Research on the Evolution and Management System of Groundwater Extraction and Utilization in Shanghai

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ABSTRACT
The management of groundwater resources in Shanghai is of great significance for strengthening the dual control action of total water use and water intensity. To this end, literature review is conducted on the efficiency of water resource utilization, ecological carrying capacity evaluation of water resources, sustainable utilization evaluation of water resources, and the relationship between water resource utilization and economic growth in Shanghai. On this basis, there will be a necessity to clarify the economic development trend and water use change trend in Shanghai, clear the changes in Shanghai's industrial structure, total water use and water-use efficiency, and water use structure, explore the evolutionary process of the comprehensive transformation of groundwater resource exploitation and utilization in Shanghai from groundwater deficit to groundwater surplus, and systematically sort out the principles and management systems of groundwater resource management in Shanghai.

Keywords: *Shanghai, Groundwater, Deficit, Surplus, System.*

1. INTRODUCTION

In 2011, the No. 1 central document clearly proposed to implement the strictest water resource management system, promote the sustainable development and utilization of water resources in China, and Shanghai is one of the first pilot provinces and cities in China. Shanghai is an international economic center city for socialist modernization with Chinese characteristics. The rational allocation and efficient utilization of water resources in Shanghai play a crucial role in enhancing its comprehensive economic strength and promoting high-quality economic development. Shanghai has abundant water resources, but it is a typical water scarcity city. Since the 1860s, the abundant groundwater resources in Shanghai have become an important component of urban water supply sources. The exploitation and utilization of groundwater resources have increasingly highlighted their role in Shanghai's urban construction, economic development, and people's livelihood security.

2. LITERATURE REVIEW

According to literature review, existing research mainly focuses on the evaluation of water resource utilization efficiency, ecological carrying capacity, sustainable utilization, and the relationship between water resource utilization and economic growth in Shanghai. Firstly, regarding the evaluation of water resource utilization efficiency in Shanghai, Shen Jie et al. [1] pointed out the improvement direction of sustainable utilization of water resources in Shanghai, constructed an evaluation index system for water resource utilization efficiency in Shanghai, and evaluated the utilization efficiency and comprehensive efficiency of different water resource consumption pathways in Shanghai over the years; Pan Ting et al. [2] proposed a systematic framework for analyzing urban income, production and consumption water use, and their potential driving forces based on multi-scale input-output analysis and structural decomposition analysis. Research has shown that factors that increase the utilization of water resources in Shanghai include population, per capita output, final consumption structure, and per capita final consumption. The factors that reduce water consumption in Shanghai include technology, added value structure, output structure, added value structure, domestic imports, commodity structure, and foreign imports. Secondly, regarding the evaluation of the ecological carrying capacity of water resources in Shanghai, Ding Hua et al. [3] evaluated the ecological footprint and ecological carrying capacity of water resources in Shanghai from 2006 to 2010 using the ecological footprint method; Cao Kun et al. [4] used support vector machines to calculate, analyze, and predict the ecological footprint of water resources in Shanghai from 2001 to 2013; Zhou Fei et al. [5] calculated the water ecological footprint and water resource ecological carrying capacity of Shanghai from 2013 to 2019. Research has shown that the overall water ecological footprint of Shanghai showed a decreasing trend from 2013 to 2019. Industrial and agricultural water use were the mainstay of water resource utilization in Shanghai, and water quality was a key factor affecting the results of Shanghai's water ecological environment assessment.

Then, for the evaluation of sustainable utilization of water resources in Shanghai, Wang Guixin et al. [6] used regression analysis to simulate the influencing factors of water pollution level, available clean water quantity, water demand, and relative available clean water quantity indicators. Using the ratio of available clean water quantity to water demand, they examined the evolution trend of available clean water and water demand in Shanghai over the past 30 years; According to the requirements of building a water-saving society, Jin Sheng [7] analyzed the characteristics of rainwater utilization and management in Shanghai based on the current situation and development needs of water resources, and proposed directions and strategies for rainwater utilization and comprehensive management that are in line with the actual situation in Shanghai; Zhou Fei et al. [5] evaluated the Shanghai Water Resources Sustainable Utilization Index and found that when considering transit water, water resources are in a surplus state; The water ecological footprint of a GDP per 10,000 yuan is showing a downward trend, and the pressure on water resource development and utilization is relatively low. The sustainable utilization of water resources in Shanghai is relatively high. Finally, regarding the study of the relationship between water resource utilization and economic growth in Shanghai, Han Wenyan et al. [8] used decoupling theory and Tapio elasticity analysis method to study the relationship between water resource utilization and economic growth in Shanghai; Zhang Hengquan et al. [10-12] used the LMDI Tapio two-stage method to analyze the driving effects and decoupling status of water consumption changes in the Yangtze River Delta region, decompose the decoupling index, and explore the driving factors of decoupling status changes. Research has shown that the decoupling relationship between industrial water consumption and economic growth in Shanghai has gone through four states: strong decoupling, weak decoupling, recession decoupling, and expansion negative decoupling, which is generally in a strong decoupling state. The contribution rates of the four driving factors for water consumption in Shanghai are ranked in descending order: water intensity effect, economic income effect, population size effect, and industrial structure effect.

Overall, existing research provides important reference for improving water efficiency and controlling total water use in Shanghai. However, the literature mainly focuses on the changes in water-use efficiency, total water usage, and industry water usage in Shanghai, as well as their relationship with economic growth. Few scholars have conducted research on the changes in groundwater resource utilization and management systems in Shanghai. Based on the analysis of the economic development and water use changes in Shanghai, this paper clarifies the evolution process of groundwater resource exploitation and utilization in Shanghai, explores the comprehensive transformation from groundwater deficit to groundwater surplus, and summarizes the principles and management systems of groundwater resource management in Shanghai.

3. ECONOMIC DEVELOPMENT AND WATER USE CHANGES IN SHANGHAI

3.1 Economic Development Situation of Shanghai

Since the establishment of the People's Republic of China, from the perspective of national economic and social development, in 1949, the per capita GDP of Shanghai was only 274 yuan converted at the exchange rate of that year, which was less than 2500 yuan in 1978. After the reform and opening up, Shanghai's per capita GDP has continuously surpassed new levels. In 1993, the per capita GDP exceeded 10,000 yuan and reached 2,000 US dollars; In 1997, the per capita GDP reached 3,000 US dollars. From 1993 to 1997, it achieved the first leap, and the comprehensive economic strength rose from the average level of low-income countries to the average level of lower middle-income countries; In 2000, the second major leap was achieved, with per capita GDP rising to 30,000 yuan and reaching 4,180 US dollars; In 2001, the per capita GDP of Shanghai exceeded 4,500 US dollars, bringing its comprehensive economic strength to the level of a middle-income country. The continuous growth and changes in per capita GDP in Shanghai reflect the accelerating development pace of the national economy in Shanghai. In 2008, the per capita GDP of Shanghai exceeded the 70,000 yuan platform. At the exchange rate of that year, the per capita GDP had reached 10,529 US dollars, breaking through 10,000 US dollars for the first time, which is equivalent to the income level of a medium power in the world. In 2018, Shanghai's per capita GDP exceeded 20,000 US dollars, meeting the standards of developed economies for the first time. In 2021, the per capita GDP of Shanghai reached 26,900 US dollars. In 2022, the per capita GDP of Shanghai has exceeded 180,000 yuan.

3.2 Changes in Water Use in Shanghai

The available water resources in Shanghai include three types: local runoff, extracted groundwater, and transit water. Among them, the available surface water resources mainly come from local runoff. As an important component of water resources, groundwater resources play an important role in ensuring the safety of drinking water for Shanghai residents, supporting economic and social development, and maintaining a good ecological environment. Usually, the development and utilization of groundwater resources are mainly used for production and domestic water in industries such as textiles and chemicals. The main uses of groundwater resources extracted in Shanghai can be divided into three categories: first, for daily water supply in areas where intensive water supply pipelines have not yet been laid, such as Chongming Island and other islands; Secondly, it is used for high-quality drinking water; Thirdly, it is used as a backup water source in emergency situations in Shanghai. The rational development and utilization of groundwater resources in Shanghai plays a crucial role in coordinating the water demand for production, daily life, and ecology in the entire city and various districts, allocating water resources supply to different users in a reasonable manner, and coordinating the economic, social, and ecological benefits of Shanghai.

3.2.1 Changes in Total Water Use and Efficiency

From the perspective of changes in total water use, from 2000 to 2010, the utilization of water resources in Shanghai remained stable with an increase, with surface water supply being the main source. Among them, the total water supply in Shanghai was 11.186 billion cubic meters in 2000 (surface water supply was 11.1062 billion cubic meters), the total water intake increased to 12.128 billion cubic meters in 2005 (surface water supply was 12.053 billion cubic meters), and the total water intake increased to 12.629 billion cubic meters in 2010 (surface water supply was 12.609 billion cubic meters). From 2011 to 2020, Shanghai issued the No. 1 central document of 2011, implemented the strictest water resource management system, carried out the action plan of double control of total water consumption and intensity, and strictly controlled the total water consumption. The water intake in Shanghai has rapidly decreased from 9.749 billion cubic meters in 2011 to 7.664 billion cubic meters in 2015, further decreasing to 7.262 billion cubic meters in 2020. The water intake in 2020 decreased by 35.08% compared to 2000. In 2021, the water intake in Shanghai slightly increased to 7.743 billion cubic meters.

From the perspective of changes in water-use efficiency, from 2000 to 2010, Shanghai's water-use efficiency continued to rise. In 2000, the water consumption per million yuan of GDP was 238m^3. In 2005, it was only 125.3m^3, a decrease of nearly 50%. In 2010, it was below 100m^3 (reduced to 75 m^3). From 2011 to 2020, Shanghai strengthened the dual control action of total water consumption and intensity. The water consumption per 10,000 yuan of GDP decreased from 51m^3 in 2011 to 31m^3 in 2015 and 19m^3 in 2020, respectively, and further decreased to 18m^3 in 2021.

3.2.2 Changes in Water Use Structure

Since the 15th Five-Year Plan period, the domestic water consumption and its proportion in Shanghai have gradually increased, while the proportion of agricultural water consumption has continued to decline, which is basically similar to the modernization development process of major cities. Among them, from 2000 to 2010, the domestic water consumption increased from 1.443 billion cubic meters to 2.436 billion cubic meters, and the proportion of domestic water consumption increased from 13.31% to 19.29%; The agricultural water consumption increased from 1.531 billion cubic meters to 1.708 billion cubic meters, but the proportion of agricultural water consumption decreased from 14.12% to 13.52%; Industry is the largest water user, with its water consumption increasing from 7.862 billion cubic meters to 8.485 billion cubic meters. However, its water usage proportion gradually decreases, from 72.53% to 67.15%. Since the implementation of the strictest water resource management system in Shanghai in 2011, the water use structure has undergone significant changes. On the one hand, the ecological water consumption and its proportion have rapidly increased, with the ecological water consumption continuously increasing from 74 million cubic meters in 2012 to 85 million cubic meters in 2019. From 2020 to 2021, there was a slight decrease, dropping to 84 million cubic meters and 82 million cubic meters respectively. The proportion of ecological water use in 2013, 2019, and 2021 was 0.85%, 1.12%, and 1.1%, respectively. On the other hand, in 2011-2021, the agricultural water consumption decreased from 1.681 billion cubic meters to 1.529 billion cubic meters, with a slight increase in the proportion of water consumption, from 17.2% to 19.7%; the industrial water consumption decreased from 5.563 billion cubic meters to 3.668 billion cubic meters, with the proportion of water consumption decreasing from 57.1% to 47.4% (a decrease of nearly 10 percentage points); the domestic water consumption decreased from 2.505 billion cubic meters to 2.465 billion cubic meters, with the proportion of water consumption increasing from 25.7% to 31.8%. Overall, by 2021, industrial water remained the largest water user, followed by domestic water, agricultural water, and ecological water.

4. THE EVOLUTION PROCESS OF UNDERGROUND RESOURCE EXPLOITATION AND UTILIZATION IN SHANGHAI

Since the first deep well was excavated in 1860, the development and utilization of groundwater resources in Shanghai has a history of more than 160 years. The amount of underground exploitation and utilization in Shanghai has also gone through stages such as excessive development and utilization, controlled development and utilization, and artificial recharge, showing a "fluctuating" process of "slow rise - rapid rise - gradual decline - rapid rise - slow decline". Shanghai has achieved a comprehensive transformation from groundwater deficit to groundwater surplus, and has now entered the era of groundwater surplus.

4.1 Expansion Period of Groundwater Deficit

From 1860 to 1949, the groundwater deficit in Shanghai slowly expanded. Shanghai began to exploit groundwater in 1860. Due to unplanned management, the groundwater mining output is in the process of slowly increasing year by year. Since 1860, the American business Qichang Foreign Firm dug the first deep well on the Bund of Shanghai. During 1860-1921, the annual mining output of groundwater reached about 0.3 million cubic meters. Due to the unscientific exploitation of groundwater resources, significant ground subsidence has occurred since 1921. In 1948, the urban settlement reached 21mm. By 1949, there were 708 deep wells in the urban area and 95 wells in the suburb of Shanghai, and the mining output of groundwater increased to 87.5 million cubic meters.

From 1949 to 2000, the groundwater deficit in Shanghai rapidly expanded. From the founding of the People's Republic of China to the mid-1960s, with the development of production, the mining output of groundwater resources in Shanghai entered a stage of rapid rise, resulting in a sharp decline in the groundwater level. In 1950-1957, the average daily mining output in the urban area was 2.22-339 million cubic meters. In 1958, the groundwater mining output increased to 160 million cubic meters. During the Great Leap Forward from 1958 to 1960, there were more than 1000 deep wells in the urban area, with an average daily mining output of 358-368,000 m^3. By 1963, the exploitation of groundwater resources in Shanghai had reached its peak. There were 1079 deep wells in the city, with an annual mining output of 202 million cubic meters, which was mainly concentrated in the urban area, forming a large groundwater depression funnel, leading to obvious land subsidence. There were disasters such as tidal water coming ashore, blocked navigation, docks sinking, and road ponding. In the worst case, the annual subsidence reached 110 mm. From 1949 to 1956, the average ground subsidence was 40mm/a, and from 1957 to 1962, it reached a historical high of 98mm/a. By 1965, the average ground subsidence in the urban area was 1.69 meters, which was the fastest period of ground subsidence in Shanghai's history.

Since the middle and late 1960s, after gradually realizing that groundwater resources are not inexhaustible, related organs in Shanghai began to control the total amount of groundwater exploitation, and determined the principle of "strict control and reasonable exploitation" of groundwater exploitation. The mining output of groundwater resources entered a stage of gradual decline. Since 1966, Shanghai has implemented planned water use and restricted the extraction of underground water resources. Groundwater recharge has begun to be fully implemented, and a city wide groundwater recharge has been carried out through the use of artificial recharge measures that directly inject surface water into underground aquifers. By strengthening planned management and water conservation management, groundwater exploitation management changed from useless water plan to planned management, and by 1968, groundwater mining output had dropped to 54.16 million cubic meters. In the 1970s, the city's groundwater mining output remained between 75 million cubic meters and 95 million cubic meters. Meanwhile, after years of effort, the groundwater level has risen and ground subsidence has been controlled. From 1966 to 1971, the ground subsidence situation in the urban area of Shanghai began to stabilize. After 1972, the annual subsidence amplitude of the ground was controlled at around 5mm.

In the 1980s and 1990s, with the development of market economy brought about by reform and opening up and the need for rural water improvement, the demand for groundwater has further increased year by year, and the mining output of groundwater has rapidly increased. The annual mining output of groundwater has reached 120 million cubic meters, and the groundwater recharge is only 30 million cubic meters. From 1990 to 1995, the annual ground subsidence in the urban area of Shanghai was around 10mm. With the development of urban tap water construction, the capacity of tap water supply has been improved and the public water supply network has been continuously extended. Since 1995, the management department has actively implemented the measure of replacing groundwater with tap water in the areas where the municipal tap water network reaches. In 1995, the mining output of groundwater in the city was controlled at 130 million cubic meters.

During the Ninth Five-Year Plan period, influenced by the adjustment of industrial structure and the improvement of macroeconomic conditions, the economic development of the Yangtze River Delta region has been rapid. Provinces and regions such as Jiangsu and Zhejiang, adjacent to Shanghai, have greatly increased the development and utilization of groundwater resources. At the same time, the work of groundwater recharge has been affected to a certain extent, which has greatly weakened the groundwater recharge in Shanghai and led to a further decrease in the groundwater level of the aquifer. In 1996, the mining output of groundwater rose to 150 million cubic meters, and the land subsidence exceeded the warning line of 10 mm. In 1998, the development and utilization of groundwater in Shanghai continued to adhere to the protection principle of "strict control and reasonable exploitation", and continued to actively and effectively control land subsidence in Shanghai through a series of management measures such as compressing, replacing groundwater, and repairing specialized recharge wells. In 1998, the groundwater mining output decreased to 120 million cubic meters, 21.06 million cubic meters less than that in 1997, and the groundwater recharge reached 18.058 million cubic meters, 1.3642 million cubic meters less than that in 1997. In 1999, the actual mining output of groundwater in the city was 104.45 million cubic meters, which was one of the best years to control the total amount of groundwater exploitation. The annual mining output has recovered to the level of the 1980s, and the actual groundwater recharge volume is 15.055 million cubic meters. In 2000, the goal of controlling the mining output of groundwater in the whole city within 100 million cubic meters was achieved. The mining output of groundwater further decreased to 94.59 million cubic meters, and the groundwater recharge also decreased to 14.79 million cubic meters.

4.2 Reduction Period of Groundwater Deficit

During the period from the 15th to the 11th Five-Year Plan, the groundwater deficit in Shanghai continued to shrink. In the 21st century, in order to alleviate the pressure of land subsidence, Shanghai has taken a number of positive measures to compress the exploitation of groundwater and reduce leakage, and implemented a total amount control system for groundwater exploitation. The mining output of groundwater in Shanghai has gradually declined. The government has strictly controlled the excavation of new wells, replaced deep well water with tap water, helped district and county enterprises to carry out leak detection and plugging of water supply networks, strengthened the planned water use management of groundwater, and ensured the daily life and production water of Shanghai residents and enterprises. In addition, Shanghai has raised the groundwater level and controlled ground subsidence by extending the water supply pipeline, closing deep wells, and injecting tap water back into the groundwater layer.

During the Tenth Five Year Plan period, Shanghai accelerated the process of intensive water supply in the suburbs, promoted the integration of urban and rural water supply, and fundamentally reduced the mining output of groundwater. In 2003, in order to alleviate the pressure of ground subsidence, Shanghai began to implement total control over groundwater extraction. The Shanghai Municipal Water Affairs Bureau strengthened its control over groundwater exploitation and began to gradually reduce the mining output of groundwater. The total mining output of groundwater in Shanghai was about 97.93 million cubic meters, and the groundwater recharge was 13.02 million cubic meters. From 2004 to 2005, by implementing intensive water supply in the suburbs and merging and switching some township water plants, Shanghai increased its efforts to merge small water plants in the suburbs and closed 31 deep wells of various types. In 2004, the city's groundwater mining output was 87.51 million cubic meters, 10.42 million cubic meters less than that of the previous year. The annual reinjection volume was 14.12 million cubic meters, 1.1 million cubic meters more than that of the previous year. In 2005, the pattern of groundwater exploitation and artificial recharge in Shanghai changed greatly. With the promotion of intensive water supply, the mining output of groundwater in the whole city decreased significantly to 74.52 million cubic meters, less than the planned mining output of 80 million cubic meters, only 37.5% of the highest mining output in history.

During the "Eleventh Five Year Plan" period, with the policy support of the Shanghai Municipal Government, Shanghai implemented more strict management on groundwater exploitation, and set the management goal of developing 10 million cubic meters of groundwater progressively every year. In principle, no new wells will be dug when the water supply network reaches the area, and the maximum mining output of existing deep wells will be limited. By 2010, the mining output of groundwater in Shanghai had been controlled within 20 million cubic meters (1971 million cubic meters), reaching the lowest standard since the founding of New China, while the groundwater recharge volume had expanded to 18.93 million cubic meters, and the dynamic balance of groundwater exploitation and irrigation in Shanghai had basically been achieved.

4.3 Groundwater Surplus Period

Since 2011, Shanghai has entered a period of groundwater surplus. In 2011, the mining output of groundwater in Shanghai was reduced to 13.51 million cubic meters, and the reinjection volume was increased to 18.61 million cubic meters. For the first time, the reinjection volume was greater than the mining output volume, realizing the transition from groundwater deficit to groundwater surplus, and the groundwater level has recovered significantly. In 2012, the mining output of groundwater in Shanghai was further reduced to 10.94 million cubic meters, and the recharge increased to 19.35 million cubic meters. The mining output of groundwater in Shanghai has been greatly reduced, and the recharge has been greater than its mining output for two consecutive years. In principle, wherever surface water can reach in Shanghai, the exploitation and utilization of groundwater would gradually stop. The development and utilization of groundwater in Shanghai has shifted from conventional water supply to strategic reserve water sources. Meanwhile, the land subsidence in Shanghai decreased from 8.4 mm in 2005 to around 6 mm in 2011, which is the highest level in history.

During the 12th and 13th Five Year Plans, Shanghai further reduced the exploitation of groundwater and maintained that the amount of artificial recharge exceeded the amount of exploitation for 10 consecutive years. By 2015, the groundwater mining output was only 4.3 million cubic meters, but the groundwater recharge has expanded to 23.28 million cubic meters, and the proportion of exploitation and recharge is less than 1:5. From 2015 to 2019, the amount of groundwater recharge exceeded 20 million cubic meters for five consecutive years. By 2020, the mining output of groundwater has dropped to 1.05 million cubic meters, and the groundwater recharge volume has declined, but it is still as high as 18.1 million cubic meters. By 2021, the mining output of groundwater will be less than 1 million cubic meters (only 974,100 m^3), the reinjection volume will be

17,074,800 m^3, and the proportion of exploitation and reinjection will reach 1:17.5. For 11 consecutive years, the artificial recharge of groundwater is greater than the mining output.

5. PRINCIPLES AND MANAGEMENT SYSTEM OF GROUNDWATER RESOURCES MANAGEMENT IN SHANGHAI

In practice, the main impact of excessive exploitation of groundwater resources in Shanghai is manifested as: the first is the emergence of a groundwater depression funnel (the groundwater level is horizontal under natural conditions), followed by soil compression, and finally leading to ground subsidence. Shanghai, as a coastal city, is one of the earliest provincial-level cities in China to recognize the hazards of land subsidence. Land subsidence has been listed as one of the main geological hazards facing Shanghai. From 1966 to 2011, the cumulative ground subsidence in Shanghai was about 0.29m. The negative effects of environmental issues such as rising sea levels due to rapid ground subsidence have a cumulative effect. Therefore, in order to strengthen the scientific management of groundwater resources, control excessive exploitation of groundwater, and prevent ground subsidence, Shanghai has taken various scientific, effective, and reasonable measures to limit the development and utilization of groundwater resources, in order to control the factors that cause disasters. At the same time, the 3rd meeting of the Standing Committee of the Shanghai Municipal People's Congress voted to pass the "Regulations on the Prevention and Control of Ground Subsidence in Shanghai", which came into effect on July 1, 2013.

5.1 Principles of Groundwater Resource Management

Since the promulgation of the New Water Law in 2002, the total amount control system for groundwater extraction in Shanghai has been actively explored and practiced. In 2011, Shanghai began implementing strict groundwater management systems to vigorously reduce groundwater extraction, effectively suppress ground subsidence, and ensure urban safety. In 2012, Shanghai carried out the formulation of the "Draft Measures for the Administration of Water Intake Permits and Water Resource Fee Collection in Shanghai" and publicly solicited opinions. By strengthening the management system of water intake permits and water resource fee collection and utilization, it is necessary to further promote the conservation and rational development and utilization of water resources. Since 2013, the development and utilization of groundwater resources in Shanghai has shifted from conventional water supply to strategic reserve water sources. The strictest groundwater resource management system in Shanghai is based on the allowable mining output of groundwater resources in various regions of Shanghai as the red line of development and utilization control, and the establishment of the red line of the system centered on the control of total groundwater use and water allocation management. According to the principle of unified scheduling of water resources, it is necessary to coordinate the ratio between surface water and groundwater, conventional and unconventional water sources, and main and guest water sources in Shanghai, control the total amount of groundwater resources extraction and allocate them reasonably, establish and improve emergency and strategic reserve mechanisms for groundwater, and implement the development and protection strategies for groundwater resources in various regions of Shanghai, which can be regarded as a major strategic measure for Shanghai to accelerate the transformation of its economic development mode. It is a must to first clarify the basic principles that should be followed in the development, utilization, and management of groundwater to strengthen the scientific management of groundwater resources in Shanghai, including three major principles:

5.1.1 Principles of Balanced Irrigation and Harvesting, Supplementing Deficiencies with Abundant Resources, and Sustainable Utilization

According to the hydrogeological conditions of different regions, there is a necessity to optimize the regional water use structure, adjust the layout of groundwater exploitation according to the occurrence and distribution patterns of groundwater resources, improve the effective infiltration of precipitation, reduce evaporation and transpiration losses, and effectively utilize soil water. Through artificial recharge of groundwater mining output, the dynamic balance of groundwater exploitation and irrigation can be realized, the land subsidence can be effectively controlled, the sustainable utilization of groundwater resources can be promoted, and the water ecological environment of groundwater can be gradually restored.

5.1.2 Principles of Reasonable Regulation, Shallow Focus, and Deep Moderation

It is necessary to reasonably adjust and control the groundwater level, increase the underground water storage space, and reduce the shallow and middle groundwater mining output. For areas with rich deep groundwater resources and no major environmental geological problems after development and utilization, the deep mining output can be appropriately expanded in a planned way to achieve the best water use efficiency with the minimum subsidence.

5.1.3 Principles of Joint Regulation, Comprehensive Planning, and High-quality Utilization

Transforming from surface water storage as the main approach to combined surface and underground water storage, there is a must to adhere to the principle of balancing surface water, groundwater, and upstream and downstream water resources. According to the priority of meeting the domestic water needs of residents and taking into account the order of industrial, agricultural, and ecological water use, reasonable development and utilization of groundwater should be carried out, and high-quality groundwater resources should be prioritized to ensure urban life.

5.2 Groundwater Resource Management System

Shanghai should further improve and establish a sound system for managing groundwater resources, as well as strengthen the effective implementation and execution of systems such as the total amount control system for groundwater extraction, groundwater evaluation and monitoring system, public participation system, groundwater source protection and strategic reserve system, and groundwater market trading system.

5.2.1 A Combined System of Total Groundwater Extraction Control and Recharge

The combined system of total groundwater exploitation control and reinjection is to control the maximum mining output of groundwater within a certain period of time and a certain region, and the total amount of groundwater allowed to be taken by each administrative region shall not exceed the sum of the mining output amount of the hydrogeological unit involved, so as to prevent groundwater overexploitation and its problems, and promote the sustainable use of groundwater resources. For special situations such as emergency drought resistance, the principle of using abundant resources to make up for poor ones is adopted. By utilizing the long-term regulation capacity of underground reservoirs, groundwater is moderately overexploited during the emergency period, and the overexploited portion is deducted year by year after the emergency period. At the same time, through artificial recharge of groundwater and other protective measures, the overall dynamic balance of long-term groundwater extraction and irrigation can be achieved.

5.2.2 Groundwater Evaluation and Monitoring System

The groundwater evaluation and monitoring system refers to the establishment and improvement of a groundwater resource evaluation system, including the evaluation of groundwater quantity and quality, the evaluation of groundwater extraction technology conditions, the evaluation of environmental benefits, and the evaluation of groundwater protection measures. There is a necessity to accelerate the establishment and improvement of a dynamic monitoring station network system covering groundwater. Based on the current network situation and actual needs, speed up the construction of groundwater protection planning stations and the upgrading and renovation of existing stations, improve the layout of groundwater monitoring stations, increase the density of groundwater monitoring station network layout, set up dedicated monitoring wells, improve the quality of monitoring data, enhance monitoring and data transmission methods, and improve data collection and transmission efficiency.

5.2.3 Public Participation System

The public participation system endows the public with decision-making power in managing groundwater activities and substantially participates in decision-making processes such as groundwater development and utilization planning. The public can obtain information on groundwater resource evaluation through relevant channels, and can supervise and hold accountable the evaluation process of relevant departments. Special groundwater legislative hearings should be established to enable the public to participate in the decision-making process of groundwater management activities and fully express their opinions. The water administration department may implement economic stimulus measures to provide economic rewards to individuals, enterprises, or environmental organizations that have made outstanding contributions in groundwater management activities, stimulate public enthusiasm for participating in groundwater management, and establish channels for citizen relief to prevent infringement of citizens' decision-making rights.

5.2.4 Groundwater Source Protection and Strategic Reserve System

The protection and strategic reserve system of groundwater source areas should follow hydrogeological laws, scientifically divide the scope and protective layers of groundwater protection zones, adopt scientific and strict protective measures, and effectively prevent the water quality of groundwater source areas and recharge areas from being polluted. There is also a necessity to strengthen the strategic reserve of groundwater source areas, search and explore more groundwater source areas, develop emergency groundwater source planning schemes, and transform from disorderly emergency water supply to orderly emergency water supply for emergency water supply.

5.2.5 Groundwater Market Transaction System

The groundwater market transaction system is to utilize market tools and economic incentive mechanisms to improve the efficiency of groundwater resource utilization. The first is to establish the initial water rights allocation rules for groundwater resources, and determine the initial water rights allocation mode and method for groundwater resources based on factors such as the total amount of available groundwater and population in the region, as well as the impact of mining activities on the environment, which will reflect the principle of fair distribution of natural resources. The second is that under the macroeconomic regulation of the government, administrative controls are relaxed. In the secondary market trading process of groundwater rights, the transfer price is freely negotiated between water rich and water scarce individuals to determine a reasonable price for groundwater rights trading, reflecting market efficiency. The third is to strengthen the trading supervision of the groundwater market and publicly disclose information on groundwater rights trading to the society. Before the transaction, the water rights transferor shall publish the information of the transferred water rights in the media; after the transaction, the state regularly publishes the recent water rights trading situation and changes in water rights.

6. CONCLUSION

In 2022, the per capita GDP of Shanghai has exceeded 180,000 yuan, and the added value of the tertiary industry in Shanghai has increased to 3309.742 billion yuan. The proportion of the tertiary industry is close to 75%, and Shanghai's economic structure is accelerating transformation and urban functions are rapidly improving. From 2011 to 2021, Shanghai has issued the No. 1 central document of 2011, implemented the strictest water resource management system, carried out the action plan of double control of total water consumption and intensity, and strictly controlled the total water consumption. The water intake in Shanghai has rapidly decreased from 9.749 billion cubic meters to 7.743 billion cubic meters, and the water consumption per 10,000 yuan of GDP has decreased from 51 m^3 to 18 m^3. The agricultural water consumption decreased from 1.681 billion cubic meters to 1.529 billion cubic meters, the industrial water consumption decreased from 5.563 billion cubic meters to 3.668 billion cubic meters, and the domestic water consumption decreased from 2.505 billion cubic meters to 2.465 billion cubic meters. Overall, industrial water consumption remains the largest user, followed by domestic water, agricultural water, and ecological water. Shanghai has achieved a comprehensive transformation from a groundwater deficit to a groundwater surplus, and since 2011, Shanghai has entered the era of groundwater surplus. Shanghai has adopted various scientific, effective, and reasonable management principles and policy systems to strengthen the management of groundwater resource exploitation and utilization. The development, utilization, and management of groundwater follow three major principles: the principles of balanced extraction and irrigation, supplementing deficiencies with abundant resources, and sustainable utilization; the principles of reasonable regulation, shallow focus, and deep moderation; and the principles of joint regulation, comprehensive planning, and high-quality utilization. The management system for groundwater development and utilization in Shanghai mainly includes a combination of total groundwater extraction control and recharge system, groundwater evaluation and monitoring system, public participation system, groundwater source protection and strategic reserve system, and groundwater market trading system.

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