DOI 10.15302/J-SSCAE-2022.07.001

Water Security in Beijing–Tianjin–Hebei Region: Challenges and Strategies

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Abstract: The Beijing–Tianjin–Hebei region suffers from a high bearing pressure of water resources and its water ecosystem is severely damaged. For future development, it is necessary to analyze the water security risks and propose targeted countermeasures, thus to ensure the coordinated development of the Beijing–Tianjin–Hebei region and build this region into a world-class urban agglomeration. In this study, we summarize the key national policies, socio-economic development trends, and ecological protection requirements of the region. In addition, we analyze the water security status and relevant major scientific issues. Our findings are as follows. (1) The contradiction between supply and demand of water resources is the primary problem that threatens water security in the Beijing–Tianjin–Hebei region, and water resources in the region will probably continue to decay by 1–2 billion m3. Therefore, to guarantee the security of the regional water system, 3.9–6 billion m3 of water needs to be transferred into this region via the South-to-North Water Diversion Project. (2) To address the shrinkage and drying of regional rivers and lakes, groundwater overexploitation, and other severe water ecological problems, we propose a layout for the ecological protection and restoration of rivers and lakes and clarify the healthy groundwater levels for different areas: 8–20 m in piedmont plains, 3–5 m in central plains, 6–10 m in urban areas, and 2–3 m in the eastern coastal area. (3) To improve the weak links of the flood control system in the region such as a low pass rate of flood control standards and the difficulty in activating flood detention areas, this region needs to strengthen the routine–emergency integrated management and prepare countermeasures for over-level floods.
Keywords: Beijing–Tianjin–Hebei region; water security; efficient utilization of water resources; groundwater level restoration; river and lake ecology protection

1 Introduction

The Beijing–Tianjin–Hebei (BTH) region is China's densely populated and economically developed region, as well as a region of water shortage, serious water pollution, and significant degradation of water ecology. The sharp contradiction between resources and environmental support and development leads to poor water security [1] . Presently, a series of major national strategies and water control measures, such as the coordinated development of the BTH region, the construction of the Xiong'an New Area, the ecological restoration of the Yongding River, and the comprehensive management of groundwater over-extraction in North China, have been presented in the BTH region, profoundly impacting the future regional water security situation. Therefore, holistically studying the

Received date: November 29, 2021; **revised date:** December 30, 2021
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Funding program: CAE Advisory Project "Challenges and Countermeasures for Water Security in Beijing–Tianjin–Hebei Region toward 2050" (2021-XY-06); National Science Fund for Distinguished Young Scholars (52025093)
Chinese version: Strategic Study of CAE 2022, 24 (5): 008–018
Cited item: Zhao Yong et al. Water Security in Beijing–Tianjin–Hebei Region: Challenges and Strategies, *Strategic Study of CAE,* https://doi.org/10.15302/J-SSCAE-2022.07.001

management of regional water resources guarantee, groundwater restoration, river and lake ecological restoration, and excessive flood prevention is of great practical significance for the development of the BTH region [2] .

The consulting project "Research on China's Water Security Strategy and Related Major Policies" (2016), organized and completed by the Chinese Academy of Engineering, proposed an overall strategic framework, major strategies, and specific development proposals for national water security [5] , which provided top-level technical guidance for research on water security in the BTH region. Supported by the 13th Five-Year Plan National Key Research and Development Plan, the "Beijing–Tianjin–Hebei Water Resource Security Technology Research and Development Integration and Demonstration Application" project is an important research outcome formed around the BTH water resources security guarantee [6] . The results systematically answer two major scientific questions: (1) the evolution mechanism of the water cycle and the model of the healthy water cycle in areas with strong human activities and (2) the multi-objective cooperative allocation of water resources under intense competition conditions. Based on the research progress and the new national concept of water governance, this study explores and proposes strategic measures to solve water security problems in the BTH region. It is an inevitable requirement to ensure the healthy and sustainable development of the regional ecological, economic, and social environment, as well as a reliable case for the efficient allocation, utilization, and management of water resources in similar water-scarce areas.

Overall, the water security problem in the BTH region is a contradiction between insufficient carrying capacity and overloading of development, as well as the contradiction between the imbalance of economic development structure and the lag of ecological environment protection. Owing to the combined effects of various influencing factors and the new characteristics constantly presented in the development process, previous study conclusions still need improvement regarding comprehensiveness and applicability. Therefore, this study focuses on the ecological recovery and high-quality development goals of the BTH region to determine the current status of water security studies, situation analysis, and scientific problems. This study proposes regional water security assurance strategies based on existing study results and new water governance requirements.

2 Water security in the BTH region

2.1 The mismatch between economic and social development and water supply capacity leads to the prominent contradiction between the supply and demand of water resources

Because the carrying capacity of water resources severely restricts water demand, the BTH region has been in a tight balance for a long time. The water resources only account for 0.7% of the country's total water resources; however, they carry 5% of the country's arable land, 8% of the population, and 10% of the total economic output. From 2014 to 2020, the annual average water consumption in the BTH region was 2.53×10^{10} m^3, of which the local surface water and groundwater supply was approximately 2.11×10^{10} m^3, and the reclaimed water and external water supply was approximately 4.2×10^{9} m^3. In 2020, the water consumption efficiency of the BTH region was at an advanced level locally and abroad [7] . For example, the per capita water consumption was 227 m^3, the water consumption of ten thousand CNY of GDP was 29 m^3, the water consumption of ten thousand CNY of industrial value added was 12.8 m^3, and the average water consumption of agricultural irrigation was 160 m^3/mu (1 mu ≈ 666.67 m^2).

Notably, with the coordinated development of the BTH region and the promotion of ecological civilization, key areas such as the Beijing Municipal Administrative Center and the Xiong'an New Area in Hebei will have agglomeration effects while relieving the non-capital functions of Beijing, which presents new and higher requirements for development and ecological water consumption. In contrast, the Haihe River Basin has the most severe surface water attenuation among the first-level basins in China. Compared with the first water resources evaluation period (1956–1979), the average surface water resources decreased by 1.66×10^{10} m^3 from 2001 to 2016, among which the water resources in mountainous and hilly areas accounted for more than 75%. This is more than three times the amount of water planned to be transferred to the BTH region in the first phase of the middle route of the South-to-North Water Diversion Project (SNWDP) and more than 60% of the total water consumption in the region. A decline in water resources intensifies regional water contradictions.

2.2 Long-term economic and social crowding out of the ecological environment water causes serious damage to the water ecological environment

To support the demand for water for socio-economic development, the utilization rate of water resources in the BTH region reached 106%, which was still as high as 70% after the first phase of the eastern and middle routes of

DOI 10.15302/J-SSCAE-2022.07.001

the SNWDP was completed. However, the serious overloading of regional water resources also leads to serious damage to the aquatic ecosystem, which is highlighted by the cut-off of river flow, shrinking of lakes and wetlands, low connectivity of rivers, and low aquatic biodiversity.

According to the third water resources survey and evaluation, the main river reaches in the BTH region dried up for an average of 217 days per year from 1980 to 2017, and 70% of the river reaches dried up for more than 300 days. In addition, the areas of major lakes, such as the Baiyangdian Lake and Hengshui lakes, have decreased by 70% since the 1950s. For example, in the early 1950s, the average annual water inflow into the sea in the BTH region was $2.38\times10^{10}m^3$. However, influenced by the construction of large- and medium-sized water storage projects, climate change, and the surge of economic and social water consumption, the annual water inflow into the sea has become increasingly less and even less than $2\times10^9 m^3$ after 2000. In 2010, the annual water inflow to the sea showed a recovery trend but only increased to $6.3\times10^9m^3$.

The BTH region is also the most seriously overexploited groundwater area in China, with overexploitation area and amount accounting for approximately 37% of the country. The cumulative groundwater over-extraction in the BTH Plain is over $1.5\times10^{11} m^3$, and the Hebei Plain is almost the whole area of over-extraction. From 1986 to 2013, the Hebei Plain became the world’s largest groundwater over-extraction and funnel areas, with a cumulative decrease of 6.68 m in groundwater level and an average annual decrease of 0.247 m. Groundwater overexploitation leads to a series of ecological and environmental problems, such as land subsidence and seawater intrusion [8] .

2.3 Weaknesses in the river basin flood control system remain prominent; old and new problems in flood control and disaster reduction coexist

The special geomorphological pattern of the BTH region determines the importance of flood control. Located in the front of the Taihang and Yanshan mountains, the transition zone from the piedmont to the plain is short, the river system is fan-shaped, short-source flows are urgent, floods rise and fall steeply, and rainstorm floods are easily produced in a short time. Therefore, extremely high requirements for flood forecasting, flood control, and drought emergency response have been proposed.

Currently, the control of weak links of water conservancy in the BTH region, such as large- and medium-sized reservoirs, major backbone rivers, and small- and medium-sized rivers, has not been fully completed. For example, the current flood control standard of backbone rivers is less than 50%; river silt congestion, aging and disrepair of levees, and disordered development of estuaries have caused a general decline in flood discharge capacity. The BTH flood storage and detention area has more than five million residents, and the cultivated land area is more than $6\times10^5 hm^2$. Engineering and safety construction in flood storage and detention areas cannot meet the actual requirements. Once the flood discharge is not well controlled, the scope and impact of flood disasters can easily be expanded, and even the situation of “small water results in large flood” will be caused.

Urban flood control and drainage have recently become a new focus. Owing to the increase in urban building areas and cement-hardened roads, the area of natural “sponges” is significantly reduced, resulting in frequent urban waterlogging and other phenomena. From 2017 to 2019, a total of 2.41 million people were affected by urban waterlogging in the BTH region, resulting in a direct economic loss of 4.4 billion CNY. In addition, heavy rain in some cities has caused waterlogging and casualties. As a result, waterlogging capacity does not match and adapt to the level of economic and social development, which has become a shortboard and restricting factor of urban development in the region.

3 Water security situations in the BTH region

3.1 Higher requirements

The proposal of the *Outline of Coordinated Development of the Beijing–Tianjin–Hebei Region* indicates that the coordinated development of BTH has entered a new stage of full implementation and accelerated promotion [11] . Ensuring the implementation of major national strategies has become the core task of water governance in the BTH region, introducing new requirements for regional water security. For the BTH region, the following aspects are particularly critical: to perform a good job in the systematic management of “mountains, rivers, forests, fields, lakes, and grasslands” and realize multi-functional coordination; multi-dimensional governance and development of water resources, water security, water ecology, water environment, water culture, economy, and society should be realized. We will work hard to promote the intensive use of water resources and prioritize saving water.

3.2 Change of the pattern for population and economic development

Since 2001, the national population growth rate has decreased. Currently, the national population is changing following a new trend (Fig. 1), and studies predict that the 14th Five-Year Plan period will register negative growth [12] . In the BTH region, the population growth rate shows two stages: rapid growth before 2010 and a sharp decline after 2010 (after 2015, the population growth rate has been lower than the national level). Based on the population flow situation, the population inflow areas in the BTH region in the past decade are mainly Beijing and Tianjin, and the net outflow area is Hebei Province. During the 13th Five-Year Plan period, the BTH urban agglomeration showed a net outflow trend after deducting the natural population growth. Beijing has changed from a net inflow of population to a net outflow [14] , and Tianjin has a similar trend. Therefore, the peak population of the BTH region is likely to reach ahead of schedule.

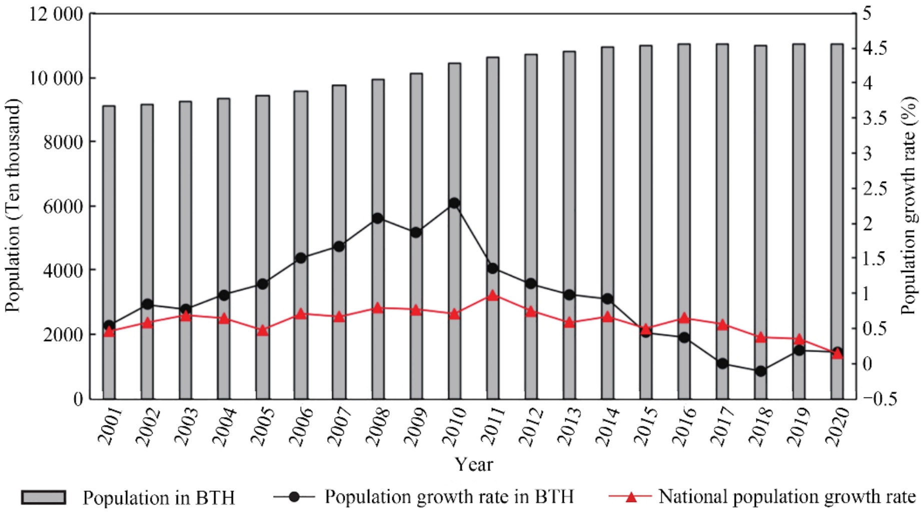

Fig. 1. Trends of population change in China and the BTH region.

The BTH region is an important driver of China's economic development. Under the guidance of major strategies, economic and social development patterns have gradually been adjusted. Xiong'an New Area in Hebei Province is positioned as a green, ecological, and livable new urban area, a leading innovation-driven development area, a demonstration area for coordinated development, and a pilot area for open development. The Beijing Municipal Administrative Center is developing into a world-class demonstration area for harmonious and livable cities, new urbanization, and coordinated development of the BTH region. The construction of the Grand Canal cultural belt strives to provide the initiative in the whole country through the organic combination of regional water management, urban construction, cultural development, and historical protection. The adjustment of economic and social patterns has presented new requirements for regional water resource security, which can promote the restoration and management of water ecology in the BTH region as well as ensure water security for economic and social development, which is a major challenge for water resource regulation in the BTH region.

3.3 Continuous upgrading of targets for ecological and environmental improvement

Since 2014, several ministries and commissions have jointly promoted the implementation of the three-year pilot project of comprehensive treatment of groundwater over-extraction in Hebei Province. The *Action Plan for Comprehensive Treatment of Groundwater Overexploitation in North China* (2019) [15] suggested that by 2022, under the condition of normal water inflow, the annual groundwater exploitation amount in the BTH region will be reduced by 2.57×10^9 m^3, and the current reduction rate of overexploitation will be no less than 70%. By 2035, we will strive to fully realize the balance between groundwater extraction and replenishment and gradually fill the excess and deficit of groundwater. These comprehensive management measures presented new goals and requirements for supply-side guarantees and demand-side control of water resources in the BTH region.

The ecological recovery of rivers and lakes is an important aspect of high-quality development in the BTH region. To solve the problems of river and lake drying, the Ministry of Water Resources coordinated the three provinces to jointly conduct ecological water replenishment action for rivers and lakes. As a result, by the end of 2020, the cumulative ecological water replenishment of rivers and lakes in the BTH region was 1.14×10^{10} m^3, and

DOI 10.15302/J-SSCAE-2022.07.001

the length of rivers and lakes with water in the treatment area increased to 1873 km (2.1 times that of before water replenishment), and the new water surface was 734 km^2 (1.9 times that of before water replenishment). Despite this, the ecological water shortage of rivers and lakes in the BTH region has not been fundamentally reversed, and there is still a large gap with the regional positioning target.

4 Analysis of major scientific problems of water security in the BTH region

4.1 Attenuation law and evolution prediction of river basin water resources

Ninety-two percent of the BTH region is in the Haihe River Basin, and 67% of the Haihe River Basin is in the BTH region. Under the dual influence of climate change and human activities, the total surface water resources in the Haihe River Basin, where the BTH region is located, decreased by 58% from 2.88×10^{10} m^3 during 1956–1979 to 1.22×10^{10} m^3 during 2001–2016. The "Beijing–Tianjin–Hebei Water Resource Security Technology Research and Development Integration and Demonstration Application" project shows [16] that the average surface water resources decreased by 1.17×10^{10} m^3 from 1980 to 2000 compared with that from 1956 to 1979. The primary influencing factor was rainfall variation (60%), followed by vegetation restoration. Compared to 1980–2000, the average surface water resources decreased by 4.9×10^9 m^3 from 2001 to 2016, and the most significant contribution was the impact of mountain vegetation restoration on the attenuation of surface water resources (accounting for 54%), followed by the impact of rainfall change.

Water resources in the Haihe River Basin are significantly affected by climate change, land use patterns, vegetation quality, groundwater depth, and other factors. This study used four key elements to configure a future prediction scenario scheme. Through the combination of different scenario elements, the distributed water allocation and cycle model was used to predict the evolution law of water resources in the Haihe River Basin in the future. Although the current climate conditions and groundwater depth are maintained, the water resources in the Haihe River Basin will continue to decline by 1×10^9–2×10^9 m^3 compared to the current situation, which is affected by the rapid development of urbanization and large-scale vegetation restoration.

4.2 Peak water consumption study and demand forecast

The peak value of natural development water consumption and the water resources carrying capacity are key factors affecting the regional total water consumption. According to the research results of this research group [17] , total water consumption development can be characterized as a triadic driving mechanism of "economic and social scale growth is positively driven–water consumption efficiency level improvement is negatively driven–water supply conditions are constrained," which is shown as an adaptive increase curve yielding to the resource-constrained. There are three types of water consumption growth curves according to different degrees of water resource constraints: natural growth type (curve ABDEF), development constraint type (curve ABDGH), and severe stress type (curve ABIJ) (Fig. 2).

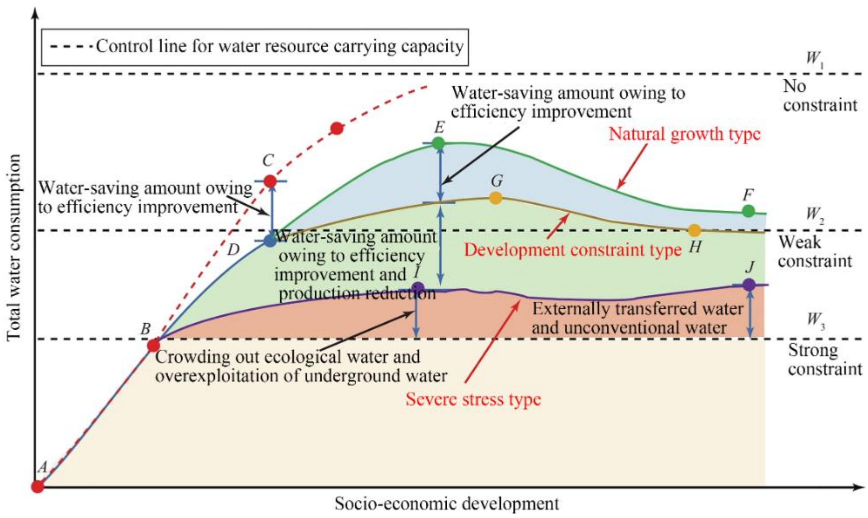

Fig. 2. Adaptive growth curve subject to resource constraints.

Note: W_1 refers to the total water consumption without any constraint; W_2 refers to the total water consumption with weak constraint; *W3* refers to the total water consumption with strong constraint.

The major developed countries have observed peaks in water consumption. Referring to their total water consumption and the development process of economic and social, the peak water consumption for natural development depends on economic and social development factors, including economic and social scale (GDP per capita reaches 20 000 USD), industrial structure (the proportion of the tertiary industry reaches 60%), and social structure (urbanization rate exceeds 70%). Using this standard, Beijing has already met the economic and social conditions for peak water consumption, Tianjin is close to this condition, and Hebei Province does not meet this condition. Further projection of water demand in the BTH region, using the actual water consumption in 2018 as the baseline for the current level of annual water demand, the economic and social water demand will peak around 2035, with a total of 2.57×10^{10}–$2.75\times10^{10}m^3$, and maintain the scale or decline slightly after 2035.

4.3 Measurement of water consumption demand of the SNWDP

The transferred water of the SNWDP is an important source of water, guaranteeing water security in the BTH region, and a reasonable amount of water transfer is the basis for supporting the future healthy development of the region [18] . The "Beijing–Tianjin–Hebei Water Resource Security Technology Research and Development Integration and Demonstration Application" project systematically analyzed the security of the BTH region water system under different scales of new external water transfer [16] . According to the current evaluation of water resources, the middle route of the South-to-North Water Transfer First Stage Project, and the amount of water diverted from the Yellow River, under conditions of guaranteeing reasonable economic and social water demand, minimizing water consumption of the eco-environment, and balancing groundwater extraction and replenishment, the water shortage in the BTH region will reach 2.9×10^9 m^3 in 2035 if no additional external water transfer is considered. When the additional external water transfer is 2.9×10^9 m^3, only the minimum water consumption of the eco-environment and groundwater extraction and replenishment can be guaranteed, and the overloaded water ecosystem can hardly be repaired. In contrast, if the newly transferred water is 5×10^9 m^3, it can meet the requirements of groundwater restoration for 50 years while guaranteeing suitable water consumption of the eco-environment, and the BTH region will no longer have a water shortage, and the ecosystem can be fully restored.

Thus, to ensure the future economic and social development and water system security of the BTH region and the safety of the water system, the baseline water transfer amount of the SNWDP should be 2.9×10^9–5×10^9 m^3. Furthermore, considering the continuous decay of water resources in the basin, the water supply gap will be further increased by approximately 1×10^9 m^3; therefore, the ideal amount of water to be transferred from the SNWDP should be configured at 3.9×10^9–6×10^9 m^3.

4.4 Water level goals for healthy groundwater remediation

In the BTH region, achieving the balance of groundwater exploitation and replenishment is the stage goal of comprehensive treatment of overexploitation. The ultimate goal of the comprehensive treatment of overexploitation is to supplement the groundwater amount based on the balance between harvesting and replenishment to restore the groundwater level to the level that can maintain the health of the ecological environment. This study proposes the concept of a "healthy groundwater level" as a framework for future groundwater remediation. A healthy groundwater level refers to the groundwater level that maximally supports economic and social development based on safeguarding regional ecological health. According to different groundwater functions, it can be divided into two categories of upper and lower limit water levels. The former includes groundwater levels for maintaining healthy recharge of surface water bodies, curbing seawater intrusion, and maintaining vegetation health. The latter includes groundwater levels for controlling salinization, safe urban buildings, and underground aquifer storage.

From comprehensive study results [19] , the suitable groundwater level in the BTH region (Fig. 3) is 8–20 m in the piedmont plain area, 3–5 m in the central plain area, 6–10 m in the urban area, and 2–3 m in the eastern coastal area. In addition to restoring the groundwater level, the amount of over-extracted groundwater should also be restored. Based on the changes in groundwater level and ground settlement amount from 1959 to 2019, preliminary results were obtained based on numerical groundwater simulation. As of 2019, the accumulated overdraft in the BTH Plain was 1.375×10^{11} m^3, and the recoverable groundwater overdraft amount was 8.77×10^{10} m^3 (80% for shallow groundwater and 20% for deep groundwater, Fig. 4).

DOI 10.15302/J-SSCAE-2022.07.001

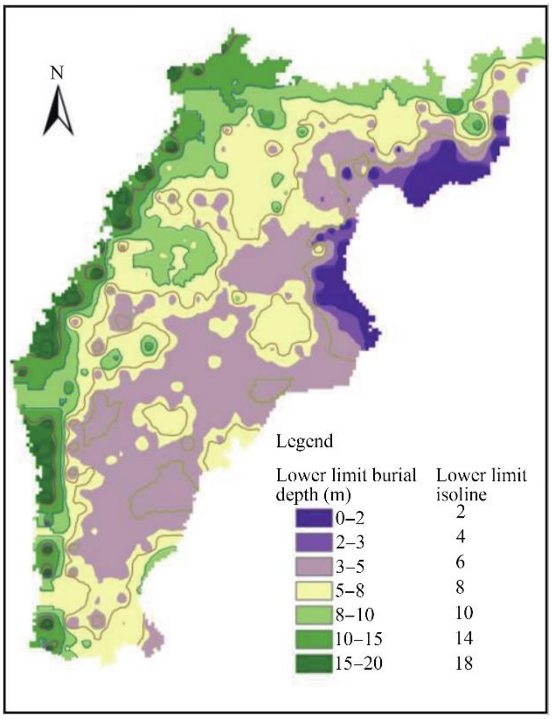

Fig. 3. Distribution of lower limit groundwater depth in the BTH plain.

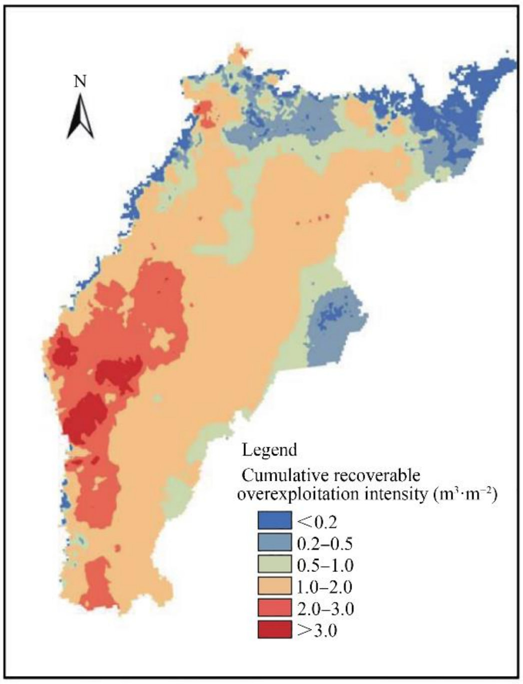

Fig. 4. Distribution of recoverable groundwater amount in the BTH plain.

4.5 River and lake ecological protection and restoration layout and path

Shrinking and drying up rivers and lakes in the BTH region are serious problems, and ecological functions are damaged. Therefore, the ecological protection and restoration of rivers and lakes rely on the overall improvement of the water ecology in the basin. In this study, the layout of ecological protection and restoration of rivers and lakes is proposed based on an analysis of the characteristics of major rivers and lakes and ecological water problems in the Haihe River basin (Fig. 5). (1) In the Luanhe area, the water conservation function of upstream and ecological barriers should be conducted to enhance the ecological water replenishment capacity, promote the change from ecological water assessment to ecological flow, and strengthen shoreline management. (2) In the

Beisihe area, enhancing ecological barrier construction, establishing ecological scheduling and water guarantee mechanisms, preventing and controlling urban surface source pollution, and implementing a clear water retreat strategy should be conducted. (3) In the Daqinghe area, through the joint deployment of multiple water sources, the ecological replenishment capacity of the upstream reservoirs should be enhanced, the ecological hydrological rhythm of Baiyangdian Lake and other regions should be restored, and agricultural water conservation and emission reduction should be strengthened. (4) In the Zi−Zhangwei River area, enhancing ecological dispatch, restoring and protecting important wetland and corridor functions, and strengthening agricultural water conservation and emissions reduction should be implemented. (5) Agricultural water conservation and emission reduction should be strengthened in the Tuhai−Majia River area. (6) Construction of the middle route of the SNWDP water resources allocation and ecological replenishment belt, the eastern route of the SNWDP–Great Canal water quality assurance and ecological restoration belt, coastal mudflats wetland protection and restoration, and functional enhancement belt.

In the time dimension, the three-step strategy to achieve comprehensive recovery of rivers and lakes in the BTH region is as follows: 2020–2025, curb the trend of shrinking water space, restore the water area of rivers and lakes, and commit to the full line of important rivers to water; 2026–2035, the ecological flow of rivers and lakes will be guaranteed regularly, and the overall water environment and water ecology of the region will reach a safe level; and 2036–2050, the regional water environment problems will be comprehensively solved, and the long-term mechanism of water ecological security will be built and operated efficiently.

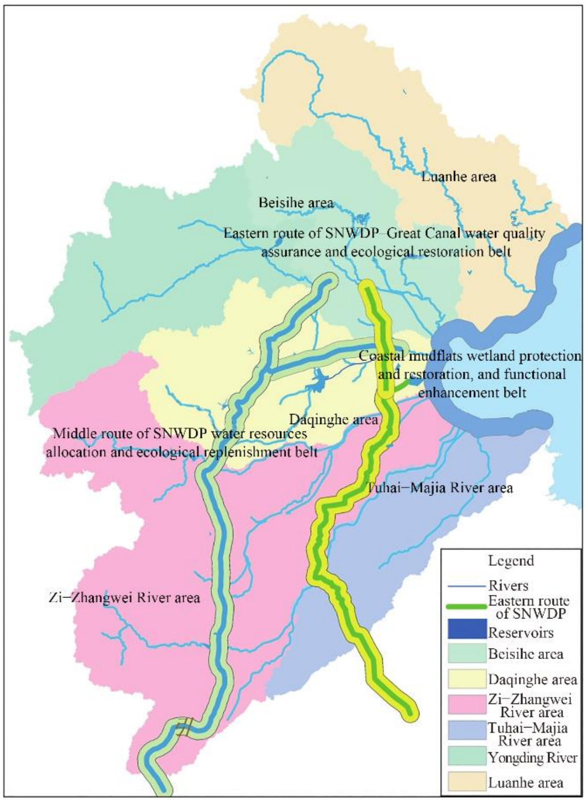

Fig. 5. Overall layout of “Five Areas and Three Belts” for water ecological restoration in the Haihe river basin.

5 Water security measures in the BTH region

5.1 Strengthening the conservation and intensive use of water resources by controlling the total amount, optimizing the structure, and improving the efficiency

To alleviate the problems of unbalanced water saving in the BTH region, the high proportion of agricultural water consumption, and the large proportion of industries with high water consumption, strengthening the management of water resource demand in the whole basin and industry is necessary.

First is controlling the total amount of irrigation and urban scales. According to the carrying capacity of water resources, there is a need to rationally determine the development layout and scale and study and formulate the

DOI 10.15302/J-SSCAE-2022.07.001

carrying limit of the stage. In areas with severe overexploitation of groundwater, comprehensive coordination of national strategic goals, such as groundwater pressure exploitation and food security, and strict control of irrigation and planting areas of high-water-consuming crops are required. For example, in the dam area, to build a functional area for water conservation and an ecological environment support area in the capital, the irrigated land area should be reduced orderly, and groundwater exploitation should be reduced. Then it is necessary to strengthen urban greening and water saving, scientifically implement vegetation restoration in mountainous areas, and use water to meet greening needs.

Second is continuously optimizing the main structure of the industry, planting, trade, and consumption. It is necessary to strictly control the development and utilization of water resources, reasonably determine the economic layout, and optimize the industrial structure, shifting from “heavy industry + producer services” to “high-end manufacturing + technological innovation.”

Third is implementing in-depth water conservation in the entire industry of life, industry, and agriculture. In addition to traditional water-saving work, we will explore the water-saving potential of various industries and optimize the water-saving models. For example, agriculture has shifted from a high-yield irrigation model to a high-efficiency water-use model, which has promoted leapfrog development with the research and development, promotion, and application of disruptive water-saving technologies, and life has expanded from terminal water saving to building system water saving.

Fourth is utilizing unconventional water sources, such as reclaimed water and seawater. We will strictly implement the *Guiding Opinions on Promoting Sewage Resource Utilization* (2021) and scientifically establish the overall regional sewage resource utilization goal. It is necessary to timely formulate special plans for the development of the seawater desalination industry in coastal areas, promote the gradual distribution of high-water-consuming industries to the coast, improve the level of water supply security for seawater desalination, and improve policies and regulations related to the seawater desalination industry.

5.2 Strengthening “water amount–level–quality” three-dimensional restoration

The long-term cumulative over-exploitation of groundwater in the BTH region is significant. Therefore, it is necessary to strengthen the groundwater “amount–level–quality” three-dimensional and persistent restoration based on comprehensive management of current groundwater over-exploitation to achieve groundwater system health.

The first is to clarify the goal of a “healthy groundwater level.” The BTH region exhibits strong human activity. Therefore, the restoration of the groundwater level should consider the natural ecology and the needs of human activities and social development to meet the service functions of different groundwater types and realize groundwater’s healthy development.

The second is to prevent and control the risks of groundwater safety systems. Long-term over-exploitation of groundwater in coastal areas has caused seawater to invade inland freshwater, resulting in salinity of the water quality; groundwater exploitation should be strictly controlled to prevent seawater intrusion. In addition, ground subsidence caused by groundwater exploitation is extremely detrimental. Since the 1970s, the scale of groundwater exploitation and utilization in the BTH region has gradually expanded. As a result, the problem of land subsidence is becoming increasingly prominent and has begun to affect the safety of buildings and even compress and dry the aquifer.

The third is to build a dynamic groundwater monitoring and early warning system. In the future, precipitation in the BTH region will be an important factor affecting comprehensive groundwater recovery and replenishment balance. Therefore, a dynamic prediction model of groundwater should be constructed on a seasonal scale to evaluate the current status and changing trends of groundwater levels in real time, and a groundwater dynamic monitoring and early warning system should be established according to the early warning levels and thresholds of groundwater in different over-exploitation areas.

The fourth is to improve the management of motorized wells and strengthen groundwater reserves. It is necessary to improve the sealing mechanism of groundwater wells, implement dynamic tracking, and classify the management of groundwater wells. Furthermore, strategic reserves of groundwater should be implemented. For example, the Taihang Piedmont Plain is distributed in a nearly north–south direction and forms a large-capacity Piedmont freshwater aquifer system that can be used as an underground storage space for water resources.

The fifth is to emphasize the persistence of groundwater governance. Presently, the governance effect of high investment in the short term has begun to appear. However, groundwater has a slower response speed and a longer restoration period than surface water (internationally, the groundwater governance effect is usually evaluated in units of 10 years), and groundwater governance should be included in the medium- and long-term development plans for water conservancy at the national level to be targeted and sustained to maintain resource input.

5.3 Local water–external transfer water–reclaimed water complementing each other to promote the ecological recovery of rivers, lakes, and wetlands

Because of the economic and social development trends and water resource conditions in the BTH region, the problem of insufficient ecological water can only be solved by the complementation of “local water–external transfer water–reclaimed water.”

The first is to implement the action of safeguarding the ecological basic flow of the piedmont reservoir. The establishment of ecological basic flow discharge facilities and ecological dispatch mechanisms in the piedmont reservoir ensure ecological basic flow. The ecological basic flow target of zoning classification should be formulated considering the natural and current discharge flow before and after the construction of the piedmont reservoir.

The second is to implement actions to improve the ecological water amount in the BTH region. It is necessary to strengthen the control of total water consumption and allocation, thus, playing the role of maximum rigid constraints on water resources. Furthermore, strengthening the ecological water replenishment of the east and middle routes of the SNWDP effectively improves the guarantee of the regional ecological water amount and the amount of water entering the sea.

The third is implementing urban and clean water recycling. Urban drainage is the main water source for rivers and lakes in regional plains. Therefore, the implementation of clear water drainage and recycling is an important way to solve the problems of poor water quality and insufficient ecological water in rivers and lakes in the plains. In addition, improving the waste and sewage collection pipe network, increasing the waste and sewage collection rate and concentration, improving the basic capacity and effluent quality of the sewage treatment plant, and gradually implementing Class IV and quasi-Class IV water discharge standards are recommended.

Fourth, actions should be implemented to improve the horizontal and three-dimensional connectivity of rivers and lakes. The BTH region locate at the East Asia–Australia migration route for migratory birds. The habitats and migration paths of migratory birds are key points of regional water ecological protection, which presents higher requirements for the horizontal and three-dimensional connectivity of regional rivers, lakes, and wetlands. Therefore, strengthening the protection and restoration of biodiversity in the main and tributary river floodplains, continental beaches, lakes, reservoir bays, coastlines, estuaries, and tidal flats and improving the horizontal connectivity between rivers and affiliated lakes and wetlands is required. In addition, the restoration of wetland network patterns should be strengthened, and the three-dimensional connectivity of regional water wetlands for migratory bird habitation and migration should be improved.

5.4 Optimizing the water conservation management model in mountainous areas to prevent further attenuation of runoff in hilly areas

Since 2000, the amount of water resources in the mountainous areas of the Hai River Basin has been severely reduced, seriously threatening the water supply and ecological security of the basin.

The first is to change the governance model of hilly areas. In land greening, soil and water conservation, and ecological restoration in hilly areas, water is used to determine green, and the vegetation carrying capacity of water resources is quantified. For areas with high vegetation coverage, soil and water conservation measures such as artificial tree planting should not be carried out on a large scale. However, they should adhere to near-natural restoration, protect existing natural forests, and take natural regeneration and natural ecological restoration as the main forms of vegetation construction.

The second is to strengthen agricultural water conservation in hilly areas. It is important to rationally plan the irrigation area of farmland in hilly areas, develop low-water-consuming crops and planting models, promote efficient water-saving irrigation production methods such as drip irrigation and micro-irrigation, and improve the utilization rate of water resources. Implementing the project of returning farmland to the forest (grass) should be continued, focusing on the restoration of natural vegetation, and avoiding excessive construction of storage facilities such as reservoirs, water cells, terraces, and fish-scale pits while maintaining the health of the ecological environment in the mountains and protecting limited runoff water resources.

DOI 10.15302/J-SSCAE-2022.07.001

The third is to fully consider the impact of water resource attenuation on the scale of water transfer required for follow-up projects of the east and middle routes of the SNWDP. Presently, the relevant state departments are studying and formulating follow-up project planning for the east and middle routes of the SNWDP, the influence of water resource attenuation factors in the BTH region should be fully considered. The balance between water supply and demand in the water-receiving areas of the east and middle routes of the SNWDP should be studied and determined scientifically. The scale and overall layout of the amount of water to be transferred should be clarified to ensure the long-term safety of water resources in the BTH region eventually.

5.5 Focusing on optimizing the follow-up projects of the middle and east routes of the SNWDP and improving the water grid structure

The BTH water network is a typical natural–artificial composite water network. Based on the natural water system, the optimization of artificial water grids, such as water diversion projects, is of great significance to the sustainable economic and social development of the BTH region, groundwater pressure extraction, and the improvement of water ecological functions.

First is optimizing the scale and route of follow-up projects for the eastern route of the SNWDP. In the eight years since the construction of the East Route Project, the highest additional consumption rate of water supply north of the Yellow River was less than 20%, and the problem of idle assets was imperative. Therefore, the 100 m^3/s water supply capacity of the Yellow Tunnel in the first phase of the East Route Project should be fully utilized to expand the water supply to the BTH region and alleviate the problem of groundwater overexploitation. Additionally, the follow-up project must divert northerly water to Beijing to build a stable pattern of dual-source guarantees in the capital. Meanwhile, it is suggested that the plan to enter Beijing via Baiyangdian Lake be compared and demonstrated. As shown in Fig. 6, this scheme has five major advantages over the existing planning routes. First, ecological benefits will be more fully exerted, connecting important rivers, lakes, and wetlands such as Baiyangdian Lake, Hengshui Lake, and Yongding River, which can naturally replenish water to the plain river network water systems such as the Fuyang, Daqing, and Yongding rivers. Second, the coverage of artesian flow will be wider, and it will have a stronger linkage with projects such as the middle route of the SNWDP and the diversion of the Yellow River to Hebei, which will be conducive to building a diversified and complementary BTH water resources security network. Third, water quality target guarantee of water transfer has stronger rigid constraints on water environment governance, and the route to Beijing via Baiyangdian Lake will go deeper into the hinterland of the North China Plain, which will be conducive to driving water ecological environment governance in the entire BTH region. Fourth, for Beijing, the route plan to enter Beijing via Baiyangdian Lake has noticeable comparative advantages and is more sustainable, not only in terms of the comprehensive benefit of the project but also the reliability of the water supply and the economy of water consumption. Fifth, for Xiong’an New Area, the transfer of water through Baiyangdian Lake can provide a stable and reliable water source for the construction of an ecologically livable urban area.

Second is that the benefit of the middle and east routes of the SNWDP can extend northerly to the Luan River Basin. Whether it is the first phase of the east and middle routes of the SNWDP, which has already been connected to water, or the original plan of the follow-up project, the northernmost end of the water-receiving area only supplies water to Beijing and does not include the Luan River Basin. However, the project to divert Luan into Tianjin in the early 1980s established an engineering connection between the water-receiving area of the SNWDP and the Luan River Basin. Therefore, if the water allocation plan in the receiving and non-water-receiving areas of the SNWDP can be optimized in its entirety, the pattern of the Luan River water system can be improved, the dividends of the SNWDP can be shared, and no additional engineering measures and capital investment are required. Consequently, only through the adjustment of the Luan water diversion allocation plan can the strategic benefits of the SNWDP be extended northward to the Luan River Basin, benefiting cities such as Chengde, Tangshan, and Qinhuangdao and more than 10 million people, which will generate huge social, economic, and ecological profits. Therefore, the specific implementation needs to consider the need for ecological environmental protection and economic and social development in the lower reaches of the Luan River in the planning plan for the follow-up project of the middle and east routes of the SNWDP, further optimizing the normal water distribution plan, and ensuring high-quality economic and social development of the Luan River Basin.

Third, the BTH water supply scale in the follow-up project of the middle and east routes of the SNWDP should consider the regional water resource attenuation factor. The follow-up project of the middle and east routes of the SNWDP plays an important role in alleviating the overexploitation of groundwater in the BTH region, ensuring the health of rivers and lakes, and supporting economic and social development. When determining the BTH water supply scale for the follow-up project of the SNWDP in the middle and east routes, the fact that the regional water resources continue to decline should be considered. Considering the BTH water demand reaching the peak in 2035 as the guaranteed target, when the additional water amount of the follow-up project of the middle and east routes of the SNWDP reaches 3.9×10^9 m³ while ensuring the water demand for normal economic and social development, the minimum ecological water demand for rivers and lakes can be achieved. While the additional water amount of the follow-up project of the middle and east routes of the SNWDP reaches 6×10^9 m³, a balance between the ecological water demand of rivers and lakes and a balance of groundwater extraction and replenishment can be achieved.

The fourth is to enhance the water resource regulation and storage capacity of water-receiving areas. Following the opening of the SNWDP, water-receiving areas have become more dependent on river water. Therefore, fully using existing storage reservoirs, properly building online storage and storage projects, enhancing the storage capacity of receiving areas, and effectively ensuring the water supply's safety is necessary. In addition, it is necessary to implement the dynamic regulation of the flood-limited water level and the drought-limited water level of the reservoir, establish a scientific calculation and decision-making system for the dynamic flood-limited and dry-line water levels, and improve the comprehensive efficiency and benefits of normal operation, drought relief emergency operation, and flood control emergency operation of the entire hydrological cycle management of the reservoir.

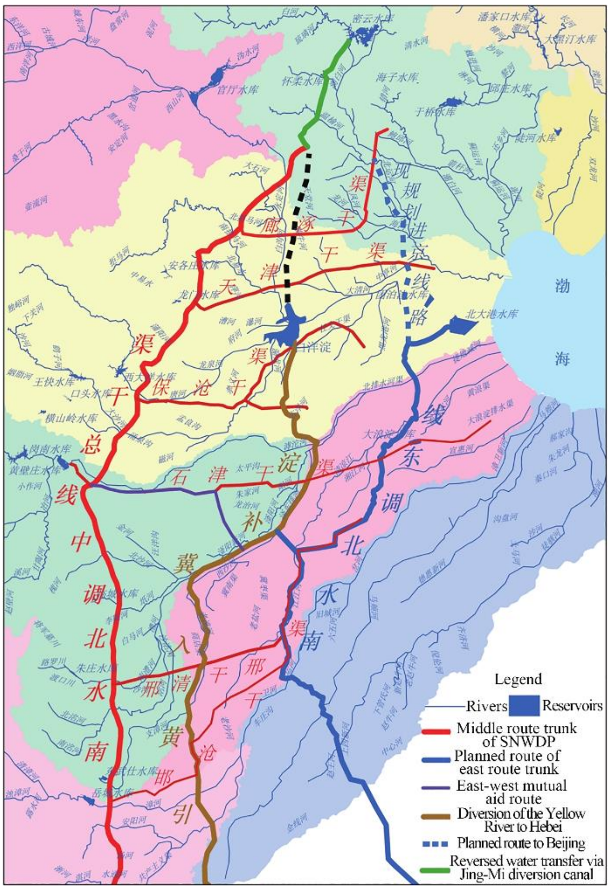

Fig. 6. Routes of the follow-up project of the eastern route of the SNWDP.

Note: The blue dotted line is the existing planned route of the eastern route, and the black dotted line is the alternative plan to enter Beijing through Baiyangdian Lake.

5.6 Coordinating normality and emergency response and improving the shortcomings of disaster prevention against severe floods in the basin

Considering the difficulties in flood forecasting in the BTH region, the low coverage of joint flood control of reservoirs, and the lag in the construction of flood storage and detention areas, it is urgent to strengthen the overall management of normal and emergency situations and improve the shortcomings of flood disaster prevention.

DOI 10.15302/J-SSCAE-2022.07.001

The first is coordinating normal and emergency situations and implementing routine response measures. In addition to providing emergency disaster relief, preventive measures should be strengthened. First, it is necessary to carry out flood control projects in important river sections, focusing on improving the flood discharge capacity of the newly built houses around the Xiong'an New Area and the flood discharge capacity of the Zhaowangxin River. Second, an integrated air–space–ground flood monitoring system can be built. Through an organic combination of high-resolution aerospace, aerial remote sensing technology, and ground hydrological monitoring technology, all-round and whole-process real-time collaborative monitoring and efficient processing of rain conditions, river and lake water conditions, engineering dangers, floods, and other disasters in the basin can be achieved. Finally, it is expected to ensure the reasonable and effective application of flood storage and detention areas and timely revision and refinement of flood storage and detention areas and emergency response plans according to changes in topography and features to ensure that floods can be "divided, stored, and withdrawn."

The second is to work on the "forecast, early warning, rehearsal, and planning" and adopt measures to handle floods that exceed the standard. First, we should improve the level of flood forecasting, conduct investigations on the underlying surface of the watershed, revise the parameters of existing forecasting models and plans, and implement rolling forecasts using real-time monitoring data to improve the accuracy of flood forecasting. In addition, we can attempt to expand the scope of flood disaster early warning services, expand and deepen the existing flood disaster early warning information services, and comprehensively expand from the industry to the public and lifeline system industries, such as transportation, energy, water supply, power supply, and communications related to the flood disaster system, to form a normalized professional early warning service mechanism. Additionally, we should improve the intelligence level of flood disaster forecasting, fully utilize digital and intelligent means, and carry out simulation previews of the storage and discharge conditions of reservoirs, river courses, and flood storage and detention areas according to the forecast of rainwater to achieve real-time dynamic updates of information on flood evolution, flood control engineering system operation, and inundation impact, and provide scientific decision support for engineering scheduling. Finally, it is important to dynamically revise the flood disaster prevention plan, implement the plan preparation method based on multi-scenario and massive plans, form a real-time correction and dynamic adjustment system for the flood plan that exceeds the standard, and fully utilize the risk map results to refine the personnel transfer plan.

6 Conclusions

Shortage of water resources is the most prominent water security problem in the BTH region. The decline in water resources intensifies the competition for water in the region. In the future, with the absorption and aggregation effect brought about by the construction of key areas, such as the Beijing Municipal Administrative Center and the Xiong'an New Area in Hebei, it is predicted that the demand for water in the economy and society will continue to rise. To cope with the contradiction between the supply and demand of water resources, it is necessary to optimize the industrial structure, improve water consumption efficiency, and continuously strengthen the management of water resources demand. However, regional water resource attenuation factors should be considered when determining the BTH water supply scale for the follow-up project of the SNWDP.

The shrinking and drying up of rivers and lakes and long-term overexploitation of groundwater are the most serious ecological problems in the BTH region. To restore important river and lake ecological functions and the overall recovery of groundwater level, this study proposed a layout for the ecological protection and restoration of rivers and lakes and the restoration goal of a "healthy groundwater level." Considering the endowment of water resources in the region, we should implement the three-water complement of "local–external transfer–regeneration" to promote the ecological recovery of rivers, lakes, and wetlands, as well as strategic measures of "water amount–level–quality" three-dimensional groundwater restoration.

Because of the prominent shortcomings of the flood control system in the BTH region and the increased risk of urban flooding, this study proposed a coordinated management strategy for normal and emergency situations. Regarding conventional countermeasures, the level of hydrological monitoring should be improved, and the scale and layout of flood storage and detention areas should be optimized and adjusted. In response to excessive floods, advanced technologies, such as digital watersheds and flood risk numerical simulations, can be applied to make early warnings, forecasts, rehearsals, and plans.

Determining the water security problem is necessary to support a national strategy for the coordinated development of the BTH region. With the implementation of the SNWDP, the comprehensive control of regional groundwater overexploitation and the implementation of river and lake ecological recovery actions have provided a rare opportunity to comprehensively improve water security. To achieve this goal while improving water security, the next step should focus on the response to the continuous decline of regional water resources, the contradiction between insufficient water resources and food production tasks, non-point source pollution caused by the rise of groundwater levels, and the excessive dependence on external water transfer for ecological restoration of rivers and lakes.

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