meets the necessary amount of data to run the model.

The Fixed-Effects equation is presented in Eq [1], in which the most important variables that may affect the water price has been incorporated.

$$WPA_{it}= \propto_1 NWT_{1,it}+\propto_2 PP_{it}+\propto_3 Q_{it}+\propto_4 ET_{it}+\propto_5 AS_{it} +\propto_6 AI_{it} +\propto_7 LAG1\ WPA_{it} +\propto_8 LAG1\ PP_{it}+\propto_9 LAG1\ Q_{it} +\gamma_1 SE_1+\gamma_2 SE_2+\gamma_3 SE_3+\gamma_5 SE_5 \quad [1]$$

where,

WPA: Water price in Agriculture Sector
NWT: Number of Transactions [N]
PP: Rainfall [mm/six-months]
Q: Water Volume in Aconcagua River [LS]
ET: Evapotranspiration [mm/six-months]
AS: Agriculture Land Surface [acres]
AI: Agriculture Incomes [UF]
LAG1 WPA: Lag(1 period) Water Price [UF/LS]
LAG1 PP: Lag(1 period) Rainfall [mm/six-months]
LAG1 Q: Lag(1 period) Water Volume in Aconcagua River [LS]
αk: is the coefficient for the drivers
γm: is the coefficient for the binary regressors (sections in ARB)
The results are presented in tables below.

The results are presented in Table 5.

From the panel model regression of fixed effects, the best fit was done with the Non-linear (log model) in the seller case (supply curve), and linear model in the buyer case (demand curve). The most important drivers that define the supply curve are evapotranspiration, rainfall and land surface. In the demand curve, the drivers are the water price (lag-1) and the incomes of agriculture activities.

Table 5. Water price variables equation / fixed effects, Figueroa San Martín (2016)

	Agriculture Sector Sellers				Agriculture Sector Buyers			
Variable	Coefficien	SE	t-	P-val	Coefficie	SE	t-stat	P-val
Linear Panel Data Model								
Number of Transactions [N]	2.476	4.220	0.58	0.560	-4.837	7.160	-0.676	0.502
Rainfall [mm/six-months]	-0.136	0.202	-	0.505	-0.151	0.393	-0.383	0.703
Water Volume [LS]	-0.167	0.114	-	0.150	-0.097	0.219	-0.444	0.659
Evapotranspiration [mm/six-months]	-0.210	0.111	-	0.064	0.098	0.193	0.506	0.615
Agri. Surface [acres]	0.045	0.037	1.23	0.224	-0.027	0.062	-0.436	0.665
Agri. Incomes [UF]	0.000	0.000	0.23	0.812	0.000	0.000	1.907	0.062
Lag(1) Water Price [UF/LS]	0.042	0.133	0.31	0.752	0.470	0.233	2.019	0.048
Lag(1) Rainfall [mm/six-months]	0.330	0.247	1.33	0.189	-0.056	0.445	-0.126	0.900
Lag(1) Water Volume [LS]	-0.101	0.093	-	0.283	0.222	0.178	1.251	0.216
S1	-88.210	324.28	-	0.786	-52.320	502.9	-0.104	0.917
S2	-180.040	386.77	-	0.642	43.097	585.6	0.074	0.941
S3	-514.660	569.20	-	0.366	102.408	874.7	0.117	0.907
S5	-216.500	390.29	-	0.579	-19.005	602.3	-0.032	0.975
R-Squared	0.141				0.174			
Adjusted R-Squared	0.110				0.141			
F-statistic	0.856				1.287			
p-value	0.570				0.265			
Non-linear Panel Data Model - Log-scale								
Number of Transactions [N]	0.385	0.219	1.75	0.086	0.076	0.194	0.394	0.695
Rainfall [mm/six-months]	-0.210	0.116	-	0.077	0.022	0.113	0.195	0.846
Water Volume [LS]	-0.194	0.250	-	0.441	-0.274	0.250	-1.095	0.278
Evapotranspiration [mm/six-months]	-1.371	0.766	-	0.080	0.141	0.683	0.206	0.837
Agri. Surface [acres]	12.564	6.017	2.08	0.042	1.167	5.424	0.215	0.830
Agri. Incomes [UF]	-0.480	1.229	-	0.698	1.440	1.107	1.301	0.199
Lag(1) Water Price [UF/LS]	0.094	0.136	0.68	0.495	0.296	0.138	2.137	0.037
Lag(1) Rainfall [mm/six-months]	0.052	0.138	0.37	0.711	0.166	0.123	1.348	0.183
Lag(1) Water Volume [LS]	-0.581	0.290	-	0.051	0.378	0.295	1.281	0.206
S1	-89.076	52.841	-	0.092	-30.354	48.09	-0.631	0.528
S2	-92.168	53.920	-	0.087	-30.351	48.97	-0.620	0.536
S3	-97.618	56.175	-	0.082	-31.238	51.06	-0.612	0.541
S5	-92.301	54.013	-	0.087	-30.121	49.13	-0.613	0.540
R-Squared	0.239				0.162			
Adjusted R-Squared	0.187				0.131			
F-statistic	1.636				1.179			
p-value	0.133				0.327			

SE: standard error, t-stat: t-statistic, P-val: P-value
-: not applicable

6 CONCLUSIONS AND RECOMMENDATIONS

The Ecosystem Service Approach links the underlying science of the environmental valuation to the policy development, aiming to account for the full range of ecosystem service types (provisioning, regulating, cultural and supporting) in policy appraisal and decision-making process. This approach is appropriate for defining the links between different socio-economic values and changes in the ecosystem functioning such as river hydrology. Specifically in this study, the Total Economic Value concept is used in producing an estimation of the change in socio-economic value associated with a change water delivery (Pascual and Muradian 2010).

Complemented with IWRM principles and principally defining water as a finite and vulnerable resource and water as an economic good, the Ecosystem Service Approach and the TEV meet the requirements of maximizing the economic and social welfare, by an equitable manner assuring the sustainability of vital ecosystems (GWP 2000).

In this study, the feasibility of assessing water price and comprehending water issues in Aconcagua river basin through the Ecosystem Service Approach, the Total Economic Value concept, and Market Price methodology, are fully developed.

The most important result is the average of water price in the transactions in Aconcagua river basin, which reaches a price of 125 UF/LS (160,000 US dollars per Gigalitres in a year). This study also includes the spatial behaviour of the water price and the drivers and factors that control the value of the water. These factors are principally the location, the type of water users (quantity, power, interests, and willingness to pay), the kind of water rights (permanents, conditional), the allocation mechanism and, in the case of the water market, the number of transactions between its users.

The Total Economic Value approach and the market price valuation are not merely econometrics analysis. Moreover, they are considered as the mechanisms that should promote the sustainability of water resources through the use of high values of water (Van der Zaag and Savenije, 2006).

Nevertheless, the applicability and implementation of the Ecosystem Service Approach and TEV valuation in ARB and other comparable basins have to be designed as a complement in improving the water market allocation mechanism, providing key information to the stakeholders and the decision-makers.

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ANALYTICAL STUDY ON THE WATER RESOURCES CARRYING CAPACITY OF LARGESCALE ENERGY BASES ON THE MIDDLE-UPPER REACHES OF THE YELLOW RIVER

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ABSTRACT

The water resources carrying capacity is one of the most crucial evaluation factors in China's energy development planning. This paper reckons the regional water resources supply-demand statuses in different scenarios in seven largescale energy bases on the middle-upper reaches of the Yellow River by 2020, and analyzes their water resources carrying capacity based on the analysis on water consumption features in the energy industry and the prediction of water saving engineering level in the future energy industry. The results show that the water demand will still increase rapidly in these energy bases on the reaches of the Yellow River during the 13th Five Year Plan. The new water demand will come to 1.406 billion cubic meters by 2020 in coal mining and washing, coal power and coal chemical industries in seven energy bases along the middle-upper reaches of the Yellow River; and a new water quantity of 859 million cubic meters is still needed in consideration of the water-saving enforcement measures in the water-saving technological advance related to the energy production. The imbalance between supply and demand of water resources in energy bases will be aggravated further in the background of limited regional water resources supporting capability.

Keywords: Middle-upper reaches of the Yellow River; energy base; water resources carrying capacity; water resources restriction; water resources management.

1 INTRODUCTION

Before the middle period of this century, China will continue a rapid economic growth, keep the stronger momentum in energy dependence, has a rapid increase in total energy demand, and put forth the higher requirement for energy security (Wang, 2008).

The middle-upper reaches of the Yellow River are one of the important energy enrichment regions in China and play a very important strategic role in China's energy security. However, for what is unmatched with energy cases, the region is also one of the areas where there is a sharp imbalance between supply and demand of water resources in China (Ye et al., 2010; Wang et al., 2000). The water resources has exerted a serious restriction to the construction of energy bases, for example, the provinces such as Shanxi, Inner Mongolia and Ningxia which have abundant coal resources are more stranded by water shortage.

2 LAYOUT AND WATER RESOURCES SITUATIONS OF ENERGY BASES

2.1 Layout of energy bases

14 largescale coal production bases had been built up in China by the end of the 12^{th} Five Year Plan according to the *12^{th} Five Year Development Plan of Coal Industry*, seven of which were built in the middle-upper reaches of the Yellow River, accounting for 60.4% of total predicted resources of the 14 largescale coal bases.

Table 1. Seven largescale energy bases in the middle-upper reaches of the Yellow River.

Name of base	Province	City
Shendong	Inner Mongolia	Erdos, Wuhai and Baotou
Ningdong	Ningxia	Yinchuan, Wuzhong
Northern Shanxi	Shanxi	Datong, Shuozhou, Lvliang and Xinzhou
Jinzhong	Shanxi	Taiyuan, Jinzhong, Yuncheng and Linfen
Northern Shaanxi	Shaanxi	Yulin, Yan'an
Huanglong	Gansu, Shaanxi	Pingliang, Qingyang, Tongchuan, Xianyang
Henan	Henan	Pingdingshan, Zhengzhou, Shangqiu, Samenxia, Xuchang, Xinxiang, Hebi,

Name of base	Province	City
		Luoyang and Jiaozuo

2.2 Water resources situations

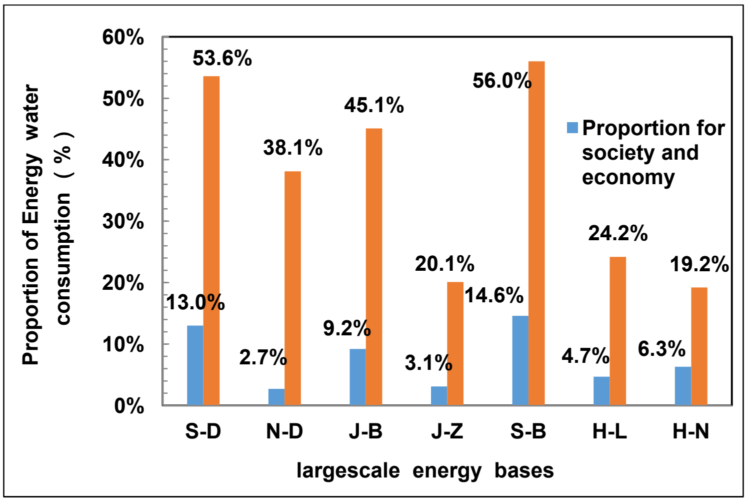
The Yellow River Basin is hailed as the “energy basin” of China, with a gigantic development potential, and it has a quite important place in the national energy development. The Basin belongs to the water-deficient area in the northwest inland river basin, and the water shortage is seriously restricting its sustainable development of economy and society (Liu and Lu, 1993). Its average per capita water quantity is 473m^3, only 23% of the national average. The natural annual runoff in the rivers and mountains in the Basin is around 49.8 billion cubic meters (Lijin) in recent decade (2004-2013), the annual average water withdrawal is around 37 billion cubic meters, and the rate of exploitation and utilization exceeds 70%, which surpasses the water carrying capacity of the Yellow River.

The annual average per capita water quantity is only 396m^3 in the seven coal bases in the Basin, only accounting up 19% of the national average.

2.3 Current situations of water withdrawal and utilization

The industrial water withdrawal and consumption (surface and underground) take up a larger proportion in the water withdrawal and consumption structure of the social and economic development in the whole Basin (farm irrigation, forest, fishery, husbandry, industry, town public, resident life and ecological environment).

The water consumption for society and economy came to 27.21 billion cubic meters in the administrative region involved in seven energy bases on the middle-upper reaches of the Yellow River in 2012, of which the industrial water consumption is 6.361 billion cubic meters. The water consumption for energy is 1.763 billion cubic meters, accounting for 6.48% of total social and economic water consumption, and 27.72% of total local industrial water consumption. The water consumption for the key energy bases on the middle-upper reaches of the Yellow River occupies a larger proportion in that of regional national economy and industry.



Note: S-D, N-D,J-B,J-Z, S-B, H-L, H-N represent Shendong, Ningdong, Northern Shanxi, Central Shanxi , Northern Shaanxi, Huanglong and Henan largescale energy bases respectively.

Figure 1. Proportion of water consumption for energy accounted for that of society, economy and industrial in seven largescale energy bases.

3 PREDICTION OF WATER DEMAND FOR DEVELOPMENT OF ENERGY BASES

3.1 Prediction of water demand for coal mining and washing industry

The water consumption quotas for coal mining and washing industry of provinces and regions involved in seven energy bases on the middle-upper reaches of the Yellow River can be determined based on the water quotas of coal mining and washing industry as well as *the Clean Production Level Evaluation in Coal Industry* issued by the national and provincial governments at all levels, as shown in Table 3.

The raw coal yield reached 1.983 billion tons in seven coal bases on the middle-upper reaches of the Yellow River, accounting for 55% of total national raw coal output based on the list of top-100 municipal coal mines in raw coal output and the Statistical Bulletin of National Economy and Social Development of Some Regions issued by the China National Coal Association (CNCA) in 2012. According to the 12th Five Year Development Plan and the results of the mid and long-term development plan, the statistics was made about the production capacity and the new capacity by 2020 in seven largescale energy bases compared with current situations. It is expected that by 2020, the new coal capacity will be planned up to

522 million tons in the seven energy bases on the middle-upper reaches of the Yellow River, and the total capacity will come to 2.505 billion tons, where Northern Shaanxi and Huanglong energy bases have fastest increases of production capacity.

Based on the 2020 raw coal capacity and coal mining & washing product quotas planned by the key energy bases, the new coal water demand for the bases by 2020 was analyzed and estimated as shown in Table 2.

Table 2. Prediction of water demand for coal mining and washing by 2020 in seven largescale energy bases.

Name of base	Current coal capacity (10^8 tons)	New coal capacity by 2020 (10^8 tons)	Water quota (m^3/ton)		New water demand in 2020 (10^8 tons)	
			limited value	Advanced value	limited value	Advanced value
Shendong	7.00	0.84	0.35	0.15	0.17	0.07
Ningdong	0.61	0.69	0.45	0.32	0.31	0.22
Northern Shanxi	4.88	0.45	0.35	0.23	0.13	0.08
Jinzhong	1.64	0.15	0.35	0.23	0.05	0.03
Northern Shaanxi	3.54	1.42	0.35	0.15	0.50	0.21
Huanglong	0.72	1.47	0.42	0.175	0.70	0.29
Henan	1.44	0.20	0.6	0.2	0.12	0.04
Total	**19.83**	**5.22**	**0.41**	**0.21**	**1.98**	**0.94**

Based on the maximum water withdrawal limited by current water intake quota, the new water demand will reach around 198 million cubic meters for key energy bases by 2020. In consideration of development and application of water saving technology, the coal mining and washing technology can be improved, and the water saving techniques can be popularized. By this way, the estimated new water demand will get to around 94 million cubic meters, and the water saving quantity will be 104 million cubic meters by the advanced values of water intake quotas.

3.2 Water-demand prediction of power generation industry

The *Guide of Water Use Efficiency for Key Industries* jointly issued by four departments in 2013, namely Ministry of Industry and Information Technology, Ministry of Water Resources, State Statistics Bureau and the National Water Conservation Office, provides the advanced value, average value and limited value of water intake for unit generating and installed capacities of different cooling modes (circulating, once-through and air cooling) in thermal power industry. In addition, all provinces published their own thermal power water intake quota indexes (Song et al., 2008; Jiang and Han, 2008). The analysis was made on thermal power water-consumption quota, present actual average water-consumption quota and future advanced water-consumption quota in the provinces.

In view of the air cooling technology applied in the new thermal power installed units, the limited values and advanced values in the table are the values corresponding to air cooling units guiding water intake quotas issued by the provinces. The missing values of certain provinces can be referred to the survey data of the *Guide of Water Use Efficiency for Key Industries*. Table 4 shows the water consumption quotas for coal mining and washing industry involved in provinces in seven energy bases on the middle-upper reaches of the Yellow River.

According to related statistics (Wang and Zhang, 2010; Lin et al., 2011), the new installed capacity will come to 224,500MW in largescale energy bases on the middle-upper reaches of the Yellow River by 2020 compared with present situations. Supposing the present water use efficiency remains unchanged for original thermal power installed units, and the new thermal power installed units are of air cooling type, it is predicted that the new water demand for the energy bases will reach around 889 million cubic meters based on the limited values of issued water intake quotas. If the water saving technology is further popularized to realize the advanced values of issued water quotas, the new water demand is expected to be 540 million cubic meters, as shown in Table 3.

Table 3. Predictions of new water demand in thermal power industry by 2020 for seven largescale energy bases.

Name of base	Present generating capacity (10^8 kW•h)	New installed capacity by 2020 (10^4MW)	Water consumption quota (m^3/MW•h)		New water demand in 2020 (10^8 m^3)	
			limited value	Advanced value	limited value	Advanced value
Shendong	1109.86	5.29	0.8	0.5*	2.11	1.32
Ningdong	672.67	4.57	0.95*	0.5*	2.17	1.14
Northern Shanxi	941.72	0.87	0.54	0.432	0.24	0.19
Jinzhong	825.39	1.04	0.54	0.432	0.28	0.22
Northern Shaanxi	468.29	3.91	0.54	0.432	1.06	0.84
Huanglong	483.18	2.90	0.54*	0.432*	1.19	0.72
Henan	1850.30	3.87	0.95*	0.5*	1.84	0.97
Total	**6351.41**	**22.45**	**0.69**	**0.46**	**8.89**	**5.40**

Note: The data with "*" denote the province can't set corresponding water quotas. It may be assumed by the lowest water use level referring to the survey data of the *Guide of Water Use Efficiency for Key Industries.*

3.3 Prediction of water demand in coal industry

The water consumption quotas are summed up in Table 4 based on the water consumption quotas for coal chemical products issued by the provinces on the middle-upper reaches of the Yellow River.

Table 4. Water consumption quotas for coal chemical products.

Name of base	Province	Water consumption quota for coal chemical products (m^3/ton)					
		Coal-to-to-gas (m^3/1000 m^3)	Coal-to -liquids	methanol	Dimethyl ether	Olefin	Coke
Shendong	Inner Mongolia	8	6	10	1.5		0.5-1.6
Ningdong	Ningxia						
Northern Shanxi	Shanxi	15	25	8	1.5	1.5	0.8-1.8
Jinzhong	Shanxi	15	25	8	1.5	1.5	0.8-1.8
Northern Shaanxi	Shaanxi	15	25	8	2	2	1.4
Huanglong	Gansu			10		1.5	2.2
	Shaanxi	15	25	8	2	2	1.4
Henan	Henan			20.3		22	3

Note: The industrial water consumption quotas issued by some provinces are not involved in coal chemical products.

The *Coal Deep Processing Demonstration Projects Planning*, a programmatic document of coal chemical industry drafted by the National Energy Administration, proposed that 15 coal chemical demonstration projects to be approved and constructed step by step during the 12^{th} Five Year Plan. These projects are expected to be constructed and put into operation by 2020. The new coal chemical projects constructed in seven largescale energy bases on the middle-upper reaches of the Yellow River are shown in Table 6.

The new water demand is available by calculation for coal chemical industry in seven energy bases on the middle-upper reaches of the Yellow River based on the proposed coal chemical projects as well as the coal chemical product quotas in provinces and regions (Table 5). By the predictions, total new water demand will reach 321 million cubic meters for new coal chemical products by 2020 according to present water consumption quotas and levels. If the advanced technology is applied to improve cooling efficiency and water consumption level, then the water demand can be reduced significantly at 224 million cubic meters in total.

Table 5. New water demand of coal chemical industry by 2020 for seven largescale energy bases.

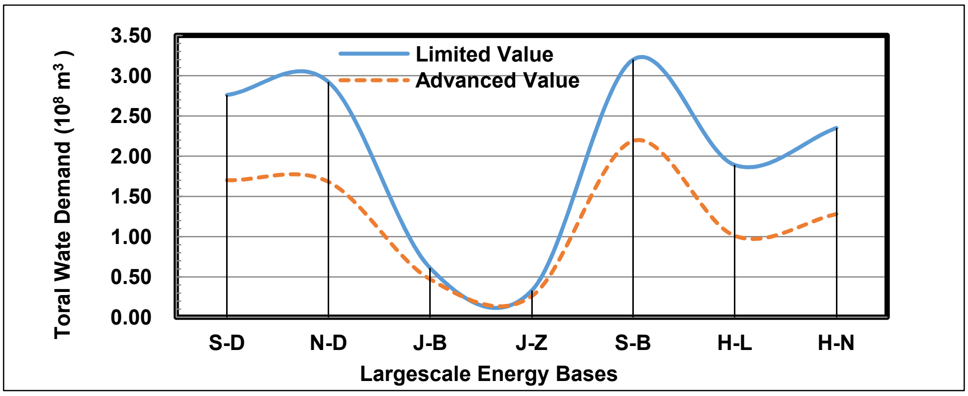
Name of base	Present coal chemical scale	New coal chemical scale by 2020	New water demand by 2020 ($10^8 m^3$)	
			limited value	Advanced value
Shendong	Methyl ether: 400,000 tons; direct coal-to-liquids: 1.08 million tons; indirect coal-to-liquids: 160,000 tons; coal-to-dimethyl ether: 400,000 tons; calcium carbide: 800,060 tons; coal-to-gas: 3.6 billion m^3; coal-to-glycol: 1 million tons; coal-to-methyl alcohol: 1 million tons; coal-to-olefin: 600,000 tons	Coal-to-dimethyl ether: 3 million tons; coal-to-gas: 600,000 tons	0.47	0.32
Ningdong	Coal-to-olefin: 520,000 tons; methyl alcohol: 130 million tons; tar: 300,000 tons; coking: 330 million tons; oil refining: 5 million tons; heavy oil catalyzing: 800,000 tons; FGD gypsum: 200,000 tons	Coal-to-indirect liquefaction: 4 million tons	0.44	0.32
Northern Shanxi		Coal-to-methyl alcohol: 3 million tons; coal-to-olefin: 600,000 tons	0.25	0.20
Jinzhong	Coal coking: 100,000 tons		0.00	0.00
Northern Shaanxi	Coal-to-methyl alcohol: 400,000 tons	Coal-to-indirect liquefaction: 4 million tons; coal-to-olefin: 7 million tons	1.65	1.13
Huanglong			0.00	0.00
Henan	Coal-to-glycol: 400,000 tons; coal-to-methyl alcohol: 750,000 tons	coal-to-olefin: 600,000 tons	0.40	0.27
	Total		**3.21**	**2.24**

3.4 Total water demand of all bases by 2020

To sum up, total new water demand is expected up to 1.406 billion cubic meters for coal mining and washing, coal power and coal chemical industries by 2020 in the largescale energy bases on the middle-upper reaches of the Yellow River, and the three industries' water demand accounts for 14%, 63% and 23% respectively in total water demand. If the water saving measures are further taken to improve the popularization of water saving technology, total water demand can reduce to 859 million cubic meters, with a water-saving amount of 547 million cubic meters. See Table 6.

Table 6. New water demands by 2020 for seven largescale energy bases, Unit: $10^8 m^3$.

Name of base	Coal industry		Coal power industry		Coal chemical industry	
	limited value	Advanced value	limited value	Advanced value	limited value	Advanced value
Shendong	0.17	0.07	2.11	1.32	0.47	0.32
Ningdong	0.31	0.22	2.17	1.14	0.44	0.32
Northern Shanxi	0.13	0.08	0.24	0.19	0.25	0.20
Jinzhong	0.05	0.03	0.28	0.22	0.00	0.00
Northern Shaanxi	0.50	0.21	1.06	0.84	1.65	1.13
Huanglong	0.70	0.29	1.19	0.72	0.00	0.00
Henan	0.12	0.04	1.84	0.97	0.40	0.27
Total	**1.98**	**0.94**	**8.89**	**5.40**	**3.21**	**2.24**



Note: S-D, N-D,J-B,J-Z, S-B, H-L, H-N represent Shendong, Ningdong, Northern Shanxi, Central Shanxi , Northern Shaanxi, Huanglong and Henan largescale energy bases respectively.

Figure 2. The comparison of high and low water demand for seven largescale energy bases in 2020

From geographical distribution, Shendong, Ningdong and Northern Shaanxi energy bases have a highest water demand increment by 2020, and the new water demand accounts for 63% of total new water demand.

4 STUDY ON THE WATER CARRYING CAPACITY OF ENERGY BASES

The water demand for the development of energy bases is affected by water use efficiency and the scale of energy industry. The water resources conditions and engineering water-supply capacity in specific regions as well as the possible water resources quantity for energy development are affected by the water-use competitive relation among different sectors and the governments' strategic support of macroscopic water resource allocation (GHOSE, 2009). Thus, this study designs different developing scenarios by two ways in the analysis on the suitability of water resources and energy.

4.1 Available water supply of water resources

4.1.1 Available water supply under policy restraints

China is carrying out the strictest water resources management system, and its kernel is to strictly implement the water consumption control, comprehensively push for the construction of water-conserving society, strictly control total discharge capacity into rivers and lakes, and establish water resources management responsibility and the systems of examining and assessment. Moreover, it sets up the three red lines: control of water resources exploitation and utilization, control of water-use efficiency (WUE) and the limiting pollution load of water functional zone. In January 2013, the State Council issued the *Measures for the Examination of the Most Stringent Water Resources Management System* (hereinafter referred to as the "Measures"), making clear the control indexes of three red lines for water resources management of provinces and regions which serve as the basis of assessment to these provinces and regions. After that, the provinces and regions decompose these indexes further within their administrative districts. The control indexes of red lines for the resources development and utilization by 2020 in administrative districts in seven largescale energy bases on the middle-upper reaches of the Yellow River, that is, the control indexes of total regional water quantity are shown in Table 7.

Table 7. Control indexes of red lines for water resources development and utilization by 2020 for seven largescale energy bases on the middle-upper reaches of the Yellow River.

Name of coal base	Present water supply and consumption (10^8 m^3)	control indexes of total water consumption (10^8 m^3)	Difference of water consumption between present and red-line indexes (10^8 m^3)
Shendong	29.15	30.18	1.03
Ningdong	42.84	43.51	0.67
Northern Shanxi	23.69	30.63	6.94
Jinzhong	36.68	48.50	11.82
Northern Shaanxi	9.96	16.15	6.19
Huanglong	17.45	23.60	6.15
Henan	112.33	130.84	18.51
Total	**272.1**	**323.41**	**51.31**

In 2012, total water consumption came to 27.21 billion cubic meters in the prefecture-level administrative districts involved in seven largescale energy bases; the control indexes of total water consumption will get to 32.341 billion cubic meters by 2020. Compared with the present situation in 2012, these districts will have a possible water consumption increment of 5.131 billion cubic meters by 2020, which will satisfy the water demand in development of social and economic industries. One part of the increment may be used to guarantee the development of energy bases.

The administrative districts in Shendong and Ningdong energy bases will have a quite less water consumption increment in total water control indexes by 2020 against present situation, with an extremely limited water supply below the red-line criteria by 2020. Tapping the potential of present water stock and seeking for external water supply will be main ways of water-supply security for the development of energy bases.

4.1.2 Analysis on new water supply capacity

Based on *the national water resources integrated planning* (2008) and *the Yellow River Basin Water Resources Integrated Planning* (2008), the water supply capacity of new water source projects (surface water project and non-conventional water utilization) will reach 6.39 billion cubic meters in the administrative districts of seven largescale energy bases on the middle-upper reaches of the Yellow River by many ways of building water source projects and strengthening unconventional water utilization and inter-regional water replacement. The water source supply quantity is 520 million cubic meters by the water replacement among the regions.

In the paths of water security in energy bases, both unconventional water and water replacement can be basically regarded as the water supply special for energy bases. This part of new water supply comes to 865 million cubic meters as shown in Table 8.

Table 8. Water supply capacity of the regional water-supply security project by 2020 in seven largescale energy bases.

Name of coal base	**Present water supply (10^8 m^3)**	**New water source project (10^8 m^3)**		**Water replacement**
		Surface water project	**Unconventional water utilization**	
Shendong	29.15	2.67	0.33	1.64
Ningdong	42.84	2.84	0.66	2.56
Northern Shanxi	23.69	3.8	0.4	-
Jinzhong	36.68	11.5	0.3	-
Northern Shaanxi	9.96	7.34	0.56	1.00
Huanglong	17.45	4.3	0.6	-
Henan	112.33	28	0.6	0
Total	**272.1**	**60.45**	**3.45**	**5.2**

By 2020, the maximum local regional water-supply increment is determined by the relatively small values of total water consumption control indexes in the most stringent water resources management system and the regional project water supply capacity. If there is a high total water consumption control index and a scarce project water supply capacity, then the regional water supply increment will be limited by the water supply capacity, and otherwise it is limited by the control index of the most stringent water resources management. On the other hand, the water resources shortage may be handled also by the inter-regional or intra-regional water right transfer, and the water quantity from the water right transfer is not included in total water quantity control index of the most stringent water resources management.

By sufficient comparison of the relations between the regional water consumption increments and project water supply capacity, the available water supply increment will reach 5.25 billion cubic meters by 2020 for the regions in the energy bases (Compare the data of the last column of Table 7 and the second, third column of Table 8), where, the water right replacement will come to 520 million cubic meters.

4.2 Analysis on suitability of water resources and the water demand for development of energy bases

4.2.1 Design of water supply scenarios

The water demand for development of energy bases is affected by water use efficiency and the scale of the energy industry. Both water resources conditions and project water supply capacity in specific regions as well as the possible water resources quantity for energy development may be affected by the water use competitive relation among different sectors and the governments' strategic support of macroscopic water resources allocation. Thus, this study designs the following three different calculating scenarios in 2020 by two ways in the analysis on the suitability of water resources and energy:

Scenario (1): In the case of new water use, it is assumed that the share of water used in regional social and economic water use will remain unchanged in 2020, that is, the current situation of energy base water consumption accounted for the proportion of total regional water use will still be used in 2020 (the present proportion see Figure 1). This scenario will be the minimum value of energy base water supply protection.

Scenario (2): Taking into account the country's policy on water demand security policy for major energy base, it is assumed that the proportion of the energy base water use in regional social and economic water consumption in 2020 is 2 times of the present situation.

Scenario (3): Taking into account the country's policy on water demand security policy for major energy base, it is assumed that the proportion of the energy base water use in regional social and economic water consumption in 2020 is 3 times of the present situation. This scenario will be the maximum value of energy base water supply protection.

Table 9. New available water supply for seven largescale energy bases by 2020 Unit: 10^8 m^3.

Name of coal base	Water supply to energy bases	Water supply from other new water source projects							Available water supply for energy bases		
		Total quantity	Proportion per present water consumption		Proportion per present 2-time water consumption		Proportion per present 3-time water consumption				
			Proportion	Water quantity	Proportion	Water quantity	Proportion	Water quantity	Low limit	Mid limit	Upper limit
Shendong	1.97	0.7	13.0%	0.09	26.0%	0.18	39.0%	0.27	2.06	2.15	2.24
Ningdong	3.22	0.01	2.7%	0.00	5.4%	0.00	8.1%	0.00	3.22	3.22	3.22
Northern Shanxi	0.40	3.8	9.2%	0.35	18.4%	0.70	27.6%	1.05	0.75	1.10	1.45
Jinzhong	0.30	11.5	3.1%	0.36	6.2%	0.71	9.3%	1.07	0.66	1.01	1.37
Northern Shaanxi	1.56	5.63	14.6%	0.82	29.2%	1.64	43.8%	2.47	2.38	3.20	4.03
Huanglong	0.60	4.3	4.7%	0.20	9.4%	0.40	14.1%	0.61	0.80	1.00	1.21
Henan	0.60	17.91	6.3%	1.13	12.6%	2.26	18.9%	3.38	1.73	2.86	3.98
Total	**8.65**	**43.85**	**-**	**2.95**	**-**	**5.89**	**-**	**8.85**	**11.60**	**14.54**	**17.50**

The available water supply of new local water sources is distributed by present water consumption proportion. The new available water supply for energy bases by 2020 will be 1.16 billion cubic meters. In consideration of the supporting of policies, the new available water supplies for energy bases by 2020 are 1.451 and 1.75 billion cubic meters respectively.

4.2.2 Analysis on supply and demand matching

A comparative analysis is done on available water supplies in different water supply scenarios and total water demand in different water quotas as shown in Table 10.

Table 10. Analysis on water resources supply and demand matching for seven largescale energy bases by 2020.

Name of base	New water supply for energy bases			New total water demand	
	Low limit	Mid limit	Upper limit	Limited value	Advanced value
Shendong	2.06	2.15	2.24	2.76	1.70
Ningdong	3.22	3.22	3.22	2.92	1.68
Northern Shanxi	0.75	1.10	1.45	0.61	0.47
Jinzhong	0.66	1.01	1.37	0.33	0.26
Northern Shaanxi	2.38	3.20	4.03	3.20	2.19
Huanglong	0.80	1.00	1.21	1.89	1.01
Henan	1.73	2.86	3.98	2.35	1.28
Total	11.60	14.54	17.50	14.06	8.59

Shendong base has a lower water sources carrying capacity, and the regional water supply capacity still will not meet the water demand of the base by 2020 even if the preferential policies are available; the base must adopt the efficient ways in production techniques and water utilization for its development. The area where Ningdong, Northern Shanxi and Jinzhong energy bases are located, is of water resources carrying capacity to a certain extent, and their regional water supply capacity by 2020 meets the water demand of their construction and development. Both Northern Shaanxi and Henan bases have an insufficient water resources carrying capacity, and they should take into account that the preferential policies for energy production at the present level of water utilization, or the efficient production techniques and water utilization to be applied to meet the water demand of the bases. The Huanglong energy base has a lower water resources carrying capacity, and should fully take into account the factor of preferential policy in the future. At the same time, the efficient production techniques and water consumption should be applied to meet the water demand for construction and development of the base.

4.3 Analysis on uncertainties of water security in energy bases

(1) Problems in high demand and low supply: This study predicts that there are two scenarios in the water resources supply for energy bases by 2020, that is, high water supply (full policy supporting) and low water supply (per present water consumption proportion) scenarios; in water resources demand, there are also high water demand (by limiting water consumption index value) and low water demand (by advanced water consumption index value) scenarios. If the low water supply scenario encounters the high demand, then the water demand should not be guaranteed for Shendong, Northern Shaanxi, Huanglong and Henan energy bases;

(2) Problem of low water-supply security rate in special years: In this study, the regional project water supply capacity adopts the data in the average annual rainfall condition, and the control indexes of total water consumption in the most stringent water resources management also apply the limited values of water consumption in regions in the average annual condition. However, the rainfall is in an inter-annual uneven distribution on the middle-upper reaches of the Yellow River. With high and low water changes, it is lower in the regional water security rate in the drought year. So, it is partially optimistic for the results of water supply estimation for energy bases by average annual rainfall condition;

(3) The future water environment quality requirement can become a strict restraint to the development of energy bases. The development of energy bases means a severe test to regional water environment protection. China gradually pays attention to water environment protection, and the water qualification rate should be improved greatly in the period of the 13^{th} Five Year Plan against the 12th Five Year Plan. This means a strict requirement for development of energy bases, and also a further constraint to their development.

5 CONCLUSIONS

(1) The water demand for energy production will still be in a continual increase on the middle-upper reaches of the Yellow River during the 13th Five Year Plan. It is predicted that the new water demand will come to 1.406 billion cubic meters in coal mining and washing, coal power and coal chemical industries for the seven energy bases on the reaches. Though the water-saving techniques for energy production advance rapidly, a new water quantity of 859 million cubic meters is still needed;

(2) The competitiveness will be aggravated further in water resources development and utilization of energy bases on the middle-upper reaches of the Yellow River. During the 13th Five Year Plan, Northern Shaanxi, Huanglong, Shendong and Ningdong energy bases on the middle-upper reaches of the Yellow River will be developed further in a greater scale. This will intensify the competition inevitably in water utilization between industries and regions in the background of limited regional water resources security capacity. It is predicted that the imbalance between supply and demand of water resources will be aggregated further in energy bases, and greater challenge will be faced in guaranteeing water resources demand of energy bases;

(3) The water demand for energy production can be guaranteed moderately during the 13th Five Year Plan under many measures taken. By systematical study and analysis, the water utilization can be guaranteed in energy bases by 2020 in the prerequisite of water supply enlargement and demand control. Based on the estimation of their planned development scales, the difference of water demand is about 547 million cubic meters between the general and sufficient water-saving scenarios in seven energy bases on the middle-upper reaches of the Yellow River by 2020. Thus, the water-use efficiency should be improved greatly in the energy industry;

(4) Both unconventional water use and water amount replacement become important supporting measures for the development of energy industry. The energy industry, especially coal industry, on the middle-upper reaches of the Yellow River faces the pressing water resources restriction in its development. In a shortage of natural water resources, the following measures should be taken to solve the problem of thirsty in energy industry: ①Importance attached to developing

unconventional water sources and sufficiently making use of recycled water. ② Actively exploring the inter-industrial and inter-regional water source replacement, and transforming the industries with low-efficiency water utilization to the energy industries with high-efficiency water utilization by market means (Wang et al.,2009). China had done the pilot work of different types of water right trade in seven provinces and cities since 2014.

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DYNAMICS OF ALGAL GROWTH IN EXPERIMENTAL ENCLOSURES IN THE PANJIAKOU RESERVOIR, HEBEI PROVINCE, CHINA

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ABSTRACT

The present study of the drinking water supply source, Panjiakou Reservoir (Hebei Province, China), provides an illustration of the potential link among fish food, algal biomass and structure, and two different fishes. Five polythene enclosures were installed near the fish aquaculture cages in this reservoir. This paper focuses on algae including their growth dynamics and community structure alteration. Results from approximately 50 days' observation indicated that the introduction of fish food greatly encouraged a blue-green and green algae outburst, and that the presence of bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*) can be reduced up to 79.47% and 65.22 % of the total algae biomass, respectively, as compared to the enclosure only with fish food. Moreover, culturing two kinds of fish changed the algae dominance from the larger blue-green algae to smaller green algae. Algae species dominance analysis indicated that the introduction of fish food reduced the diversity of the phytoplankton community, and Anabaena developed to be the single predominant species. Fish species impacted significantly on the dominance of algae species. The suppression of Anabaena by the bighead carp (*aristichthis nobilis*) contributed greatly to the decline of the blue-green algae biomass. The reduction in nutrient availability owing to the abundant food utilization by common carp (*cyprinus carpio*) and the regulation of phytoplankton composition caused the dominance of Vlothrix sp and Coelastrum in the common carp (*cyprinus carpio*) culturing enclosure. Further statistical analysis showed that the chemical oxygen demand (COD) and water temperature were positively and negatively related to the total algae biomass, respectively.

Keywords: Algae; Bighead Carp (*Aristichthis Nobilis*); Common Carp (*Cyprinus Carpio*); experimental enclosure; growth dynamics.

1 INTRODUCTION

In recent years, theoretical analysis and experimental research about intensive marine aquaculture effects on water environment have been widely reported (Buschmann et al., 2006; Lee et al., 2003). In China, it was reported that 27% of red tides happened in relation to marine aquaculture activities (Zhao et al., 2003). With the growing demand for fishery products, aquaculture activities have also greatly expanded in inland freshwater, which is generating an increasing concern over their environmental impacts (Lee et al., 2003). However, relatively little research studied the algal blooms caused by aquaculture activities in inland freshwater reservoirs and lakes. Eutrophication of inland freshwater, resulting in the rapid growth of algae and forming water blooms, has become one of the most severe environmental problems, damaging or destroying its ecological functions and services, including drinking water supply, flood mitigation, fishery (Johnson and Revenga, 2001).

To guarantee the water demand for industrial development, rural irrigation, and domestic use, reservoir construction is of great importance to efficiently store the rainfall during the rainy season and discharge the valuable water resource during dry periods. So far, this kind of water management policy has become the most important and commonly used strategy in many water resource shortage areas.

The expansion of aquaculture activities may deteriorate the receiving water quality. Uneaten fish food and faeces are regarded as the main wastes in aquaculture, which introduce excessive nutrients to the corresponding water zone (Wu et al., 2012; Guo et al., 2009; Buschmann et al., 2006; Lee et al., 2003). Both nitrogen and phosphorus are the essential nutrients in fish food to achieve a good growth of fish. Meanwhile, these two nutrients are also required for algae growth. Fish culturing can influence algae growth at variable levels. During the enclosure experiment conducted in the Paranoá Reservoir, Brasilia, Brazil, the presence of

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silver carp greatly reduced the dominant blue-green algae biomass (Starlìng and Rocha, 1990). In another study, 1000 silver carp and 500 bighead carp (*aristichthis nobilis*) led to a 45.31% decrease in total phytoplankton biomass (Liberman, 1996). On the contrary, Domaizon and Devaux reported that silver carp inefficiently grazed down particles less than 20 μm and the suppression of herbivorous cladocerans resulted in the increase of small size algae, which subsequently resulted in a negligible reduction of cyanobacteria dominance (Domaizon and Devaux, 1999). Similar phenomenon was also found by Radke and Kahl, who suggested that silver carp should be used to reduce the nuisance blooms of large phytoplankton species (e.g. cyanobacteria) (Radke and Kahl, 2002). As compared to silver carp or bighead carp (*aristichthis nobilis*), a positive contribution of bait-eating fish such as common carp (*cyprinus carpio*) on algae growth has been reported (Domaizon and Devaux, 1999; Zhao, 1993). Zhao found that common carp (*cyprinus carpio*) can significantly stimulate the increase in both phytoplankton and zooplankton biomass. Previous research indicated that various factors, such as total algae biomass and species (Domaizon and Devaux, 1999), zooplankton grazing pressure on dominant algae (Radke and Kahl, 2002; Arcifa et al., 1986), nutrient status (Axler et al., 1998), fish stocking density, fish species (Colautti et al., 2010; Lahab et al., 2002; Zhao,1993) and fish diet (Wang and Liu, 2008) can explain these variable results.

In order to manage the water quality at Panjiakou Reservoir at a much better level and guarantee the safety of the drinking water supply, the Haihe River Conservancy Commission, the river basin management agency for the reservoir, funded the present research to determine the impact of fish cage-culturing on the algae growth dynamics in the Panjiakou Reservoir. In this study, two kinds of fish (bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*)) were examined in the five different enclosures installed in the Panjiakou Reservoir. The objectives of the research were:

i. To trace and evaluate the algae growth characteristics with different culturing designs,
ii. To analyze the variability in algae fractions and dominance during the culturing period,
iii. To evaluate the relationships between the algae growth and the water quality variables in the fish culturing practices.

2 MATERIALS AND METHODS

2.1 Experimental sites

The Panjiakou Reservoir (118°15´E, 40°25´N) located in Qianxi County, Tangshan City, northern Hebei Province, China has a useable water surface area of approximately 40 km^2 and water storage of 2.93 × 10^9 m^3 (Figure1). The Luanhe River, Liuhe River and Baohe River are the major tributaries for the Panjiakou Reservoir (Domagalski et al., 2007). As compared to the power generation, irrigation, flood control and fishery, drinking water supply to the Tianjin City is the primary task and management objective for the Panjiakou Reservoir. In the past two decades, however, stimulated by the economic profit, fish cage-culturing has gradually developed and became the primary industry and the major income to the surrounding population. Published literature reported (Wang et al., 2008; Domagalski et al., 2007) that fish cage-culturing in the Panjiakou Reservoir began in the late 1980s and has spread all over the reservoir. The culturing area accounts for 1.7% of the total water surface with nearly 17,000 to 25,000 cages (official number), of which 7,000 to 10,000 fed bait-eating fish including common carp (*cyprinus carpio*), crucian carp (*Carassius auratus*) and grass carp (Ctenopharyngodon idellus) are the predominant species. The other 10,000 to 15,000 cages contain planktivorous silver carp (Hypophthalmichthys molitrix) and bighead carp (aristichthis nobilis).

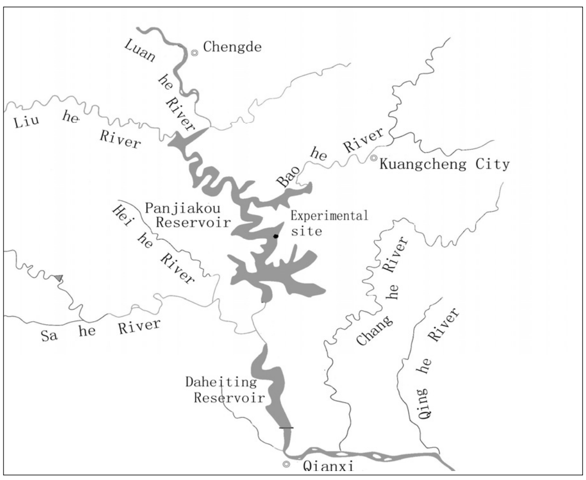

Figure1. Map of Panjiakou Reservoir showing the experimental site.

Though the fish cage-culturing history has lasted for nearly 20 years, the impact of intensive culturing in the Panjiakou Reservoir on algae growth and water quality is not well understood. Based on the water monitoring results, Wang (2008) found that total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD) concentrations were 19.3%, 238% and 4.8% higher, respectively, and dissolved oxygen (DO) was 20.9% lower in the common carp (*cyprinus carpio*) culturing water than that in the control reservoir water, and fish food addition greatly elevated the nutrients concentration and promoted algae growth.

2.2 Experimental set-up and operation

In situ enclosure experiments were conducted in the representative intensive fish culturing water area of the Panjiakou Reservoir, about 15 m from the reservoir bank. Floating rectangular frames were constructed with the material of steel pipes for simulating the fish cage-culturing conditions of the nearby fish farm. Five analogous waterproof and polythene enclosures (A, B, C, D and E) were installed within the steel frame to prevent collapsing. The dimensions of the enclosures A, B and E were 2.9 m in length, 2.9 m in width and 1.5 m in depth.

The enclosures C and D had the same design. The only difference between the enclosures A, B and E and the enclosures C and D was the depth. The depths of the enclosures C and D were 1.8 m. The additional 0.3 m water depth was designed for stocking common carp (cyprinus carpio) that prefer deeper water than the bighead carp (aristichthis nobilis). The enclosures were fixed to the reservoir bank with the help of anchors and steel ropes. Furthermore, the enclosures designed in this study were isolated from the bottom sediment and surrounding reservoir water.

In the present study, the enclosures A, B, C and D were set to examine the contribution of fish food, culturing bighead carp (*aristichthis nobilis*) with fish food, culturing common carp (*cyprinus carpio*) with fish food, mixed culturing of bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*) with fish food to the algae growth dynamics, while the enclosure E served as the control experimental without fish or fish food (Table 1). This experimental setup did not consider replicates of enclosures (Chen et al., 2009; Blomqvist, 2001) mainly due to the paramount work of chemical analysis. All the experimental fishes were obtained from adjacent fishery farms with the similar weight of 250 ± 20 g (mean ± S.D) for bighead carp (*aristichthis nobilis*) and 63 ± 9 g for common carp (*cyprinus carpio*), respectively. Soybean meal (made by Hebei Panda Feed Company, Limited) bought from the local fish farm was used as the fish diet. The organic matter, total nitrogen and total phosphorus content of the soybean meal were 88.20%, 4.67% and 0.81%, respectively.

On 18th August 2009, the enclosures were filled with reservoir water using a submerged pump. After two days of acclimation and water quality stabilization, the bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*) were stocked into the enclosures according to the designs listed in Table 1. Fish food was added three times a day with the dosages of 16.7 g to the enclosures A and B, and 20.0 g to the enclosures C and D, the selected dosages and feeding frequency were comparable to those used for the adjacent fishery farm. The fish food nutrient analysis indicated that OM, TN and TP accounted for 85 ± 2%, 4.76 ± 0.58% and 0.87 ± 0.04% of the total mass, respectively. During the experimental running period, all the fish survived.

Table 1. Experimental enclosures with different designs.

Enclosures Number	Culturing conditions				Fish food dosage (g fish food•m^{-3} water)
	Volume (m^3)	Fish species (-)	Number Stocked (-)	Stock density (g fish•m^{-3} water)	
A (fish food without fish)	12.6	N/A	N/A	N/A	1.325×3•d^{-1}
B (fish food with bighead carp)	12.6	Bighead carp	4	95.24	1.325×3•d^{-1}
C (fish food with carp)	15.1	Common carp	16	67.22	1.325×3•d^{-1}
D (fish food with bighead carp and carp)	15.1	Bighead carp Common carp	2 7	66.23	1.325×3•d^{-1}
E (without fish food and fish)	12.6	N/A	N/A	N/A	N/A

N/A: not applicable; fish food was added with a frequency of three times a day.

2.3 Water sampling and analysis

The enclosure water and surrounding reservoir water were first sampled 0.5 m below the water surface on 18th August 2009. Water samples for both enclosures and reservoir were then collected at an interval of 2 days and completed on 6th October, 2009. As compared to the enclosures, the reservoir water samples determine the background values for algae biomass and water quality variables.

All samples were analyzed on the same day. They were analyzed for the following parameters: COD, ammonia-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), dissolved total nitrogen (DTN), particulate total nitrogen(PTN), total nitrogen (TN), soluble reactive phosphorus (SRP), dissolved total phosphorus (DTP), particulate phosphorus (PP), total phosphorus (TP), electric conductivity (EC), total dissolved solids (TDS), chlorophyll-a (Chl-a), dissolved oxygen (DO), water temperature (T), and pH. Water quality parameters including COD, NH_4^+-N, NO_3^--N, TN, SRP, DTP, and TP were determined according to standard methods (APHA, 1998) if not stated otherwise. PP was the difference between TP and DTP. PTN was the difference between TN and DTN. A YSI 6600 V2-2 Multi-Parameter Water Quality Sonde was used for DO, EC, TDS, Chl-a, T and pH analysis, respectively. Each variable test had parallel samples.

The water samples were also analyzed to investigate the variation in dominant algae fractions and species. A JKY/FluoroProbe-BBE was used to measure the biomass of total algae, Cyanophyta (blue-green algae), Chlorophyta (green algae), Bacillariophyta (diatom) and Cryptomonas expressed in 10^4 cells•L^{-1} water. Furthermore, 7.5 mL of 1% Lugool's iodine solution was added to 500 mL water samples and the sample was concentrated to 30 mL after sedimentation for 24 h. After complete mixing, 0.1 mL of the concentrated samples was used to identify the algae species according to Hu and Wei (2006).

2.4 Statistical analysis

All statistical tests were performed using the Statistical Package for the Social Sciences (SPSS) software package. Significances were defined as $p < 0.05$, if not stated otherwise. An one-way analyses of variance (AN-OVA) and the Tukey's significant difference multiple range tests (Fraser et al., 2004) were carried out to assess the differences between the means of the algae biomass in different enclosures and the surrounding reservoir water. In addition, the data obtained from the enclosures A, B, C and D were fitted with two-way ANOVA to examine the influences of absence, presence of bighead carp (aristichthis nobilis) or/and common carp (cyprinus carpio) on the Cyanophyta, Chlorophyta, Bacillariophyta and Cryptomonas biomass. For all ANOVA, the tested variables were normally distributed.

3 RESULTS

3.1 Algae growth characteristics

The enclosure experiment began in late summer and ended in autumn, thus the temperature experienced a general declining (Figure 2). Figure 3 shows the changes in total algae biomass in all the enclosures and the surrounding reservoir water. During the whole monitoring period, there was no significant increase or decrease in the total algae biomass for both enclosure E and the reservoir water, and the corresponding two curves almost overlapped (Figure 3). The algae growth showed a different pattern in the fish food added enclosures. The total algae biomass was obviously higher in the enclosures A, B, C and D than that in the enclosure E. In the first week, different treatments affected the total algae biomass at a negligible level (Figure 3). After 22nd August 2009, the presence of fish food greatly stimulated the algae growth. The enclosure A exhibited advantageous, considerable increase in the total biomass and reached a maximal density of 206,000 × 10^4cells•L^{-1} on 6th October (Figure 3). The enclosures B, C, and D (with fish present) showed an irregular trend that lasted almost one month (between 24th August and 21st September). After this time, the algae growth became clear and the ranking order for the measured total algae biomass in the fish feeding enclosures was C (common carp (*cyprinus carpio*) fed) > D (common carp (*cyprinus carpio*)) and bighead carp (*aristichthis nobilis*) fed) > B (bighead carp (*aristichthis* nobilis) fed).

The biomass for Cyanophyta (blue-green algae), Chlorophyta (green algae), Bacillariophyta (diatom) and Cryptomonas are shown in Figure 4. The blue-green algae and green algae biomasses were greatly higher than the diatom and Cryptomonas, and the variations in their biomass contributed the most to the total algae growth dynamics. For the enclosure E and reservoir water, the blue-green algae and green algae biomasses were kept at a stable low level during the whole running period as compared to the fish food presented in the enclosures A, B, C and D (Figure 4). However, the fish culturing did not favor diatom propagation. The observed biomass in the enclosure E and the surrounding reservoir water was generally higher than that measured in the fish food added tests except the enclosure B. The Cryptomonas growth showed a different trend from blue-green algae, green algae and diatom. There was an irregular trend that appeared during the entire set of experiments. The biomasses of Cryptomonas in the enclosure E and reservoir water were lower than the fish food introduced the enclosures A, B, C and D in the early two weeks and later three weeks, but higher than that in the four fish food presented test in the middle two weeks (Figure 4).

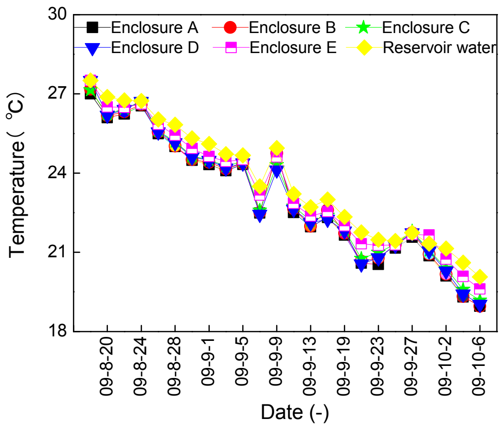

Figure 2. Variations in water temperature during the experimental period for reservoir water and culturing water in enclosures.

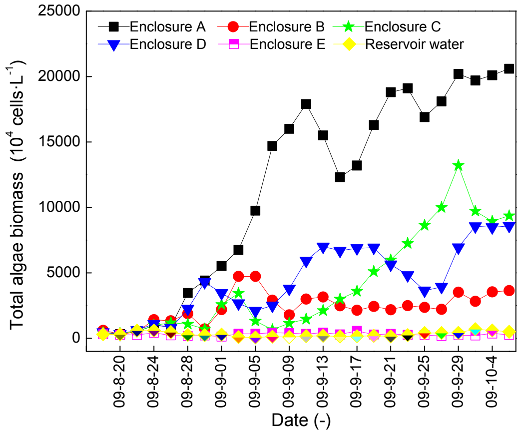

Figure 3. Variations in total algae biomass concentrations during the experimental period for reservoir water and in enclosures.

3.2 Effect of fish culturing on algae fractions

The results from further fraction analysis of the total algae biomass are shown in Table 2. It was found that blue-green algae and green algae were the primary fractions for all the enclosures as well as the surrounding reservoir water, and Bacillariophyta and Cryptomonas accounted to less than 20% of the total algae biomass (Table 2). For Cyanophyta (blue-green algae), the presence of fish food without culturing fish caused the highest biomass mean percentage of 81.67%, which occurred in the enclosure A as compared to 44.86% for the surrounding reservoir water. The confined water in the enclosure E also significantly contributed more than a 15% mean increase to percentage in contrast to the reservoir water ($p < 0.05$, Table 2). However, feeding bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*) both resulted in significant decreasing in the blue-green algae biomass. Both the enclosures B and C showed the low percentages ($p < 0.05$, Table 2). For the enclosure D, however, insignificant effect of the interactions between bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*) on blue-green algae biomass percentage can be detected when compared to the reservoir water ($p > 0.05$, Table 2).

In contrast to the blue-green algae, Chlorophyta (green algae) showed different variations in the fractions within the different treatments. One way-ANOVA test results indicated that the confined water and the introduction of fish food impacted little to the percentage concentrations observed in the enclosures A and E when compared to the reservoir water ($p > 0.05$, Table 2). However, the presence of bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*) both significantly increased the green algae percentages, and the highest mean increment of 57.20% was obtained when compared to the reservoir water ($p < 0.05$, Table 2).

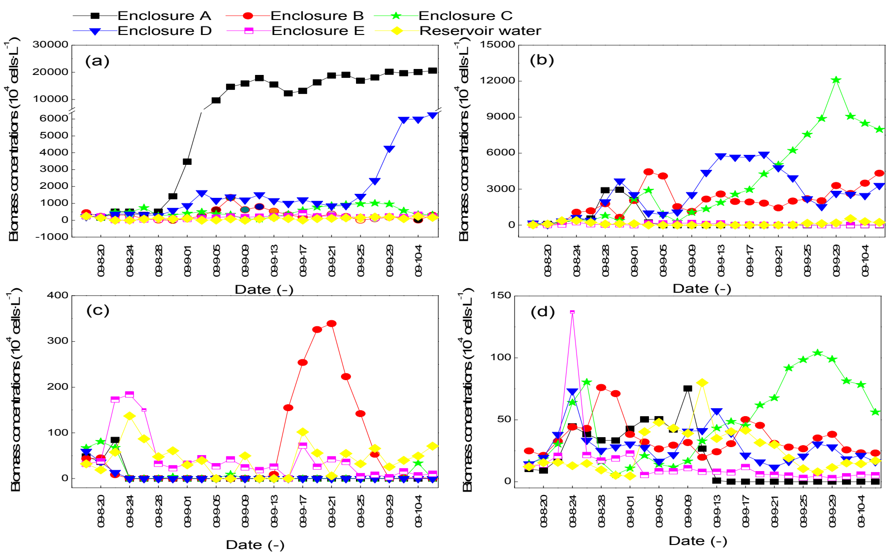

Figure 4. Variations in (a): Cyanophyta (blue algae), (b): Chlorophyta (green algae) and (c): Bacillariophyta (diatom) and (d) Cryptomonas concentrations during the experimental period for reservoir water and enclosures.

Table 2. Mean biomass concentrations ± SD and percentage for Cyanophyta, Chlorophyta, Bacillariophyta ,Cryptomonas and total algae detected in the reservoir water and culturing waters of experimental.

Variables	Reservoir water	Culturing water Enclosure A	Enclosure B	Enclosure C	Enclosure D	Enclosure E
Cyanophyta (blue-green algae)						
Concentration (10^4cells•L^{-1})	106.7±74.8^{a}	11293.4±8008.5^{b}	307.7±200.0^{a}	481.9±298.4^{a}	1693.8±854.1^{a}	184.5±93.7^{a}
Percentage (%)	44.9±26.2^{b}	81.67±28.29^{d}	18.4±11.9^{a}	22.3±16.2^{a}	38.9±21.0^{b}	60.0±27.8^{c}
Chlorophyta (green algae)						
Concentration (10^4cells•L^{-1})	82.5±31.6^{a}	383.32±78.0^{a}	2006.1±1227.6^{b}	3524.8±1586.0^{c}	2647.5±1901.7^{b,c}	101.0±70.8^{a}
Percentage (%)	19.0±13.4^{a}	22.9±2.5^{a}	76.2±25.1^{c}	73.6±22.8^{c}	58.59±22.5^{b}	26.1±15.8^{a}
Bacillariophyta (diatom)						
Concentration (10^4cells•L^{-1})	42.5±34.1^{b}	6.78±3.08^{a}	64.13±48.73^{b}	10.54±4.29^{a}	4.36±3.78^{a}	43.1±20.3^{b}
Percentage (%)	19.2±8.5^{c}	1.6±0.4^{a}	3.5±1.3^{a}	2.1±1.7^{a}	1.1±0.4^{a}	10.8±8.8^{b}
Cryptomonas						
Concentration (10^4cells•L^{-1})	31.54±27.3^{c}	19.0±12.6^{a,b}	34.9±14.1^{c}	48.5±32.3^{d}	28.3±14.2^{b,c}	8.1±3.9^{a}
Percentage (%)	19.8±10.1^{b}	0. 9±0.4^{a}	2.4±1.26^{a}	2.1±1.7^{a}	1.5±1.0^{a}	2.4±0.9^{a}
Total algae						
Concentration (10^4cells•L^{-1})	260.2±164.6^{a}	11697.3±7539.1^{c}	2401.7±1239.9^{a,b}	4068.3±3809.1^{b}	4373.3±2778.2^{b}	338.6±113.7^{a}

Values with a different superscript letters indicate significant difference at $p \le 0.05$ based on Turkey's HSD.

Two-way ANOVA was used to examine the effect of fish species on the algae growth. It was found that bighead carp (*aristichthis nobilis*) had a significant effect on blue-green algae, green algae and diatom growth but had negligible impacts on Cryptomonas growth (Table3). However, common carp (*cyprinus carpio*) led to the significant statistical differences in blue-green algae, green algae, diatom and Cryptomonas at $p < 0.05$ (Table 3). Furthermore, the interactions between bighead carp and the common carp (*cyprinus carpio*) on all the four algae fractions were significant at $p < 0.05$ (Table 3).

Table 3. Results of two-way analyses of variance examining the role of bighead carp and common carp on the biomass concentrations for *Cyanophyta* (blue algae), *Chlorophyta* (green algae), *Bacillariophyta* (diatom) and *Cryptomonas*, respectively.

Variable	Factor	F-ratio	P
Cyanophyta (blue algae)	Bighead carp	35.249	< 0.001
	Common carp	32.780	< 0.001
	Bighead carp *common carp	54.900	< 0.001
Chlorophyta (green algae)	Bighead carp	0.741	0.392
	Common carp	19.077	< 0.001
	Bighead carp*common carp	8.332	0.005
Bacillariophyta (diatom)	Bighead carp	5.032	0.027
	Common carp	6.031	0.016
	Bighead carp*common carp	7.759	0.006
Cryptomonas	Bighead carp	0.235	0.629
	Common carp	6.711	0.011
	Bighead carp*common carp	16.613	< 0.001

3.3 Variability in Algae species dominance

The variability in algae species dominance was studied for the investigation of the algae community structure and composition. During September 2009, the algae species were examined to gain more information concerning the growth under the fish culturing conditions. During the monitoring period, results from microscopic examination showed that the predominant algae species developed differently within the various enclosures and the reservoir water (Figure 5). In the surrounding reservoir water, Anabaena was the major algae species though its dominance tended to decline gradually. As compared to the enclosure E, only fish food addition resulted in the dominance of Anabaena, thus evolved as the only predominant species in the enclosure A (Figure 5). In bighead carp (*aristichthis nobilis*) culturing the enclosure B, Scenedesmus, Anabaena and Schroederia were the dominant algae species, and Scenedesmus developed its dominance and was predominant in the phytoplankton community at the end of the monitoring period. For the common carp (*cyprinus carpio*) culturing enclosure C, Vlothrix Sp and Coelastrum were the main dominant species, while Anabaena and Scenedesmus were dominant in the mixed culturing enclosure D (Figure 5).

4 DISCUSSION

As compared to the enclosure E and the surrounding reservoir water, the presence of fish food greatly stimulated the total algae biomass observed in the enclosures A, B, C and D (Figure 3 and Table 2), similar contribution of fish food to the algal growth stimulation can also be found elsewhere (Romo et al., 2004). Both nitrogen and phosphorus are the essential ingredients incorporated in formulated feed to achieve optimal growth of fish. Abundant organic matter, nitrogen and phosphorus contained in the fish food are slowly released, and then promote the algae growth correspondingly in the culturing water (Huang et al., 2004; Zang et al., 2011; Kaggwa et al., 2010; Hargreaves, 1998). In the enclosure A, the fish food addition caused the highest algal biomass and the lowest diversity of algal species. This is expected by the competitive exclusion principle that the superior competitor species would dominate a constant environment and lead to a low community richness and diversity (Figueredo and Giani, 2009). In the present study, both bait-eating common carp (*cyprinus carpio*) and planktivorous bighead carp (*aristichthis nobilis*) were chosen to investigate their contribution to the total algae biomass. For the enclosure B and C, culturing bighead carp and common carp (*cyprinus carpio*) caused 79.47% and 65.22% reduction in the total algae biomass, respectively, in contrast to the enclosure A without fish. Liberman (Liberman, 1996) found that together with silver carp, bighead carp (*aristichthis nobilis*) successfully suppressed 45.31% growth of the total phytoplankton biomass. Like silver carp, bighead carp (*aristichthis nobilis*) is an obligate filter-feeding planktivore and very efficient to control the large algal species such as cyanobacteria (Radke and Kahl, 2002; Dong, 1994). In our experiment, the total algae biomass in the enclosure B was very high and the algae fraction was actually dominated by blue-green algae and green algae, accounting for more than 90% of the total algae (Table 2). This phenomenon was in accordance with the observation from those cases (Fukushima et al., 1999; Starlìng, 1998; Datta and Jana, 1998) in which sliver carp can succeed in bio-manipulating the phytoplankton communities dominated by large species or colonial algae (mainly cyanobacteria) under eutrophic or hypertrophic conditions. Another possible reason is that the small algae, which cannot be effectively removed by bighead carp (*aristichthis nobilis*), were unable to build up high biomass within the time frame of the studies, resulting in an overall reduction of phytoplankton biomass (Radke and Kahl, 2002).

Like bighead carp (aristichthis nobilis), common carp (cyprinus carpio) also played an effective role in controlling the total algal communities dominated by cyanobacteria. This phenomenon was contradictory with that reported earlier by Zhao et al. (2003), who found that the presence of common carp (cyprinus carpio) both encouraged the growth in phytoplankton and zooplankton biomass, and the algae community tended to be colonized by large species instead of small one. However, other researchers (Kajak, 1979) argued that bait-eating fish such as common carp (cyprinus carpio) could regulate the zooplankton community composition and control the total algae biomass through the food web. In this study, we did not examine the zooplankton communities; therefore, the above speculation was still questionable and should be studied in subsequent research.

As shown in Table 2, the presence of bighead carp (aristichthis nobilis) and common carp (cyprinus carpio) resulted in the dominant phytoplankton fractions altered from Cyanophyta (blue-green algae) to Chlorophyta (green algae) in the enclosures B, C and D when compared to that in the enclosure A. Similar results were also obtained in an enclosure experiment conducted in Donghu Lake, China, which found that planktivorous silver carp had the desired effect of changing phytoplankton dominance from blue-green algae to small edible green algae (Tang et al., 2006). Common carp (cyprinus carpio) also drove the change from blue-green algal dominance to green algal dominance. The same phenomenon was also found elsewhere (Wahab et al., 2002). The possible explanation is that common carp (cyprinus carpio) optimize the phyto- and zooplankton community, and succeed in restraining the blue-green algae growth by competition with small green algae species such as Vlothrix Sp and Coelastrum.

To evaluate the potential contribution of bighead carp (aristichthis nobilis) and common carp (cyprinus carpio) to the algae growth dynamics, species dominance is a useful parameter. In the previous studies, factors including body size, stocking density, food availability, and environmental conditions had variable effects on the algae community composition in the silver carp and bighead carp (aristichthis nobilis) feeding experiments (Domaizon et al., 1999; Starlìng et al., 1998; Spataru, 1985). However, it is possible to see silver carp is an obligate filter-feeding planktivore with a highly developed filtering apparatus with mesh size ranging from 12 to 26 μm (Spataru, 1985). Like silver carp, bighead carp (aristichthis nobilis) can efficiently consume large nanoplankton and netphytoplankton but not smaller algae species. As shown in Figure 5, the presence of fish food significantly promoted larger Anabaena outburst in the enclosure A when compared to the enclosure E and surrounding reservoir water. Benefited from the consumption of bighead carp (aristichthis nobilis), Scenedesmus replaced Anabaena and developed to the predominant community in the enclosure B. Common carp (cyprinus carpio) showed a different mechanism in the algae species dominance regulation.

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Common carp (cyprinus carpio) did not directly consume phytoplankton, and the major food for common carp (cyprinus carpio) is fish diet and zooplankton. This may reduce the nutrient availability and change the phytoplankton composition, and thus cause the dominance of smaller Vlothrix Sp and Coelastrum (Huang et al., 1985).

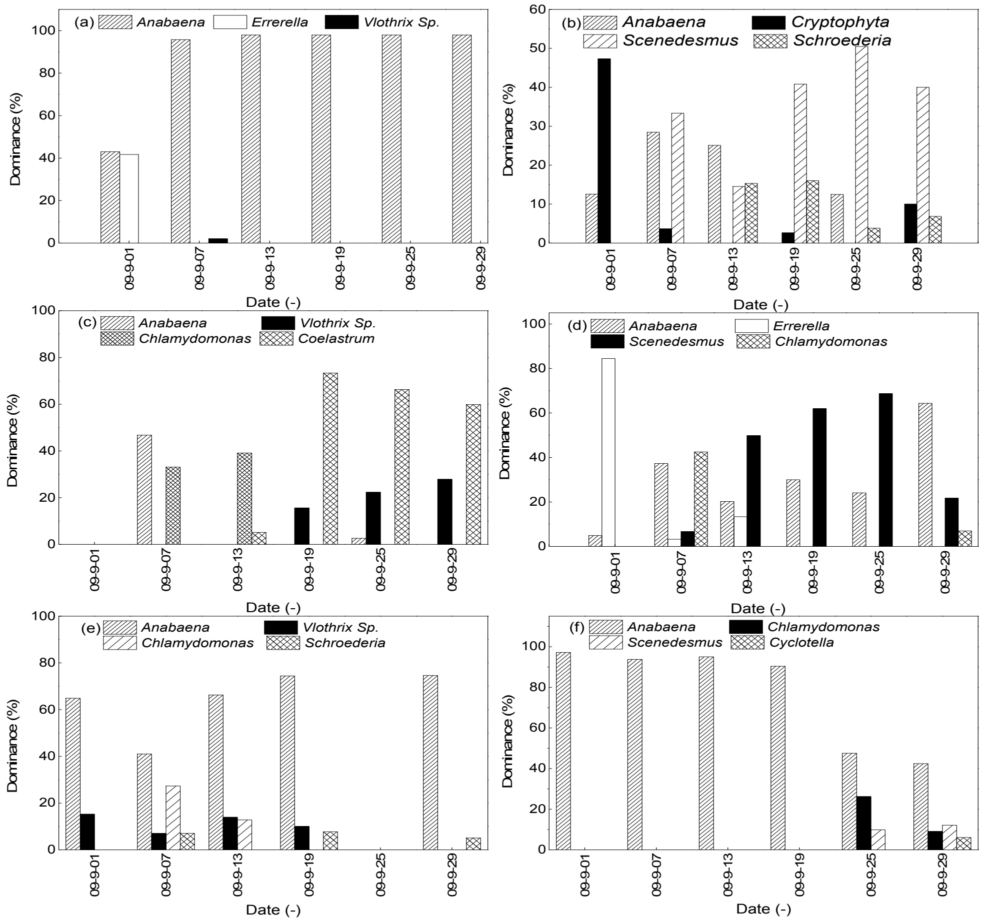

Figure 5. Variability in algae species dominance during the monitoring period for (a).fish food without fish and (b) fish food with bighead carp and (c) fish food with common carp and (d) fish food with bighead carp and common carp and (e) without fish food and fish and (f) reservoir water.

Finally, the total algae biomass was correlated to the nutrients and other water quality variables (Figure 6). It was found that positive and negative correlation coefficients have the following orders: COD > EC > TDS > NH_4^+-N and pH > DO > TN > DTN > NO_3^--N > T. Moreover, very weak correlations for pH and DO were calculated. The continuous supply of nutrients including fish diet can effectively stimulate the algae growth (Figueredo and Giani, 2009; Tang et al., 2006). Positive correlation coefficients for COD and NH_4^+-N suggest that the algae growth were indirectly stimulated by the addition of slowly released soybean meals used as fish food. Starlìng and Rocha (1990) reported that pH values during the enclosure culturing experiments decreased with the increasing phytoplankton production. Moreover, Figueredo and Giani (2009) found that pH and DO were not significantly correlated to the total phytoplankton colonized by cyanobacteria. Their findings were confirmed by our study, and it can be implied that organic matter concentrations (e.g. COD) can be used to predict the algae growth and regular reservoir water environment management to some extent.

It may be worthwhile to point out that our current study has only one setting for fish density and fish dosage in spite that we monitored most water quality and ecological variables in a systematic way. This, to a large extent, limited us from getting a full understanding of the effect of fish culture on the algal growth and water quality dynamics and from developing a set of mathematical equations for algal growth as a function of fish dosage and other environmental variables. This should be fully considered in future similar investigations. Moreover, extra care must be executed when the results in our enclosure experiments are directly applied in open reservoir water because the former could be considered at most as a mini-reservoir in terms of the water volume and much more intensified with regards to fish density and dosage. But, the results do indicate that fish agriculture in multi-annual regulating reservoirs, like Panjiakou Reservoir, must be managed well with great care or severe damage to the ecological environment quality could be prompted, such as algae boom and degradation of water quality.

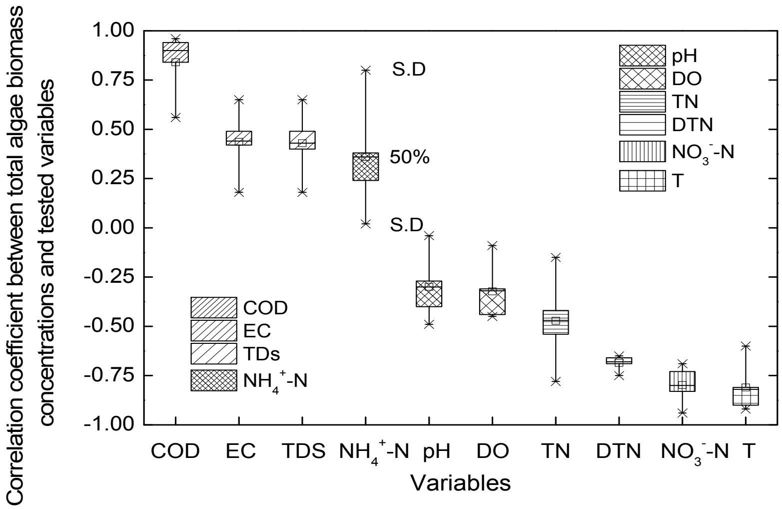

Figure 6. Distribution of correlation coefficients between total algae biomass concentrations and tested variables. S.D, standard deviation; small squares within each box center are means; lines represent 50% of the value range.

5 CONCLUSIONS

Due to the scale effect and short experimental period, the tested enclosures cannot fully reflect the practical contribution of bighead carp (*aristichthis nobilis*) and common carp (*cyprinus carpio*) culturing to the algae growth dynamics. For Panjiakou Reservoir, however, our study will clear the previous hypothesis that culturing bighead carp (*aristichthis nobilis*) may improve the water quality through phytoplankton predation while common carp (*cyprinus carpio*) may deteriorate the water quality by the stimulation of the algae growth. In fact, both fish species can significantly reduce the total algae biomass and the presence of both fish species changed the algal dominance from blue-green algae to green algae. Moreover, the fish culturing reduced biomass of the diatom (only accounted less than 5%) in contrast to the surrounding reservoir water.

As compared to the surrounding reservoir water, the presence of fish food reduced the phytoplankton biodiversity and simplified the algae community composition. Anabaena developed to be the only predominant species. Bighead carp (*aristichthis nobilis*) showed a significant consumption effect on Anabaena and resulted in declining of the blue-green algae biomass. Common carp (*cyprinus carpio*) efficiently utilized fish food and thus caused the dominance of smaller Vlothrix Sp and Coelastrum. It is suggested that bighead carp (*aristichthis nobilis*) is more effective in the directly control of blue-green algae blooms, while common carp (*cyprinus carpio*) is more useful in the reduction of the total nutrient loadings and regulation of the plankton community.

Panjiakou Reservoir has poor currents and exchange times of months and years rather than days. Eutrophication control, especially for algae bloom prevention is of particular concern for the supply water safety to the large cities such as Tianjin. For the sustainable drinking water supply and scientific reservoir management consideration, it is necessary to conduct further research to study the effect of nutrient availability, zooplankton community, environmental boundary conditions as well as the fish culturing strategy (e.g. fish food dosage and added frequency) on the algae growth.

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EVALUATION OF ECOSYSTEM DEGRADATION RESPONSE TO WATER-SAVING MEASURES IN HETAO IRRIGATION AREA, CHINA

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ABSTRACT

Hetao is the largest irrigation area with water consumption in the Yellow River basin, which is also the biggest irrigation area in arid and semiarid regions of China. Due to severe water shortage, application of water-saving measures are required to relieve water use pressure. To assess the impact of water-saving practices on ecosystem degradation in Hetao, we investigated the relationship between vegetation and depth of the groundwater table by combining Normalized Difference Vegetation Index (NDVI) with in-situ groundwater observations and using Visual MODFLOW to evaluate the effect of water saving measures on water table depth (GWD). Research findings indicated that: (1) maintaining GWD at 2.0-2.5m on growing seasons is suitable for ecosystem security; (2) GWD declines progressively with the strengthening of water-saving practices, and more than forty percent of the land will end in the risk of ecological degradation if water efficiency ratio of canal system reach the standard of the local canal liming plan as 0.66. Based on the results, a conclusion was drawn that water-saving practices with no limits in arid and semi-arid region could cause ecological damage, and this conclusion is strongly advised to be taken into consideration when stakeholders make water saving strategies in arid or semi-arid region.

Keywords: Normalized difference vegetation index; groundwater table depth; water-saving; ecosystem degradation.

1 INTRODUCTION

The Yellow River is the 2nd longest river in China and the 6th longest river in the world, which is a major source of water supply for nine provinces in the North China with about 107 million people. Agricultural irrigation is the main water use in the basin, accounting for 81% of the total water use (Zhu et al., 2003), but the irrigation water use coefficient is only 0.3-0.45. Water discharge of the Yellow River has decreased significantly since 1950s (Liu et al., 2004), especially during the 27 years from 1972 to 1998, the middle and low reaches of the river dried up 21 times (Liu et al., 2004) due to climate changes and human activities (Xu, 2005). In order to solve the contradiction between the shortage of water resources and the increasing water demand, many water-saving measures have been gradually implemented to improve the efficiency of both farm water use and water conveyance in irrigation area located in the upper and middle reaches of the Yellow River since 1990s (Cai et al., 2003). They include lining of canals, land leveling, reducing the proportion of high water consumption crops, water price reform and strengthening the canal water delivery management, et cetera (Gonçalves et al., 2007).

Long time application of these water-saving measures together has achieved significant effect of reducing agricultural irrigation water volume, and GWD also significantly decreased at the same time. However, GWD is a key factor influencing vegetation growth in arid and semi-arid regions. When the groundwater depth is very shallow, salinization caused by strong evaporation will endanger the normal growth of plants, and ineffective groundwater evaporation will bring a lot of waste of water resources; when the groundwater depth is too deep, plants root system will not be able to absorb enough water (Han et al., 2015). So, identifying suitable range of groundwater depth for vegetation growth is significant especially in ecological fragile regions. There are many studies that have quantified the suitable GWD thresholds based on one or two native vegetation species. However, there are 154 types of plants in the study area, it is unreasonable to determine the regional suitable GWD range by a particular plant species. Thus, in this study, satellite remote sensing was used to analyze the suitable groundwater depth for vegetation growth at the regional scales.

Vegetation indices have been developed to reflect the spatial and temporal changes of vegetation covers using spectral measurements on the ground (Bannari et al., 1995). There are more than 35 vegetation indices applied since the first earth resources satellite, a.k.a. Landsat-1 was launched in 1972 (Ringrose et al., 1991). These indices, in general, are formulated as the ratio of red (or visible) and near-infrared measurements, based on the fact that plant reflect less visible bands but more near-infrared radiation when compared with non-vegetated surfaces (Chen, 1996). But each vegetation index has advantages and weakness, it is therefore crucial to select the right index to evaluate the effect of GWD on plant growth in the study area. For example, the Ratio Vegetation Index (RVI) has larger error when the vegetation cover is less than 50%, but it performs well at the dense vegetation cover (Jackson, 1983). In contrast, NDVI can reduce the effect of sensor degradation by normalizing the spectral bands (Rouse, 1974). Many vegetation indices were used to correct effects which caused by some confounding factors, such as soil color, shadows, atmospheric scattering, understory vegetation, and the effect of the sensors' response (Huete, 1989; Elvidge and Lyon, 1985). For instance, The Global Environment Vegetation Index (GEMI) is designed to reduce atmospheric effects in satellite imagery at the global scale (Peddle et al., 2014); the Soil Adjusted Vegetation Index (SAVI) is a modified vegetation index reflecting the effects of soil brightness in the background (Huete, 1988); and the Enhanced Vegetation Index (EVI) is insensitive to atmospheric effects and soil effects because of joining the blue bands. It is generally believed that the NDVI is sensitive in low density vegetation areas such arid and semi-arid regions (Fuller et al., 1998; Diallo et al., 1991). Therefore, NDVI was selected in this study.

This study was conducted in an arid and semi-arid region, the Hetao Irrigation Area, as an example to develop an integrated framework to assess the impact of GWD decline caused by water-saving practices on vegetation growth at regional scales. Hetao is the most important food production bases in Northwest China, producing 35% of wheat, 37% of sunflower and 36% of sugar beet of Inner Mongolia autonomous region (IWC-IM, 1999). The source of irrigation water in Hetao is the Yellow River which supply 4.7 billion m^3 of water averagely annually, accounting for 22% of annual average runoff volume (1987-2000) on the main Yellow River. As the major water users in the Yellow River basin, Hetao irrigation area plans to reduce irrigation water by improving water efficiency ratio of canal system from 0.496 to 0.66 as of 2030. However, Hetao irrigation area locates between Kubuqi and Ulanbuh desert and serves as a vital habitat for terrestrial species. Its ecological environment entirely depends on groundwater which is recharged by irrigation water. If the groundwater cannot get enough water supply because of the increased water efficiency ratio, then the ecosystem may be suffer serious degradation. Therefore, a better understanding of suitable GWD depths in this area is important and necessary.

Taking the above into considerations, this paper aims at identifying the suitable GWD range for vegetation growth, and given this understanding, the impacts of canal system water efficiency ratio increasing on regional ecosystem security can be analyzed in Hetao, Yellow River basin. The results provide insights which could lead to better management of the scarce water resources in this region.

2 STUDY AREA

Hetao irrigation area located in Inner Mongolia (Figure 1) with an area of 5,740km2, is one of the biggest three irrigation area in China. It is also the biggest irrigation area in Asian with only one canal head. The climate in Hetao is typical inland arid and semi-arid, its annual precipitation varies from 139 to 222mm, while the annual potential evaporation is very high ranging from 1999 to 2346mm. About 77% of annual precipitation falls between June and September each year.

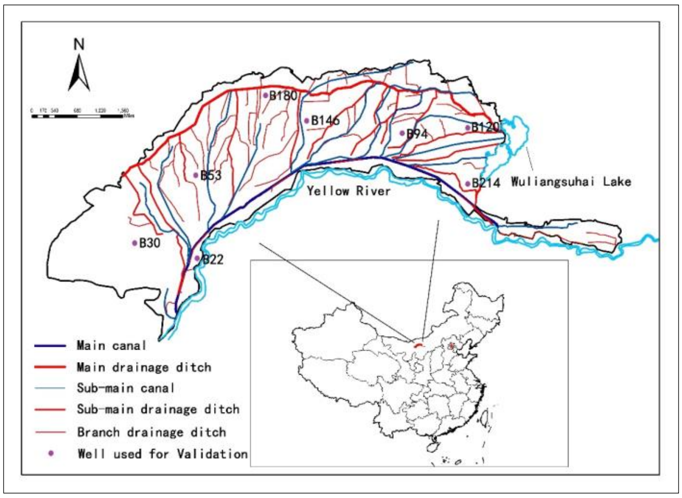

Figure 1. The location of the study area.

3 MATERIAL AND METHOD

3.1 Integrated framework

An integrated framework was developed in this study to assess the relationship combined water-saving practices and ecosystem security. This framework can be divided into three parts: firstly, quantifying the suitable GWD range for the vegetation growth by combining groundwater table depth and corresponding pixel numbers of NDVI at regional scales; secondly, assessing the impacts of various irrigation water-saving practices on groundwater table decline based on Visual MODFLOW, and analyzing the accuracy of simulation by comparing observed and calculated groundwater depth; thirdly, comparing the values between suitable GWD range and groundwater table of different water-saving scenarios, and analyzing the effect that water use efficiency increasing may bring to ecological system can be evaluated in study area. The flowchart of the integrated framework is shown in Figure 2.

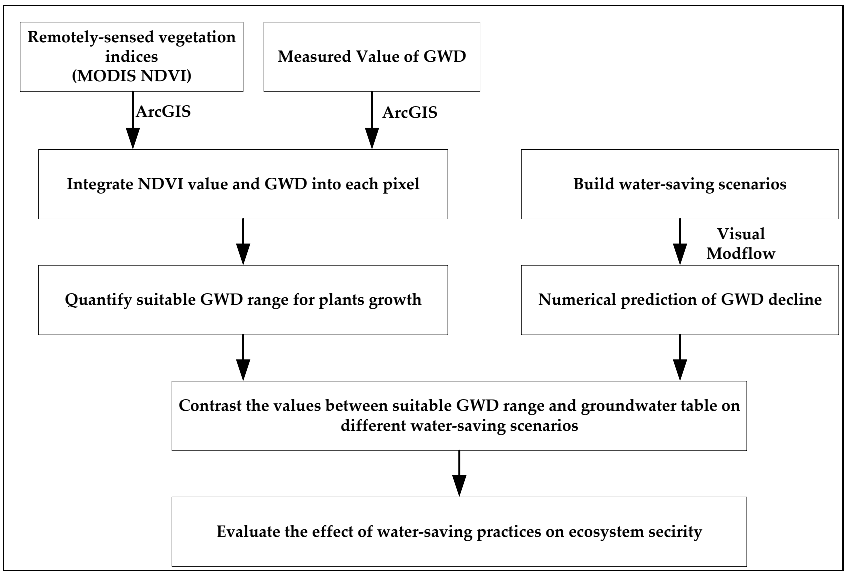

Figure 2. Flowchart of the integrated framework.

3.2 Assessing vegetation condition by NDVI

NDVI from the Moderate Resolution Imaging Spectroradiometer (MODIS) is an effective indicator to illustrate spatial and temporal vegetation variation that have been widely used in global climate change, drought monitoring, desertification control, crop yield prediction and biomass study (Jin and Sader, 2005; Sakamoto et al., 2005). The MODIS NDVI value is a ratio of the red and near-infrared reflectance which can assess the status of vegetation growth. When the NDVI value are close to 1, it means very lush vegetation. Conversely, sparse vegetation can be implied by lower NDVI value closing to 0. By calculating the NDVI value in different year, we can examine the change of the vegetation statues in every growing season.

Vegetation activity is closely related to the seasons, in this study area, April to October is the most productive period for vegetation growth. So, 56 MODIS NDVI monthly images between April to October from 2003-2010 were used as an ecological index to represent the statues of ecosystem quality of the year.

3.3 Identifying threshold of groundwater depth

Based on 224 long-term groundwater monitoring wells distributed in study area, the contour map of GWD was constructed by interpolating field measurement to the same spatial resolution grid as MODIS NDVI using ordinary kriging. By spatial overlaying and data extraction based on ArcGIS10.0, NDVI value and groundwater depth can be integrated into each pixel. Therefore, the relationship between GWD and NDVI value can be analyzed by scatter diagram made from thousands of pixels. Here, the groundwater depth corresponding to the maximum NDVI value was defined as the most suitable GWD range for plant growth.

Since the unique groundwater depth may correspond to a number of different NDVI values, so, the NDVI value was calculated by taking average of the sum at each groundwater depth class which is separated by 0.1m.

3.4 Visual MODFLOW

The modular finite-difference groundwater flow model Visual MODFLOW is a well-documented and widely used model which was selected to simulate the behavior of groundwater flow in the irrigation area (Harbaugh et al., 2000). Visual MODFLOW is composed of a main program and a number of independent modules, such as Well (WEL), River (RIV), Drain (DRN), Recharge (RCH) and Evapotranspiration (EVT), these modules also can deal with single aspects of simulation. Data imposed to Visual MODFLOW include: sink/source factors of aquifer-system, the hydrogeological parameters and the measured variables of groundwater depth.

3.4.1 Sink/source factors

Sink/source factors in study area include effective recharge, groundwater evaporation (i.e., direct evaporation and vegetation root uptake), pumping volume and the exchanges between groundwater-surface flows. The growing seasons recharge from rainfall (Rr), canal seepage (Cr), and deep percolation from field irrigation (Ir) respectively formulated as:

$$R_r = \alpha PA \quad [1]$$

$$C_r = \beta(1-\varepsilon)Q_d \quad [2]$$

$$I_r = \varepsilon b Q_d \quad [3]$$

where α is infiltration coefficients of precipitation, P is cumulative precipitation, A is rainfall recharge area, β is canal seepage ratio, Qd is the volume of canal system diversion water and ε is water efficiency ratio of canal system; b is infiltration coefficients of irrigation water applied in field. The initial values of coefficients α, β, ε, b for different recharge areas and each canals were chose from previous studies (IWC-IM, 1999).

Evaporation is the largest consumption of groundwater in study area which is calculated by EVT package. The relationship between groundwater depth and evapotranspiration rate in EVT package is expressed as a linear function between upper to lower GWD limit. When the GWD is higher than the upper limit, evaporation reached to the maximum value; conversely, if the GWD is deeper than the lower limit, the evaporation effect will be stopped. The growing season's evaporation in EVT package can be formulated as:

$$R_{ET} = R_{ETM}(GWD > h_{ul}) \quad [4]$$

$$R_{ET} = 0(GWD < h_{ll}) \quad [5]$$

$$R_{ET} = R_{ETM} \times \frac{h_{ll} - GWD}{h_{ll} - h_{ul}}(h_{ul} < GWD < h_{ll}) \quad [6]$$

where R_{ET} is evapotranspiration loss rate of groundwater, R_{ETM} is the maximum of R_{ET} in study area; h_{ul} is the upper limit of the GWD when R_{ET} is the biggest; h_{ll} is the lower limit of the GWD when R_{ET} is equal to zero. In this study, initial values of h_{ul} and h_{ll} were identified as 0m and 3m depending on previous studies (IWC-IM, 1999) carried out in Hetao.

The exploitation of groundwater in Hetao is mainly used for industrial, living and agriculture irrigation in some areas without canal system. The volume of groundwater abstraction bases upon the water consumption for per unit industrial output, local city resident population and daily living water quota, planting pattern and water demands of different crops in groundwater irrigation area.

The water discharged into the drainage ditches is not only the surface water produced by irrigation, but also a part of groundwater. Here, mineralization balance principle is used to identify the proportion of groundwater in water discharge. Mineralization balance equation in Hetao can be expressed as:

$$M_G\lambda + M_R(1-\lambda) = M_D \quad [7]$$

where M_G, M_R and M_D are the mean annual mineralization of groundwater, the Yellow River and drainage ditches respectively; λ is the proportion of groundwater in water discharge.

4 RESULTS AND DISCUSSIONS

4.1 Growing seasons NDVI value response to groundwater table depth

The statistical relationship between growing seasons NDVI value and groundwater depth from April to October in 2010 is shown in Figure.3, which revealed that the NDVI value on growing seasons significantly varies along with groundwater depth. It can be seen from Figure.3 that the different monthly images have similar characteristics and the influence of groundwater depth on vegetation growth can be summarily divided into 4 stages (Figure 4): (1)When the GWD was smaller than ha, environment quality was improved with the decrease of groundwater depth; (2) when the GWD was between ha and hb, NDVI obtained the maximum value and fluctuated around it; (3) when the GWD was between hb and hc, NDVI value decreased with the decline of GWD; (4) when the GWD was deeper than hc, the correlation between vegetation and GWD became very small, and the change of GWD did not affect the process of vegetation growth, while NDVI also reached the minimum value at this time. The relationship between NDVI value and GWD can be defined as conceptual piecewise functions, as below:

$$NDVI\ value = \begin{cases} A \times \dfrac{h_i}{h_a} & h_i \le h_a \\ A & h_a < h_i \le h_b \\ B + \dfrac{h_c - h_i}{h_c - h_b} \times (A - B) & h_b < h_i \le h_c \\ B & h_i \ge h_c \end{cases} \quad [8]$$

where A and B are the average values of continuous data which the difference between the maximum and minimum is not more than 5% in every month; ha and hb are the upper limit and lower limit of GWD threshold corresponding to A respectively, hc is the critical groundwater depth when NDVI drop to the minimum; hi is groundwater depth.

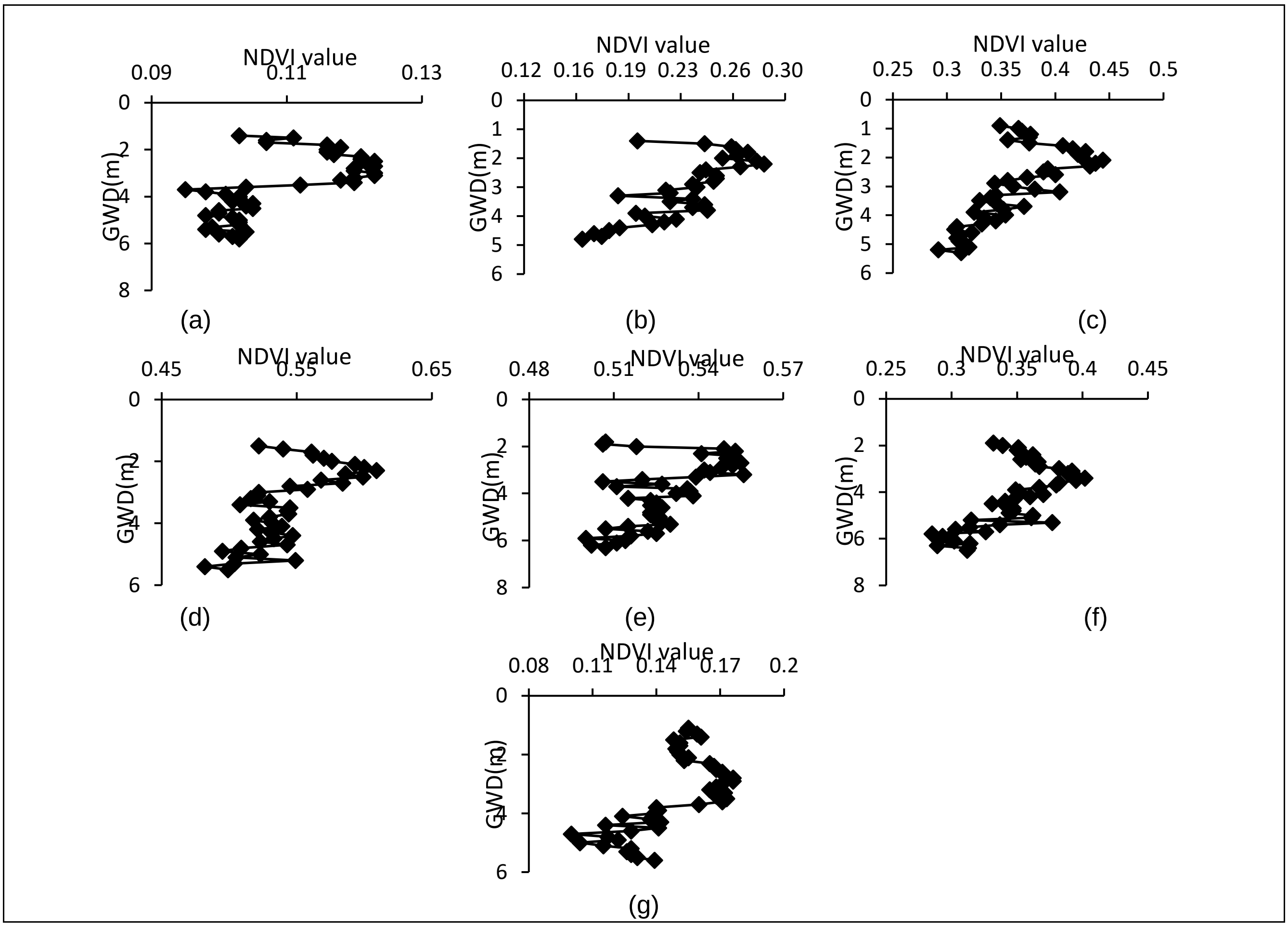

Figure 3. The relationship between NDVI value and groundwater depth in Apr (a), May (b), Jun (c), Jul (d), Aug (e), Sep (f) and Oct (g).

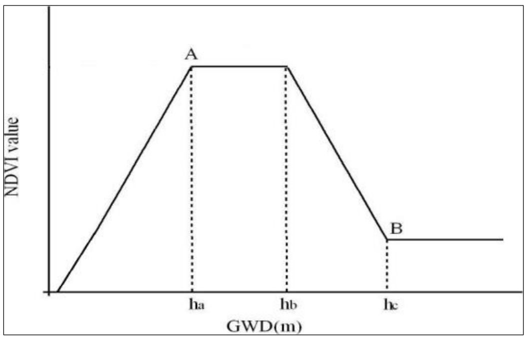

Figure 4. The impact of GWD change on NDVI value in Hetao Irrigation Area.

Obviously, identifying the value of ha and hb is important for water resources management and environment protection especially for water-deficient area. Table1 summarizes the value of ha, hb and maximum NAVI value (MNV) from 2003 to 2010 in growing seasons. The results show that GWD ranges for plants growth in Hetao were between 1.9m and 3.4m, and GWD located in range of 2.0-3.0m accounted for 75%. The suitable depth of groundwater depth mostly concentrated in the range of 2.0-2.5m from May to July (accounted for 62.5%), while in the time period from August to October and April, suitable groundwater depth mostly concentrated in the range of 2.5-3.0m (accounted for 54%). In general, maintain groundwater depth at 2.0-3.0m on vegetation growing seasons is healthy for Hetao ecosystem stability. Since the ecological environment of Hetao is fragile, it is difficult to recover in a short time if it is destroyed. In order to protect the ecological environment to be safer and reduce the harm caused by calculation error, interpolation error and resolution ration error in this region, 2.0-2.5m is chosen as the suitable groundwater table depth range for plants growth in growing seasons. Some studies has analyzed the effect of groundwater depth change on plant growth in the arid and semi-arid regions of China (Table.2). It can be observed that suitable GWD range in Northwest of China is similar, which upper limit is 2.0m in most areas and lower limit is between 3.0m and 4.5m. Through comparative analysis between our results and other research results, we think that suitable GWD between 2.0m and 2.5m is reasonable for plants growth in this region.

Table 1. Maximum NDVI value and its corresponding GWD.

		Apr	May	Jun	Jul	Aug	Sep	Oct
2003	MNV	0.138	0.256	0.442	0.585	0.539	0.331	0.172
	GWD	2.5-2.9	2.0-2.2	2.5-2.8	2.5-2.8	2.8-2.9	2.5-2.8	2.3-2.7
2004	MNV	0.141	0.282	0.477	0.489	0.494	0.352	0.182
	GWD	2.5-2.8	2.0-2.5	2.4-2.5	2.4-2.8	2.7-3.0	2.9-3.0	2.3-2.6
2005	MNV	0.144	0.305	0.465	0.553	0.356	0.359	0.181
	GWD	2.6-2.8	2.1-2.2	2.1-2.2	2.3-2.5	3.1-3.2	3.1-3.2	2.6-2.8
2006	MNV	0.122	0.288	0.476	0.566	0.471	0.287	0.182
	GWD	2.5-2.9	2.2-2.3	2.1-2.3	2.3-2.5	2.5-2.8	3.1-3.3	2.4-2.5
2007	MNV	0.146	0.312	0.441	0.542	0.519	0.344	0.179
	GWD	2.7-2.9	2.5-2.6	2.5-2.6	2.3-2.5	2.7-3.0	2.6-2.9	2.4-2.6
2008	MNV	0.135	0.273	0.461	0.551	0.556	0.361	0.177
	GWD	2.4-2.6	2.2-2.3	2.0-2.3	2.5-2.8	2.3-2.5	3.0-3.1	2.5-2.9
2009	MNV	0.163	0.331	0.452	0.561	0.512	0.305	0.136
	GWD	2.3-2.5	1.9-2.3	2.2-2.5	2.3-2.6	2.8-3.0	3.0-3.2	2.5-2.8
2010	MNV	0.123	0.274	0.438	0.589	0.556	0.394	0.175
	GWD	2.4-2.6	2.1-2.3	2.1-2.3	2.3-2.7	2.5-2.8	3.1-3.4	2.7-2.9

Table 2. The studies on the suitable GWD in Northwest of China.

Catchment	Suitable GWD for ecosystem	Reference
Inland River basins in arid regions of Chine	2.0-3.0m	Wang et al.（2002）
The Tarim River Basin	2.0-4.0m	Zhang et al. (2003)
The Yanqi Basin	3.0-4.0m	Wang et al.（2011）
The arid regions of China	2.0-4.5m	Zheng et al. (2005)
Northwest of China	2.0-4.5m	Cui et al. (2001)

At present, average GWD in growing seasons in Hetao have exceeded the upper limit of 2.0m and reached 2.07m (2010-2013). If the groundwater depth keeps the decline rate of 1.3cm every year, like in the past 25 years, GWD will only drop to 2.5m until 33 years later. It is therefore important to investigate the interactions between the water saving practices and the GWD in order to ensure the groundwater depth is not more than 2.5m.

4.2 Predicting impact of water saving on groundwater depth

Groundwater recharge is necessary to sustain the suitable depth to groundwater levels directly and protect ecological security indirectly. According to the water demand for different crops, there are two large-scale irrigation periods (May-Jul and Aug-Sep) during growing seasons to be carried out in Hetao. Besides, in order to avoid tilth salinization, about 1.4 billion m^3 water is to be used for flood irrigation in October which accounted for 35% of the irrigation water volume. Diversion process will change the groundwater depth and thus have a significant impact on vegetation growth situation. To explore the relationship between groundwater recharge and GWD, Figure 5 compares the annual capacity of water diversion against the changing groundwater tables over the study period. The trend in Figure.5 shows that the change of GWD is directly associated with the amounts of water diversion. Such a conclusion indirectly confirms that ecosystem security via water diversion. Therefore, groundwater tables are predicted by Visual MODFLOW model when water diversion is decreasing because of water-saving.

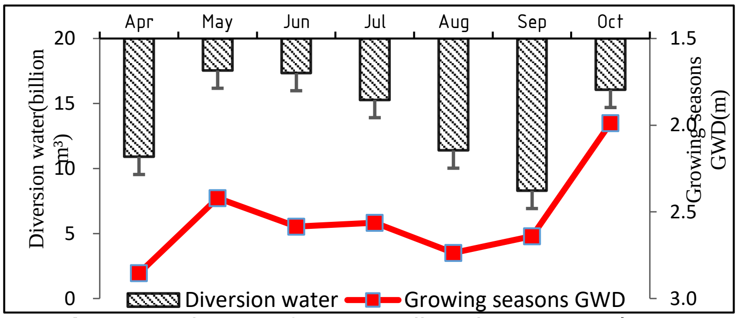

Figure 5. Change of GWD to diversion water volume.

4.2.1 Water saving scenarios

Water saving activities in Hetao has been gradually implemented in recent years. Improving canal system is the most widely used measure for reducing water conveyance losses in Hetao. The project of canal lining has clear implementation schedules. So, in this study, water-saving practices was evaluated by increasing water efficiency ratio of canal system (ε).

Canal lining is the main way to improving ε in study area, which can shorten irrigation time and reduce water loss by 70%-90% (Meng, 2002). According to the canal lining plan of Hetao in 2020 and 2030, five scenarios for canal system improvement were considered, with the value of ε from 0.496 at present to respectively 0.53, 0.55, 0.58, 0.61 and 0.66 in future. Diversion water also reduced via ε change (Eq. [2] and [3]), which the quantity of water diversion lessened by 0.30, 0.46, 0.68, 0.88 and 1.17 billion m³ respectively. (Table 3).

Table 3. Present situation and five scenarios for water saving in Hetao.

scenarios	main canal lining (km)	sub-main canal lining (km)	Branch canal lining (km)	canal lining ratio (%)	ε	diversion water (bn m³)	Diversion water reduce amount (bn m³)
Present	85.77	117.59	258.64	11%	0.496	4.72	0.00
S1	210.53	267.25	547.25	24%	0.530	4.41	-0.30
S2	257.31	320.7	700.48	30%	0.550	4.25	-0.46
S3	327.49	438.29	875.6	39%	0.580	4.03	-0.68
S4	397.67	534.5	1028.83	46%	0.610	3.84	-0.88
S5	514.63	662.78	1313.4	59%	0.660	3.54	-1.17

4.2.2 Groundwater table depth

During the running of the Visual MODFLOW model, the water table of ending time, which is called calculated groundwater head, must be iteratively compared with observed groundwater head in order to adjust hydrogeological parameters and some sources and sinks (Wang et al., 2008). Here, the model was validated with data of eight different observation wells, whose locations are given in Figure 1, for the period from January 1, 2010 to December 31, 2010 (Figure.6). The Nash–Sutcliffe efficiency (NSE) coefficient and the correlation coefficient (R^2) were also used as indicators in this study to evaluate the goodness of fit. By calculation, the NSE is 0.77 and R^2 is 0.72. The results showed high modelling efficiency and small errors of the estimate, hence, indicating that parameters were properly calibrated.

The change of groundwater depth predicted for the five water saving scenarios indicated that GWD will progressively decline with the increase of water efficiency ratio of canal system (Table.4). When the ε increased to 0.580 (S3), the average GWD in growing seasons from present 2.06m dropped to 2.5m which was equal to the lower groundwater table threshold. This means that 0.580 is the upper limit of water efficiency ratio of canal system in Hetao, and if ε is greater than 0.580, the GWD will exceed 2.5m and the ecosystem quality will decrease with the decline of GWD in Hetao. According to the water saving plan of Hetao water resources management department, ε will reach to 0.660 (S5) in 2030. Under this condition, average GWD in growing seasons will dropped to 3.24m, which reduced 57.3% compared to present value. (Simulation for all water saving scenarios were performed with 2010 data).

Figure 7 shows the spatial distribution of the groundwater depth in June for various water saving scenarios. Presently, GWD of most area in Hetao is under 1.5m. Only some areas in the southern and western parts relying on groundwater for irrigation have a GWD deeper than 2.5m. Small groundwater depression cones usually occur around the cities and towns, caused by the large groundwater abstraction for industrial and domestic usage. We can clearly see from Figure 7b, c, d, e and f that with the strengthening of water saving practices, the area where GWD decline steadily increased and some separate groundwater funnels were connected as a whole. The area with GWDs exceeded 2.5m increase from the present 942km² up to 1011km² with S3 and 1626km² with S5, i.e., from 7.5 to 8.6% and 13.8% respectively; the area where GWDs exceed 3.0m increase from 1424km² up to 1790km² and 3334km², which correspond to changes from 12.1 to 15.2% and 28.3%. So, if according to the Hetao water resources department' project that S5 scenario is to be adopted as the final water saving implementation plan, there are more than 40% of the land in study area with GWD>2.5m, it is obvious that Hetao is in the risk of ecological degradation under this condition.

Water saving practices cannot be unlimited, especially in the arid and semi-arid regions with fragile ecosystem. From this point of view, there is a conflict between reduce irrigation water and protect environment in Hetao. Conflict management in the context of integrated water resources management is essential among agricultural and environmental sectors. If the influence of agricultural irrigation on ecology is ignored when saving water, challenges from more climate change and anthropogenic activities would certainly threaten the safety of ecosystem in the study area. Therefore, this requires the adequate estimation of essential environment water requirement, irrigation water saving potential and deepened studies of groundwater table depth affected by agricultural irrigation.

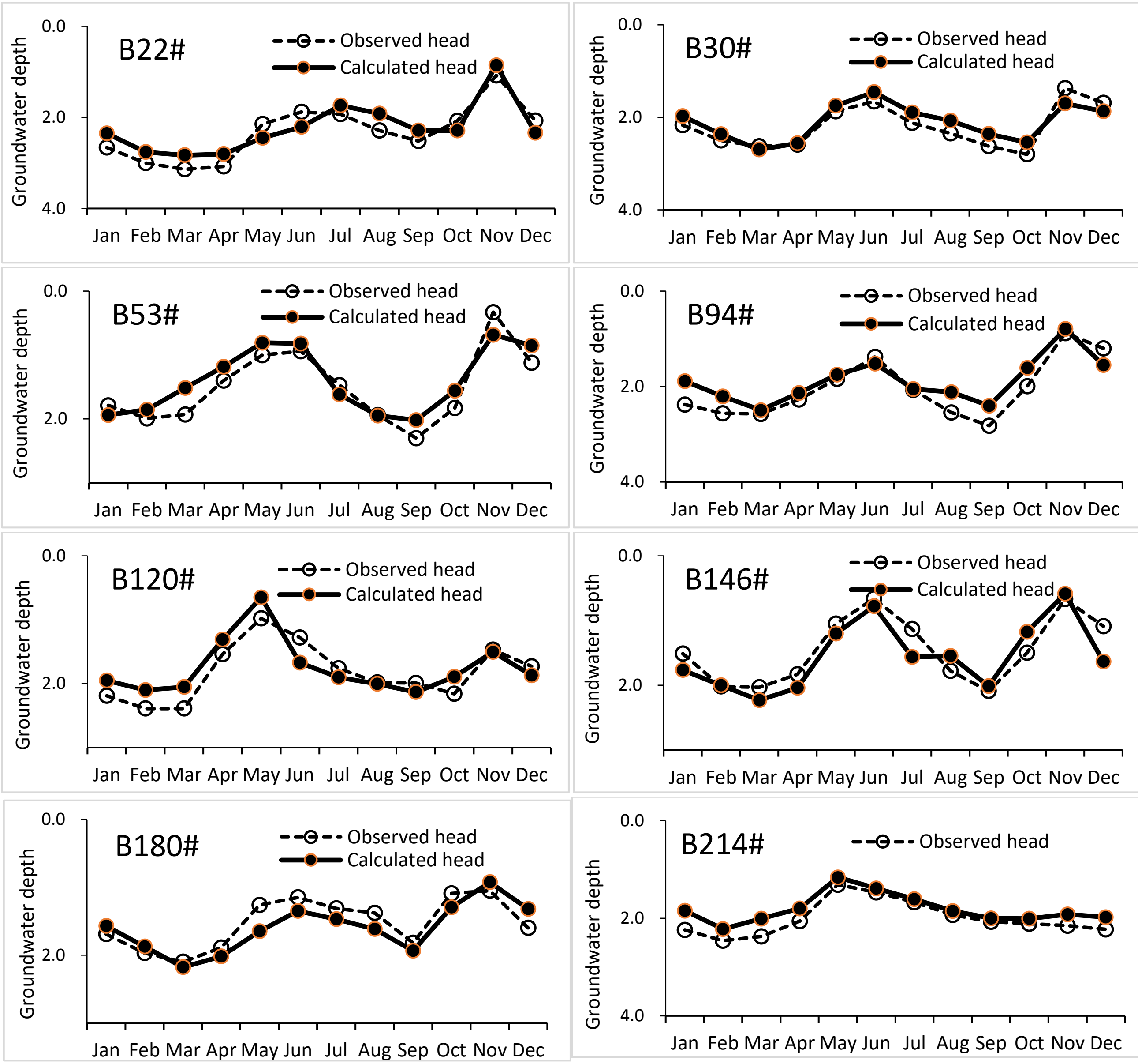

Figure 6. Comparison of observed and calculated groundwater depth at 8 observation wells used for validation.

Table 4. Predicted GWD in growing seasons for scenarios 1 to 5 unit: m.

scenarios	Apr	May	Jun	Jul	Aug	Sep	Oct	Average
Present	2.25	1.65	1.59	1.93	2.29	2.60	2.08	2.06
S1	2.25	2.03	1.78	2.12	2.32	2.68	2.02	2.17
S2	2.36	2.16	1.93	2.23	2.41	2.79	2.16	2.29
S3	2.55	2.40	2.20	2.45	2.53	2.96	2.41	2.50
S4	2.78	2.67	2.49	2.71	2.78	3.15	2.68	2.75
S5	3.27	3.20	3.07	3.24	3.31	3.37	3.23	3.24

In overall, sustainable development needs adaptive water resources management to harmonize agricultural, ecological and economic water demand in this region. To promote sustainable development in the future, some possible measures can be proposed as follows: 1) improve the efficiency of water use in industry and domesticity in order to reduce the volume of agricultural water saving; 2) increase the effectiveness of adaptive water management strategies to balance agricultural and ecological water demand; 3) analyze the possibility of water diversion from the outside to solve present situation of water resources shortage, and 4) enhance the use of remote sensing tools for environment quality assessment.

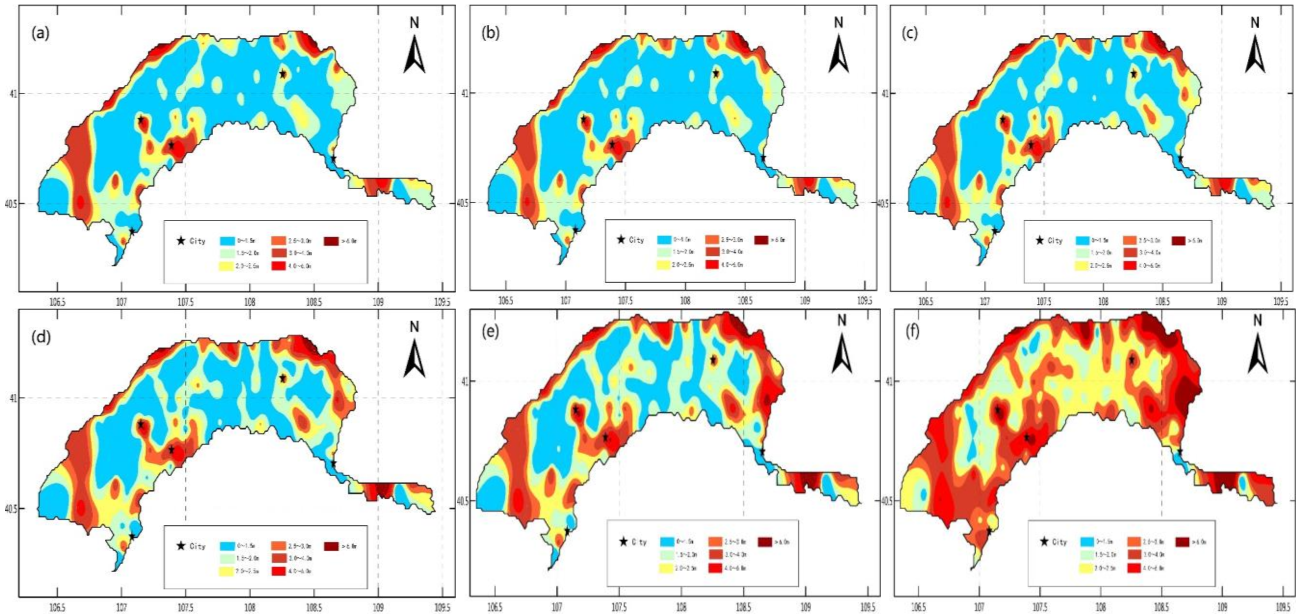

Figure 7. Spatial distribution of the GWD in June for: the present situation (a), and for scenarios 1, 2, 3, 4 and 5, respectively (b), (c), (d), (e) and (f).

5 CONCLUSIONS

Coupling the MODIS NDVI time series data with the measured GWD data in this study successfully provided us a simple statistical method to identify ecological groundwater depth threshold at the regional scale in Hetao irrigation area. The results showed that the effect of changing GWD on NDVI value can be defined as 4 stages, and only when the GWD locates in the suitable range, the vegetation can maintain the best growth state. Hence, identifying the value of suitable GWD range is important for water resources management and environment protection. In order to protect the ecological environment to be safer and reduce the harm caused by error in this region, the level of 2.0-2.5m was chosen as the groundwater table depth threshold for plants growth in growing seasons.

According to the canal lining plan of Hetao, five water saving scenarios for canal system improvement were considered and Visual MODFLOW was selected to simulate the behavior of groundwater depth change in this study. The results showed that the diversion water amount will decline progressively with the application of water saving practices. The GWD corresponded to ε changes from the present value of 2.06m to 2.17, 2.29, 2.50, 2.75 and 3.24m respectively. This indicates that 0.580 is the maximum value of water efficiency ratio of canal system in Hetao and if ε becomes bigger than 0.580, the GWD will exceed 2.5m and the vegetation system cannot grow in the best condition. If Hetao water resources department choose ε=0.660 as the final water saving implementation plan in 2030 based on the schedule, more than forty percent of the land in the study area will face the risk of ecological degradation. Therefore, a proper water-saving policy should be implemented on a basis of ecological protection. Countermeasures such as conflict managements among environmental, municipal and agricultural sectors should be proposed for achieving sustainable development in this arid and semi-arid region.

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