博士論文

Analysis of Water Quality and Purification Process Improvement for Urban Water Supply in North-Eastern China

中国東北地区の都市における水供給のための水質分析と浄化プロセスの改善に関する研究

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王 晓东

Xiaodong WANG

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Xiaodong WANG

The University of Kitakyushu
Faculty of Environmental Engineering
Department of Architecture
Gao Laboratory

Preface

This thesis research was performed at the Department of Architecture, the University of Kitakyushu. This thesis presents a comparison of water quality between the Mopanshan Reservoir and Songhuajiang River. This study has investigated the pollution source analysis and comparison of the finished water quality of the Mopanshan Reservoir and Songhuajiang River. Meanwhile, a pilot study on the enhanced conventional process and the advanced treatment in a waterwork of Harbin are proposed in this research.

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Abstract

With the continuous development of urbanization, the problem of urban water supply security in China is becoming more and more serious, even seriously affecting people's normal life. Urban water supply is an important part of urban infrastructure. It is not only the basis of urban formation, but also the basic condition to ensure the stability, development and prosperity of the city, and is inseparable from the various elements of urban economic development. Therefore, it is necessary to analyze the water quality and the distribution of pollutant sources in the water sources around the city, and put forward an effective scheme to meet the local urban development and ensure the safety of water supply. Harbin is an important city in northeast of China. Since the occurrence of the nitrobenzene pollution incident in Songhuajiang River in 2005, the water supply in its main urban area has been limited. With the development of urban economy and the continuous expansion of people's demand, the single and long-distance water supply source can not meet the urban planning requirements of Harbin. Therefore, in order to ensure the city's economic development and water supply safety, the water quality of Mopanshan Reservoir and Songhuajiang River, which are two kinds of water sources around Harbin, are analyzed comprehensively and the pollution sources are also analyzed. It is an important content of urban planning to put forward a solution.

In this paper, we compared and analyzed the water quality of Mopanshan Reservoir water and Songhuajiang River water from 2016 to 2018 based on the “Environmental Quality Standards for Surface Water” (GB3838-2002) and “Standards for drinking water quality” (GB5749-2006), so as to comprehensively understand the water quality of the two water sources in Harbin in recent years. At the same time, the characteristic pollutants of the two water sources were determined, and the distribution of the pollution sources was analyzed. The quality of the effluent after the treatment of the conventional water purification process (coagulation sedimentation filtration disinfection) of the two water sources was compared, so as to provide the basis for the subsequent response plan. In addition, based on the conventional water purification process, the operation parameters of enhanced conventional process (enhanced coagulation and enhanced filtration) and advanced water purification process mainly based on ozone-biological activated carbon (O_3-BAC) were studied through a large number of pilot scale experiments, taking Songhuajiang River water as raw water. And based on the characteristics of water quality pollution, a suitable water purification process method was proposed. Meanwhile, the water quality of joint water supply of two water sources was also preliminarily studied. This paper proposes an emergency plan for the emergency situation of water use in Harbin. In addition, we also made a preliminary engineering economic analysis on the proposed deep water purification process based on the O_3-BAC process.

The thesis consists of eight chapters and the summary of each chapter is shown as follows.

In the chapter 1, background, previous research, purposes, and configuration of the thesis are described.

In the chapter 2, the involved theories, material, research method, and process overview are presented.

In the chapter 3, we compared the water quality between the Mopanshan Reservoir and Songhuajiang River and applied WQI method to evaluate the water quality of the two drinking water sources.

In the chapter 4, the characteristic pollutants and pollution sources of the two drinking water sources are analyzed. Meanwhile, the finished water quality of the two drinking water sources are also carried out.

In the chapter 5, the enhanced conventional process in a waterworks of Harbin was researched.

In the chapter 6, we studied the advanced treatment in a waterworks of Harbin and analyzed the operating parameter of each treatment unit.

In the chapter 7, the engineering economic of the O_3/BAC process was analyzed.

In the chapter 8, the results of the thesis are summarized.

Keywords: Drinking water source, Water quality, Harbin City, Water supply security, Ozone/biological activated carbon (O_3/BAC)

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Chapter 1. Introduction

1. Introduction

1.1 Background

In the process of urban development, water plays a very important role. People's production and life are inseparable from it. It is the blood of the city, the basic needs of urban people's life, the basic guarantee of urban economic development, and the spiritual place of the city. For a city, water is not only a basic condition for production and life, but also an indispensable precious resource for ecological construction, economic construction, cultural construction and social construction. However, with the accelerating process of urbanization, the shortage of urban water resources and the harm of water pollution to the environment and ecology, as well as the problem of water quality shortage are becoming increasingly serious, which puts forward higher and more urgent requirements for the utilization of urban water resources and the protection of water environment. At the same time, the expansion of urban scale and the improvement of urban functions put forward higher requirements on water quantity, water quality, water environment, water ecology, water safety, water landscape, water culture and so on. Therefore, urban water environment planning is an important part of urban development planning, and also an important aspect of urban human settlements planning. Among them, water source plays an important role in urban development planning and ensuring the safety of urban water supply. As far as China's current development situation is concerned, the problems of water sources are mainly divided into the imbalance between water supply and urban water supply demand, and the water quality pollution of water sources.

1.1.1 Water supply and water demand

Water supply refers to the amount of water that can be provided by water conservancy projects under the given water supply conditions and considering the water demand requirements of water supply objects. It is an important link in the development of urban water supply whether the urban water supply quantity and water supply demand can be balanced [1, 2]. China is a country with serious drought and water shortage. Its total freshwater resources are 2800 billion cubic meters, accounting for 6% of the world's water resources, second only to Brazil, Russia and Canada. However, China's per capita water resources is only 2300 cubic meters, only 1/4 of the world average level. China is one of the countries with the poorest per capita water resources in the world, and there are obvious regional differences in water resources. Water resources in the north are scarce, while those in the south are relatively rich. At the same time, China is still a big agricultural country, agricultural water consumption has always accounted for a large proportion of the total water consumption. However, with the rapid development of urbanization and industry, the water consumption of various industries has not only changed greatly, but also its proportion [3, 4].

Fig. 1-1 (a) shows the changes of China's total water supply and growth rate from 2009 to 2019. As can be seen from the figure, China's total water supply reached its peak in 2013, and then with the government's governance, the growth rate of total water supply began to slow down. In recent years, the total amount of water supply in China has remained basically stable, with an average annual variation of about ±1%. In 2018, China's total water supply volume was 601.55 billion cubic meters, a year-on-year decrease of 0.46%. China's water supply market has approached saturation and entered a stable development state. In addition, according to the survey, agricultural water consumption has always been the industry with the largest water demand, often exceeding 60%. The second is industrial water, which accounts for about 20%, the third is domestic water, and the last is ecological water. As can be seen from Fig. 1-1 (b), in 2019, China's agricultural water consumption reached 367.5 billion cubic meters, accounting for 61%; industrial water consumption reached 123.7 billion cubic meters, accounting for 21%; domestic water consumption reached 87.7 billion cubic meters, accounting for 15%; and ecological water consumption reached 20.2 billion cubic meters, accounting for 3%. From the change trend of the proportion, the demand proportion of domestic water and ecological water gradually increased, while the demand proportion of industrial water decreased gradually. It can be seen that although the urban water supply and water supply demand can reach a balance, domestic water and agricultural water still occupy a large proportion. However, domestic water and agricultural water are closely related to people's life and health. Therefore, compared with the relationship between water supply quantity and water supply demand, ensuring the water quality of water supply is particularly important in ensuring the safety of urban water supply, especially the water quality of water sources.

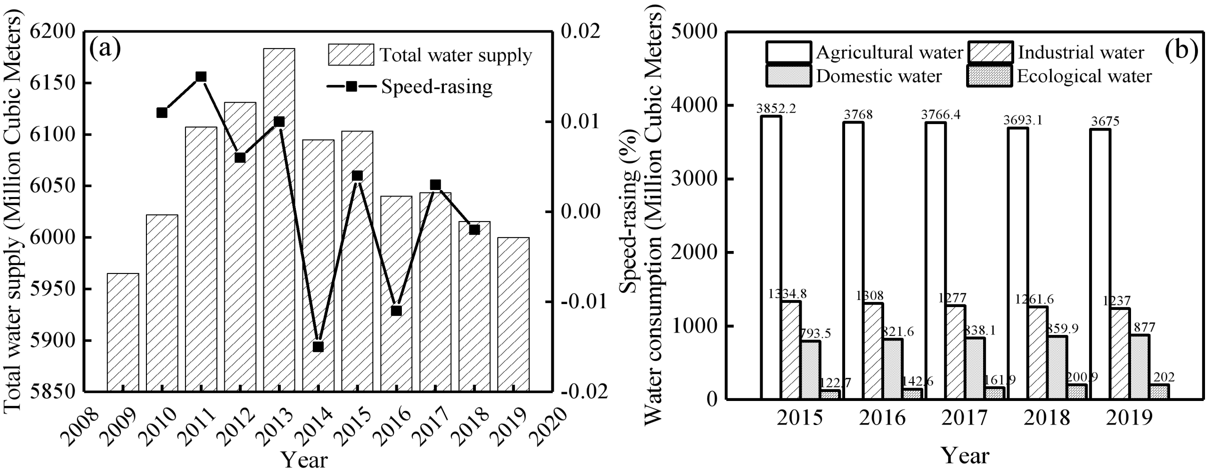

Fig. 1-1 Total water supply and water consumption of China. (a) Total water supply (b) Water consumption

1.1.2 Current situation of water supply

In recent years, with the rapid development of urban economy and society in China, the main problems faced by urban drinking water sources in China are water shortage and water pollution. Compared with the problem of water shortage, drinking water source pollution is more prominent. From the point of view of water sources, relevant reports show that one fifth of the water is below the standard [5, 6]. As a water source, the most common water forms include rivers, lakes, reservoirs and groundwater. According to the results of the national water source investigation conducted by the Environmental Protection Bureau in 1989, 48% of the surface water sources and 20% of the underground water sources could not meet the standards of drinking water sources. By 1996, the two figures had risen to 83.31% and 27.71% respectively. In 2007, the river type water sources in Hunan and Anhui Province were the most worrying, with the compliance rate of 71.40% and 3.07%; the lake reservoir type water sources in Anhui and Jiangsu Province were the worst, with the compliance rates of 60.28% and 46.70%, respectively; and the worst groundwater source was Shanxi Province, with the compliance rate of 54.16%. Through investigation and analysis, it is found that frequent natural disasters and man-made organic pollution are the main threats to the drinking water sources in China. For example, in 2012, aniline leakage from a chemical plant in Shanxi Province led to water pollution in Zhanghe River Basin, which caused serious pollution in the upstream of Yuecheng Reservoir, leading to a large area of water cut-off in Handan city. In 2013, the tailing water discharged from the local industry and mining industry in Yunnan Province was directly discharged into Xiaojiang River. The main pollutant was xanthate, which led to the emergence of "milk River" in the urban area, which seriously threatened the safety of irrigation water for the surrounding people. In addition, the landfill pit in the upstream of Miyun Reservoir in Beijing seriously threatened the water quality safety of the reservoir water source. In addition, similar water source pollution incidents occur from time to time, such as Guiyang, Guangxi, Huaihe River, Taihu Lake, Tuojiang River, Songhuajiang River and other rivers, groundwater pollution in Shandong and North China Plain, Sanmenxia reservoir, Dongguan Songmushan reservoir, Fenhe reservoir and Chongqing Qianzhangyan reservoir were polluted. It can be seen that ensuring the water quality safety of water source is very important for urban development and people's health. Therefore, it is necessary to monitor the water quality of the water source, determine the distribution of the main pollutants and pollution sources, and put forward corresponding measures in line with the development of local cities.

Harbin is located in the northernmost part of China. It is an important central city, national granary and an important manufacturing base in northeast China. At present, there are two water sources in Harbin, one is Mopanshan Reservoir located in Wuchang City, which is a lake reservoir type water source area, and the other is Songhuajiang River which passes through Harbin urban area, belonging to river type water source area. Songhuajiang River has always been an important water source in the main urban area of Harbin. However, after the nitrobenzene pollution incident occurred in 2005, the Songhuajiang River gradually withdrew from the stage as the water source of Harbin. Therefore, the municipal government decided to use Mopanshan Reservoir as the main water supply source in the main urban area. However, after more than ten years of development, Mopanshan Reservoir as a water source has gradually highlighted the following three aspects: 1) Distance. Mopanshan

Reservoir is 180 km away from the main urban area of Harbin. The water supply belongs to long-distance water transmission, and the water loss is large. 2) Once the pipe burst, the water will be cut off in the main urban area of Harbin, which seriously hinders the development of urban production and the daily life of residents. 3) Mopanshan Reservoir has the trend of eutrophication, and the water quality is getting worse year by year. With the development of Harbin City, it not only puts forward higher requirements for water supply, but also ensures the safety of water quality. Therefore, monitoring the water quality of the two water sources (Mopanshan Reservoir and Songhuajiang River) in Harbin and proposing corresponding solutions to the problems faced by the urban water sources are the top priority to solve the water supply problems in the main urban area of Harbin. In addition, due to the special geographical location of Harbin, the winter duration is as long as five months, and the ice cover period is as long as 150 days. The special climate characteristics and water environment conditions in cold regions make the water pollution problem of the basin particularly prominent. Therefore, it is of great significance for the urban development of Harbin to analyze the water quality and pollution causes of water sources in Harbin and put forward corresponding control strategies.

In this paper, the Mopanshan Reservoir and Songhuajiang water source in Harbin are taken as the main research objects. The water quality monitoring data of the two water sources in recent three years are comprehensively analyzed and deeply studied. The water quality change characteristics, characteristic pollutants and pollution causes of the two water sources are determined. In order to ensure the safety of water supply in Harbin and the healthy development of the city, an effective technological process is used to treat the water source.

1.2 Research status of water supply safety at home and abroad

Water is an irreplaceable limited natural resource that human society depends on for survival and development. Among them, drinking water is closely related to human life. Obtaining safe drinking water is the basic need for human survival, and it is related to the people's physical and mental health and normal life. With the rapid economic and social development of cities, the urban population continues to grow, the living standards of residents continue to improve, the demand for water continues to increase, and the shortage of urban water supply is becoming increasingly prominent. At the same time, due to the extensive agricultural production methods in various drinking water sources, weak rural environmental protection work, insufficient environmental supervision capabilities, environmental pollution and ecological damage are prominent, water supply quality has deteriorated and changed, and urban drinking water supply safety faces water volume and the double challenge of water quality. To solve the problem of drinking water safety management, we must first clarify the definition of drinking water safety and establish its evaluation system. The opinion generally held by scholars in the industry in China is that drinking water safety refers to convenient and timely access to sanitary, healthy and clean drinking water. The evaluation indicators are: water quality, water volume, guarantee rate, and convenience. The above indicators must meet the requirements at the same time [7, 8]. Only then can drinking water be considered safe or basically safe. The basic consensus reached so far is that water quality and water quantity are the two basic criteria for evaluating the safety of drinking water, and they are also important criteria [9, 10]. At present, in the urban areas of our country, the municipal pipe network is used for centralized water supply, so the degree of convenience does not affect the safety of drinking water. Therefore, in order to ensure the safety of water quality in drinking water sources, many domestic and foreign researchers have conducted a large number of relevant studies [11-14].

Zhu et al. [15] revealed the water supply safety of riverbank filtration wells from the comprehensive perspective of water level, quality and supply capacity of the well group. They concluded the RBF could provide turbidity, trace organic substances and major cations and anions (except for Ca^{2+} and Mg^{2+}) pre-treatment of the river water with the removal rates of 29%-95% for some water quality indicators. However, limited improvement of water quality was observed with respect to some inorganic contaminants (Fe, Mn and NH_4^+-N) because the background concentrations of them in the groundwater were higher than in the river water. When compared with the quality of the river water, the quality of RBFWs water was more stable, which made it more favorable for the design of post-treatment processes and long-term stable operation of waterworks. Shamsuzzoha et al. [16] attained the research objectives both qualitative and quantitative data were collected through household level questionnaire survey, visual observation, literature review, key informants interview (KII), sanitary inspection and laboratory analysis for water quality testing to find out the major disaster risks which have subsequent impacts on water supply system. Results showed about 54 percent of the respondents marked that increase of temperature, excessive rainfall and frequent storms are common disaster risks in the study area and around 67 percent of them mentioned that these disasters have impacts on water supply system. Li et al. [17] made use of the fuzzy comprehensive evaluation methods on the basis of fuzzy mathematics and GUI in MATLAB technology for Ji Nan urban supply system's all-round evaluation to find the potential impact factors. They found the main factors are: some pipelines are too old to be used, pipe material is aging, partial pipeline stress is too big.

1.3 Research status of water purification technology at home and abroad

Micro-polluted source water refers to water bodies that are polluted by organic matter, some of which do not meet the “Environmental Quality Standards for Surface Water” (GB3828-2002) Case III standard. The pollution degree of organic matter, ammonia nitrogen, and phosphorus in the micro-polluted water source water is relatively low, but there are many types of pollutants and the water quality is more complicated, which affects the reuse of water [18,19]. According to the nature of pollutants, the pollutants in the source water include physical pollutants, chemical pollutants and biological pollutants. Among them, physical pollutants include suspended solids, thermal pollution and radioactive pollutants. Chemical pollutants include organic compounds and inorganic compounds. Biological pollutants include viruses, bacteria, and parasites. Although the concentration of pollutants in micro-polluted water sources is generally low, the existing conventional water treatment processes have limited ability to effectively remove low-concentration organic matter, but their harm cannot be ignored. The presence of some assimilable organic substances (AOC) can cause bacteria to multiply and spread diseases. After chlorine disinfection, disinfection by-products (DBPs), such as trihalomethanes (THMs) and haloacetic acids (HAAS), are produced. These pollutants are very harmful, difficult to degrade, and have bioaccumulation and "three causes" (carcinogenic, mutagenic, Teratogenic) effect. In general, the current water quality characteristics of domestic micro-polluted water sources show the following four aspects: ① Largely affected by industrial wastewater and domestic sewage; ② A large increase in dissolved organic matter in water; ③ It is difficult to remove harmful microorganisms; ④ Endocrine disrupting substances. the removal efficiency of environmental hormones is not high [20-22]. In view of the current water quality of micro-polluted drinking water sources, domestic and foreign researchers have already begun to study new technologies for water purification, and many technologies have been applied in actual production and have achieved good results. At present, the treatment technologies that are widely used at home and abroad mainly include: enhanced coagulation, enhanced filtration, pre-oxidation technology, ozone activated carbon combined technology, biological activated carbon technology, photocatalytic oxidation, membrane advanced treatment technology, etc [23-25].

1.3.1 Enhanced coagulation

Coagulation is an effective method to remove suspended and colloidal substances in water, and it is a common treatment technology in water treatment plant [26]. Enhanced coagulation technology is to improve flocculation conditions and increase the removal rate of organic matter in conventional treatments through a certain method [27]. Zhou et al. [28] investigated the removal of polystyrene (PS) and polyethylene (PE) microplastics using PAC and $FeCl_3$ coagulation. Results showed that PAC was better than $FeCl_3$ in removal efficiency of PS and PE microplastics due to the charge neutralization. Ren et al. [29] utilized various coagulants to treat concentrated leachate of an municipal solid waste incineration. The results showed that removals of chemical oxygen demand, light absorbing substances (at 25 nm), total nitrogen, color and turbidity were 68.42%, 69.01%, 44.14%, 92.31% and 87.44% under the optimal condition. And some parts of high molecular weight compounds could be eliminated by coagulation process. Zhang et al. [30] evaluated the feasibility of integrating high-basicity polyaluminum chloride (PAC) and high-viscosity chitosan for the coagulation of low-temperature and low-turbidity water. They found that higher-basicity PAC with a larger proportion of Al_c (colloidal Al species in PAC) and smaller proportion of Al_a (monomeric Al species in PAC) was beneficial for removing turbidity and natural organic matter (NOM), as well as controlling the residual Al content. The combined coagulant exhibited an excellent coagulation performance. The similar researches could be obtained from Eskibalci et al. [31] , Ding et al. [32], Hu et al. [33], Xiao et al. [34] and so on.

Intensified coagulation usually has the following methods [35-37]：

(1) More coagulants are used to destabilize the colloid in the water, and the colloid in the water settles from the water under the adsorption of the flocs;

(2) Another flocculant is added to enhance the adsorption and bridging effect, so that the organic matter is easily absorbed by the flocs and sink, such as adding the coagulant polyacrylamide (PAM), the newly developed MR polymer flocculant, etc;

(3) Adding a new type of water treatment agent has a comprehensive effect of oxidation and coagulation, which can effectively remove organic matter in the water;

(4) Adjust the mixing and flocculation reaction time to make the agent fully play its role, that is, to improve the flocculation conditions from the hydraulic conditions;

(5) Adjust the pH value. Practice shows that when there are a lot of organic matter, the effect of pH value 5~6 is better.

Intensified coagulation requires more coagulant or other agents, which will inevitably cause the increase of agent costs and sludge treatment costs.

1.3.2 Enhanced filtration

Filtration is a process in which solid pollutants in water can be separated from water by the interception capacity of medium [38]. It is also an essential treatment method in water purification process. The enhanced filtration technology is to cultivate microorganisms on the surface of the filter material without pre-chlorination, and use the physiological activities of microorganisms to remove organic matter in the water. Enhanced filtration means that the filter material can not only reduce turbidity, but also degrade organic matter, ammonia nitrogen and nitrite nitrogen. However, there are greater difficulties in the operation and management of this technology [39]. For example, it is necessary to control the intensity of backwashing, which can not only flush away the accumulated mud, but also maintain a certain biofilm. It is necessary to control the micro-environment of the filter to facilitate the growth of microorganisms. In addition, researchers have modified the surface of the filter material to improve the removal of pollutants in the filter.

Li et al. [40] investigated the filtration performance of multi-fiber filters by computational fluid dynamics simulating. Results indicated that filtration efficiency changed with the face velocity for different particle sizes. Marais et al. [41] compared the NOM removal efficiency by granular activated carbon (GAC) filtration, an ultrafiltration membrane and conventional water treatment plant. The results indicated that the conventional water treatment processes (coagulation, sedimentation and sand filtration) removed 61% and 24% NOM as indicated by UV_{254} and dissolved organic carbon (DOC) removal, respectively. A respective reduction of 73% and 25% of UV_{254} and DOC was achieved by ultrafiltration. And the GAC filter column (preceded by a sand filter column) achieved UV_{254} removal of 86% and DOC removal of 28%. The performance and the capacity of the activated carbon filtration in the natural organic matter removal were studied by Matilainen et al. [42]. They found that regeneration of the carbon improved the removal capacity considerably, but efficiency was returned to a normal level after few months. There was about 95% of the NOM was eliminated from the raw water. A detailed comparison of sand filtration (SF) and ultrafiltration (UF) was conducted by Xu et al. [43]. The results showed that SF conferred a slightly higher removal rate for UV-absorbing compounds, humic-like substances and protein-like substances than UF, with removal efficiencies of 21.9%, 19.8% and 26.1%. However, UF process achieved significantly higher removal of algae cells (98.7%) than SF due to size exclusion. Zheng et al. [44] also carried out a similar research.

1.3.3 Preoxidation

Pre-oxidation technology refers to adding a strong oxidant to raw water, using the oxidizing power of the oxidant to oxidize and decompose organic pollutants in the water, and improve the effect of coagulation and precipitation [45, 46]. Commonly used oxidants are chlorine, ozone, potassium permanganate and chlorine dioxide. Chlorine is the most commonly used oxidant in water plants, but because organic pollutants in water can react with chlorine to produce trihalomethanes (THMs), pre-chlorination to treat micro-polluted water sources has caused concerns [47]. Ozone (O_3) oxidation is a method that has received widespread attention in water treatment due to chlorine disinfection by-products have lethal harm to the human body. The ozone oxidation method does not produce harmful halogenated compounds like pre-chlorination, nor will it remain in the water. Because ozone has a strong oxidizing ability, it can change the nature of the pollutants by destroying the molecular structure of organic pollutants. Ozone is the most widely used new oxidant. It can improve the biochemical properties of organic matter in water, help improve the flocculation effect, and reduce the dosage of coagulant. However, studies have shown that if the water contains a higher concentration of bromide ions, ozone will interact with it to produce bromate, which is more toxic. After the water containing organic matter is treated with O_3, it is possible to decompose macromolecular organic matter into small molecular organic matter. Among these intermediate products, mutagenic substances may also exist. When the amount of O_3 is limited, it is impossible to remove the ammonia nitrogen in the water, because when the organic nitrogen content in the water is high, O_3 oxidizes the organic nitrogen into ammonia nitrogen, causing the ammonia nitrogen content in the water to increase instead. In addition, O_3 is poorly oxidizing to some common priority pollutants in water such as chloroform, carbon tetrachloride, polychlorinated biphenyls, etc., and easily generates glycerin, complexed ferricyanide, acetic acid, etc., resulting in the accumulation of incomplete oxidation products [48-50]. Potassium permanganate has a good effect on removing organic pollutants in water, and can significantly reduce the mutagenicity of water. It has been used in the production test of treating micro-polluted water sources. Pre-oxidation of potassium permanganate can control the generation of chlorophenol and THMS, and has a certain color, smell and taste removal effect. It also has a good removal ability for olefins, aldehydes and ketones. However, some of the products after oxidation by potassium permanganate are precursors of base substitution mutants, which are not easily removed by subsequent processes. When the dosage of Cl_2 is high, the precursors are transformed into mutagenic substances, which increase the mutagenic activity of the effluent [51, 52]. Chlorine dioxide (ClO_2) can effectively destroy algae and phenol, and improve the color, smell and taste of water. Chlorine dioxide is an oxidizing agent, not a chlorinating agent. It will not react with organic matter in the water like Cl_2 to produce halogenated organic compounds that are harmful to humans and cause cancer. Studies have suggested that even the oxidation of ClO_2 itself can remove THMS precursors. However, due to incomplete oxidation, some small molecular organic compounds are more likely to generate trihalomethanes [53-55]. Although chemical oxidants have a good effect on removing pollutants in water, the expensive operating costs and the formation of toxic by-products are always the limiting factors for their promotion and application.

Nakada et al. [56] assessed the occurrence of Giardia cysts in raw water, and in chlorinated or ozonated water from a drinking water treatment plant (DWTP) in Brazil, over a 16-month period. They found Giardia non-viable cysts were detected more frequently in ozonated water (80%) than in chlorinated water (68.2%) or raw water (37.7%). Ozonation and chlorination resulted, respectively, in ≈27.5- and ≈13- fold reduction of Giardia infection risk, when compared to the risk calculated for raw water. Ozonation has proven more efficient than chlorination against Giardia cysts in surface water. Laszakovits and MacKay [57] investigated the removal of cyanotoxins by potassium permanganate with a focus on incorporating competition by cyanobacterial cells and dissolved organic matter (DOM). The work showed that permanganate could efficiently remove microcystins on a treatment-relevant time scale. For most bloom conditions, potassium permanganate treatment (1 mg/L) alone will be sufficient to reduce microcystin concentrations (around 10 ppb) below state regulated standards (1.6 ppb). A treatment plant for lake Kinneret water, comprising treatment by two filtration steps, flocculation and disinfection with chlorine dioxide, was studied by Limoni and Teltsch [58] with a view to evaluating the effect of ClO_2 disinfection on drinking water quality and determining the optimal mode of operation for the treatment plant. The finished water contained a residue of approx. 0.2 mg/L ClO_2, approx. 0.35 mg/L ClO_2^- and low concentrations of suspended matter (1.5 mg/L) and of chlorophyll (0.1 μg/L). Trihalomethane concentrations were negligible, and the bacteriological quality of the water was within the health authorities' requirements. It was shown that disinfection of treated water (after flocculation and filtration) was much more effective than that of raw water. Furthermore, disinfection in the optimal mode prevents accumulation of high chlorite concentrations leaving a residue of ClO_2.

1.3.4 Ozone-activated carbon advanced treatment process

Ozone activated carbon method is commonly used at the end of the process for deep removal of pollutants in water. The treated water quality is stable and the water quality standard rate is high. In particular, ozone can not only destroy the structure of dissolved organic matter in water, improve its biological assimilation, but also improve the adsorption and biological treatment effect of activated carbon filter, and prolong the regeneration cycle of activated carbon. At the same time, ozone has the function of decolorization and sterilization. Therefore, ozone activated carbon technology is gradually favored by researchers [59-61]. At present, the activated carbon used in domestic water treatment can effectively remove small molecular organics. But it is difficult to remove large molecular organics, and the organic molecules in the water are much larger. Thus, the surface area of the activated carbon pores will not be fully utilized, which will inevitably accelerate the saturation and shorten the water production cycle. After adding ozone in front of the carbon or in the carbon layer, on the one hand, the macromolecules in the water can be converted into small molecules, and the molecular structure and form of the molecules can be changed, which provides the possibility of organic matter entering the smaller pores. The organic matter on the surface of the carbon is oxidized and decomposed, which reduces the burden of the activated carbon, so that the activated carbon can fully absorb the unoxidized organic matter, so as to achieve the purpose of deep water purification. This method can give full play to the advantages of both and has been widely used at home and abroad.

Guillossou et al. [62] studied the removal of 28 organic micropollutants (OMPs) present in a real wastewater effluent by ozonation coupled to activated carbon adsorption and compared to a sole adsorption. They found the OMPs removal increased with both the specific ozone dose and the powdered activated carbon dose. Wang et al. [63] carried out an advanced treatment of bio-treated dyeing and finishing wastewater (BDFW) using ozone-biological activated carbon (O_3-BAC). They found that O_3-BAC could synergistically degrade the dissolved organic carbon (43.0%), chemical oxygen demand (45.8%), color (73.0%), and specific UV absorbance ($SUVA_{254}$) (29.7%) of BDFW. Removal of sulfonamides (SAs) by an integrated O_3-BAC process was evaluated in a pilot-scale study by Li et al. [64]. Results indicated that ozonation could effectively remove SAs from water at an appropriate ozone dose with an improvement of water quality and result in an increase of disinfection byproducts formation potential (DBPsFP). However, the BAC filtration would lead to an increase of sulfonamide-resistant bacteria and effectively reduce DBPsFP to the safety-standard level of water quality. Kosaka et al. [65] applied ozone/biological activated carbon treatment to remove haloacetamides and their precursors (HAcAm-FPs) at water purification plants. The results showed that removal of total HAcAm-FPs during advanced water purification processes ranged from 50% to 75%. Gerrity et al. [66] carried out a pilot-scale evaluation of O_3-BAC process for trace organic contaminant mitigation and disinfection. Results showed that the ozone/H_2O_2 and BAC processes were extremely effective in reducing the concentrations of a suite of trace organic contaminants after five months of continuous pilot-scale testing. Nishijima et al. [67] investigated the performance of an O_3-BAC process under long term operation. They proved that the removal of DOC and THMFP could maintain at 36% and 57% after operation for 910 days. Kim et al. [68] carried out a pilot plant study on O_3-BAC process for drinking water treatment. The results showed that biodegradable DOC increased by 20% after ozonation in O_3-BAC and was removed effectively by the attached bacteria on the activated carbon after 8 months of operation. Furthermore, Kato et al. [69], Knopp et al. [70], Lee et al. [71], Reungoat et al. [72], and Chu et al. [73] all reported the preferable removal efficiency of the O_3-BAC process.

1.3.5 Biological Activated Carbon

Biological activated carbon (BAC) technology relies on the good adsorption performance of activated carbon, cultivates microorganisms on the surface of activated carbon, and uses the biodegradation of microorganisms to achieve the purpose of removing organic pollutants. Activated carbon is a good carrier for the growth of microorganisms, and the microorganisms on the activated carbon will play a positive role in improving the water treatment effect, especially prolonging the life of the activated carbon [74-76]. Therefore, activated carbon is not only used as an adsorbent for water treatment, but can also use the synergistic effect of activated carbon adsorption and microbial degradation to achieve good economic results. The premise of the biological activated carbon method is to avoid pre-chlorination, otherwise it will be difficult for microorganisms to grow on activated carbon. This technology uses the oxidation of microorganisms to increase the removal rate of organic matter, prolong the operation cycle of activated carbon, and reduce operating costs. However, the microorganisms on the activated carbon will fall off under the action of water flow, affecting the quality of the effluent, so it is usually in the biological activated carbon filter. After adding sand filter or precision filter to ensure the water quality.

Meng et al., [77] reported that aeration could be used to enhance the removal of long-chain PFAAs during AC treatments of drinking water at environmentally. They found aeration during AC treatment of water could enhance the removal of long-chain PFAAs, and improve the performance of AC during water treatment. Piai et al. [78] performed experiments at 5 °C and 20 °C with biologically active and autoclaved GAC to assess the biodegradation of ten micropollutants by the biofilm grown on the GAC surface. They have shown that temperature is positively correlated to adsorption of iopromide, iopamidol, diclofenac and hexamethylenetetramine, but negatively correlated to adsorption of desphenyl-chloridazon, guanylurea, melamine and metformin. Meanwhile, they could also demonstrate that the adsorption capacity of GAC used for more than 100,000 bed volumes is comparable to adsorption of fresh GAC for diclofenac and benzotriazole and higher for guanylurea, metformin and hexamethylenetetramine. Zheng et al. [79] applied high-throughput qPCR and sequencing to investigate the dynamics of ARGs and bacterial communities during the advanced treatment of drinking water using biological activated carbon. The promotion of ARGs was observed, and the normalized copy number of ARGs increased significantly after BAC treatment, raising the number of detected ARGs from 84 to 159. Additionally, Twenty-nine ARGs were identified as biofilm-influencing sources in the BAC, and they persisted after chlorination. Lou et al. [80] focused on reducing the concentration of assimilable organic carbon (AOC) in treated drinking water. Experiments were conducted to evaluate the efficiency of AOC removal by biological activated carbon filters (BACF) in a pilot-scale system. The results showed that BACF reduced the total concentration of AOC. The concentration of AOC primarily indicated microorganism growth in a water supply network, and the amount of AOC in water was significantly reduced after BACF treatment. Li et al. [81] investigated the 17β-estradiol (E2) and estrone (E1) adsorption characteristics on GAC and evaluated the removal and E2 and E1 in a continuously operated GAC reactor, which was later converted to a BAC reactor. Under optimal operating conditions, the BAC reactor had an effluent E2 concentration of ~ 50 ng/L. With the empty bed contact times tested, the reactor exhibited more robust E2 removal performance under the BAC operation than under the GAC operation.

1.3.6 Photochemical oxidation

The photochemical oxidation method is a water treatment technology that makes the oxidation reaction rate and oxidation capacity significantly higher than that of chemical oxidation and radiation under the combined action of chemical oxidation and light radiation. All photooxidation methods use ultraviolet light as the radiation source, and at the same time, a certain amount of oxidant such as hydrogen peroxide, ozone or some catalysts such as dyes and humus must be put into the water in advance. It has an excellent removal effect on difficult-to-degrade and toxic small-molecule organics. The photooxidation reaction produces many highly active free radicals in the water, which can easily destroy the structure of organics. It belongs to photochemical oxidation methods such as photo-sensitized oxidation, photo-activated oxidation, photo-catalytic oxidation and so on [82, 83].

The light-excited oxidation method uses ozone, hydrogen peroxide, oxygen and air as oxidants, and combines the oxidation effect of the oxidants with photochemical radiation to generate free radicals with strong oxidizing ability. Ultraviolet-ozone combined technology can oxidize organic matter in micro-polluted water that can not be oxidized by ozone, such as chloroform, hexachlorobenzene, carbon tetrachloride, and benzene, turning them into CO_2 and H_2O, reducing the mutagenic activity in water. Its oxidation effect is better than using UV and O_3 alone. However, the ability of UV-ozone process to remove organic matter or THMs needs to be further explored. The process cost is relatively high, and it is not easy to popularize and apply.

The photocatalytic oxidation method is to add a certain amount of semiconductor catalyst to the water. It can also generate strong oxidizing free radicals under ultraviolet radiation, which can oxidize organic matter in the water. The commonly used catalyst is TiO_2. The strong oxidizing property of the method, the non-selectivity to the target and the characteristics of complete mineralization of organic matter in the end make the photocatalytic oxidation have a better application prospect in the advanced treatment of drinking water. However, the TiO_2 powder has fine particles and is inconvenient to recycle. Compared with the traditional water purification process, the photocatalytic oxidation treatment has a higher cost and complex equipment, and its promotion and use in the near future are restricted. The main problems that need to be solved when photocatalytic oxidation is put into practical application are to determine the catalyst poisoning during long-term operation and seek the ideal regeneration method; solve the separation, recovery or immobilization of the catalyst; the design of the reactor and the improvement of the utilization rate of light energy. Therefore, the photocatalytic oxidation method is rarely used in large-scale actual water plants. However, it is foreseeable that with the continuous deepening of research, photocatalytic oxidation will certainly receive more and more attention [84].

The main research object of photosensitized degradation is the petroleum pollutant linear alkanes in the water environment. The sensitizer can extract hydrogen atoms from the carbon atoms of linear alkanes to generate hydroxyl groups, which are degraded into ketones, alkenes, aldehydes, alcohols, etc. under the action of oxygen. These compounds are more easily degraded by microorganisms in the water environment than alkanes. The commonly used sensitizer for photosensitization degradation is anthraquinone.

Comparison of O_3-BAC, UV/H_2O_2-BAC, and O_3/H_2O_2-BAC treatments for limiting the formation of disinfection byproducts during drinking water treatment in India was investigated by Tak and Vellanki. [85]. The results indicated that AOP-BAC treatment was more effective in degrading precursors to THMs in highly anthropogenically influenced waters than treatment by only AOP or BAC, with O_3/H_2O_2 -BAC treatment being the most effective. The efficiency of elimination of organic UV filters by ozonation and UV_{254}nm/H_2O_2 processes was assessed and predicted in simulated treatments of sewage-impaired drinking water and wastewater effluent in bench-scale experiments by Seo et al. [86]. They mentioned that the elimination of the UV filters by the UV_{254}/H_2O_2 treatment was controlled by radical ·OH, with a marginal contribution by the UV photolysis. Graumans et al., [87] studied the effect of advanced oxidation on the cytostatic drug cyclophosphamide (CP) by comparing thermal plasma activation with UV/H_2O_2 treatment. They found the oxidative degradation of CP in PAW resulted in a complete degradation within 80 min at 150 W, while CP was also completely degraded within 60 min applying UV/H_2O_2 oxidation. Advanced oxidation process UV/H_2O_2 was evaluated by Rozas et al., [88] as an alternative treatment for the founded Organic micropollutants. Results indicated that 80% of DCL and TCS oxidation was achieved with a UV dose below 200 $mJ \cdot cm^{-2}$. For ATZ and CBZ de 80% degradation was achieved at a UV dose around 740 and 990 $mJ \cdot cm^{-2}$, respectively. CBZ was not affected by direct photolysis and the main oxidation mechanism was driven by hydroxyl radical. Yin and Shang [89] investigated the removal of three selected micropollutants (i.e., bisphenol A, diclofenac and caffeine) in drinking water using the UV-LED/chlorine advanced oxidation process (AOP) followed by activated carbon adsorption. They found the degradation of bisphenol A, diclofenac and caffeine was predominantly contributed by chlorination (>60%), direct UV photolysis (>80%) and radical oxidation (>90%), respectively, during the treatment by the UV-LED/chlorine AOP at three tested UV wavelengths (i.e., 265, 285 and 300 nm).

The photochemical oxidation method is still in the development stage. Due to the high operating cost, it is difficult to apply it in large-scale production. However, the technology is developing rapidly, and its application in production will not be far away.

1.3.7 Membrane treatment

Membrane separation method is an emerging high separation, concentration, purification and purification technology. It uses natural or synthetic polymer membrane as a medium, and uses external energy or chemical potential as the driving force to filter two-component or multi-component solutions. Physical treatment methods for separation, fractionation, purification and enrichment. Membrane separation technology is a new and high-efficiency separation technology. It has the characteristics of no phase change of substances, large separation coefficient, operation at room temperature, wide application range, chemical saving, simple device and convenient operation. In recent years, the membrane method has been recommended by the U.S. Environmental Protection Agency (EPA) as one of the best processes in the United States, while Japan has adopted membrane technology as the base technology for the 21st century, and implemented the national key project "21st Century Water Treatment Membrane Research (MAC21)" , specially developed membrane water purification system. Common membrane methods include: microfiltration, ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, pervaporation, liquid membrane and nanofiltration technology that just appeared. From the perspective of the function of membrane filtration, reverse osmosis can effectively remove pesticides, surfactants, disinfection by-products, THMs, humic acid and chroma in water. Nanofiltration membranes are used for the removal of organic substances with a molecular weight in the range of 300-1000. Ultrafiltration and microfiltration membranes can remove humic acid and other large molecular weight (greater than 1000) organic matter. Therefore, membrane filtration technology is an effective way to solve the poor quality of drinking water [90, 91].

Bu et al., [92] built a dynamic C-UF set-up to carry out the treatment of micro-polluted surface water, to investigate the characteristics of dissolved organic matter from different units. The influences of poly aluminum chloride and poly dimethyldiallylammonium chloride (PDMDAAC) on removal efficiency and membrane fouling were also investigated. Results showed that the dosage of PDMDAAC evidently increased the UV_{254} and dissolved organic carbon removal efficiencies, and thereby alleviated membrane fouling in the C-UF process. The performance of a pilot-scale PAC-MBR under intermittent aeration and short SRTs (2, 4, 6, and 8 d) was investigated by Shao et al. [93]. It was found that intermittent aeration allowed enough sludge to be kept in suspension, and to provide enough oxygen for the PAC-MBR, and consequently did not have a dramatically negative effect on the pollutants removal efficiency of the PAC-MBR. Chu et al. [94] investigated the pollutant removal mechanisms for micro-polluted surface water purification in a BDDM reactor using a gravity filtration mode to drive the BDDM filtration. They found that Bacteroidetes, Firmicutes, Proteobacteria (e.g. α-, β-, γ-proteobacteria), Verrucomicrobia, and Nitrospirae were dominant in the bio-diatomite mixed liquor and removed organic matter and ammonium nitrogen. Yu et al. [95] evaluated the use of pulsed-UVC light, applied within an ultrafiltration membrane module, together with coagulation, as a method to control membrane fouling. They obtained UVC light with enough contact time and intensity in the membrane tank could prevent measurable membrane fouling over an operational period of 32 days. Under less favorable conditions (lower UVC intensity and higher flux), the combination of UV irradiation and coagulation was still able to mitigate membrane fouling compared to the conventional pre-treatment.

The membrane method can remove macromolecular organic substances such as colloids, particles, bacteria and humic acid in water, but is almost ineffective for low molecular weight oxygenated organic substances such as acetone, phenols, acids, and propionic acid. The barriers to further application of membrane technology to water treatment are: high capital investment and operating costs, prone to clogging, the need for high-level pretreatment and regular chemical cleaning, and the problem of concentrate disposal. However, with the improvement of cleaning methods, the improvement of membrane clogging and membrane fouling, and the reduction of various membrane prices, it is believed that in the near future, the membrane method will definitely have a significant impact in the field of water supply and drainage. At present, many universities and scientific research institutes in China have conducted a lot of research on membrane separation water treatment technology. Some researchers believe that it will become the core technology of the fourth generation of water treatment technology and has broad application prospects. However, the process still lacks mature operating experience and management experience, and large-scale engineering application still needs time [96].

1.3.8 Comprehensive assessment

In general, physical and chemical methods are more efficient. In particular, the development of various combined technologies is very effective in the removal of some refractory organic matter. Through efficient oxidation, most of the organic matter in the water is removed, and the mutagenic activity of drinking water is effectively reduced. However, these methods and equipment are relatively complex and require high operating and operating conditions. In particular, cost issues have severely restricted their popularization and use. Comprehensive comparison of these types of micro-polluted water treatment technologies: enhanced coagulation and enhanced filtration are currently the most economical and effective methods, but their effects have certain limitations; activated carbon adsorption method is effective when used alone, but the processing cost is expensive, and other when the methods are used in combination, not only the effect is good, but also the life cycle of activated carbon can be prolonged. The photocatalytic oxidation method and the membrane method have good effects, but the cost is higher. Therefore, researching new water purification processes and adding new treatment measures are issues that are urgently needed for water supply researchers and water plants. In summary, the ozone-activated carbon combined technology has high applicability, and the process is mature and stable in operation. If the process is changed to ozone oxidation-biological activated carbon technology, while inheriting the advantages of the former. It can make water better, and resulting in ammonia nitrogen is converted into nitrate nitrogen, thereby reducing the amount of chlorine used after chlorination, reducing the generation of trihalomethanes, and improving the safety of drinking water.

1.4 Research on the application of O_3/BAC process at home and abroad

The first combined use of ozone oxidation and biological activated carbon (O_3/BAC) was started in the Amstaad water plant in Dusseldorf, Germany in 1961. Its success has attracted the attention of the water treatment engineering community in Germany and Western Europe. Since the 1970s, large-scale research and application of O_3/BAC water treatment process have been carried out. The more important ones are the production of Aufdem Werder in Bremen, West Germany and the pilot and production scale of the Dohne water plant in Mulheim. Applications. Germany's successful experience has gradually spread and developed in neighboring countries, and has been continuously improved. The representative ones are the Lengg water plant in Switzerland and the Rouen La Chapella water plant in France [97-99].

Ozone oxidation-biological activated carbon combined technology was introduced to China in the 1970s, and the technology began to be applied in the 1980s. The following is a preliminary investigation and survey of domestic water supply companies that use the O_3/BAC process. The main contents are as follows.

1.4.1 Meilin waterworks in Shenzhen

Shenzhen Water (Group) Co., Ltd. Meilin Water Plant is currently the largest water supply plant in Shenzhen with more advanced technology, with a daily water supply capacity of 600,000 m^3. The raw water is taken from Dongjiang, including Dongshen raw water and eastern raw water.

The main treatment process of Meilin Water Plant is:

Raw water—pre-ozone—conventional treatment—middle lift pump house—main ozone—activated carbon filter—disinfection—factory.

The main parameters of activated carbon filter are as follows:

Activated carbon pool type adopts air-water backwashing "V" type filter, a total of 24, single-cell filtration area is 96 m^2, contact time 11.3 min, filtration rate 10.9 m/h. The filter material is coal granular activated carbon, the carbon layer is 1.85 m thick, and there is a 0.05 m thick pebble supporting layer (2-4 mm).

The average backwash cycle of the filter is 48 h, and the backwash method is a three-stage air-water combined backwash. The backwash intensity is: air wash intensity 49.6 m/h, water wash intensity 28.8 m/h.

1.4.2 Bijiashan waterworks in Shenzhen

The daily treatment capacity of Bijiashan Water Plant is 520,000 m^3, and the raw water is taken from Dongjiang River, of which the water treatment capacity using advanced treatment is 260,000 m^3/d. Trial operation in March 2006, after nearly half a year of debugging, it is now in normal operation.

The main treatment process of Bijiashan Water Plant is:

Raw water—pre-ozone—conventional treatment—middle lift pump house—main ozone—activated carbon filter—disinfection—factory.

The main parameters of activated carbon filter are as follows:

The activated carbon pool type adopts the flap filter pool type, with a total of 8 seats, a single-cell filtration area of 140 m^2, and a design filtration rate of 8 m/h. The carbon layer is 2.0 m thick, with a 0.3 m thick (effective particle size 0.6~1.2 mm) homogeneous quartz sand layer underneath, and a 0.45 m thick pebble supporting layer at the bottom.

The flap valve of the flap filter is its core equipment, which is imported from the Swiss Wabag company.

The filter backwash cycle is 72 h, the backwash method is two-stage air-water backwash, and the backwash time is divided into 3 stages, namely: separate air flush (lasting 2~3 min) + separate water flushing (lasting 2~3 min)+ Quiet (1~2 min) + open the flap valve to drain water. The backwash intensity is: air wash intensity 55~57 m/h, water wash intensity 25~29 m/h, the water distribution system adopts the conventional small resistance water distribution system.

1.4.3 Nanzhou waterworks in Guangzhou

Guangzhou Nanzhou Water Plant is currently the largest advanced treatment water plant in China, with a daily processing capacity of 1 million m^3. The raw water is taken from the Shunde waterway. The advanced treatment adopts ozone-biological activated carbon advanced treatment technology. It was officially put into operation in September 2004.

The main treatment process of Nanzhou Water Plant is:

Raw water—pre-ozone—conventional treatment—middle lift pump house—main ozone—activated carbon filter—disinfection—factory.

The main parameters of activated carbon filter are as follows:

The activated carbon pool type adopts the "V" filter pool type, with a total of 48 seats. The single-cell filtration area is 91 m^2, the contact time is 12 min, and the filtration rate is 10.5 m/h. The filter material is coal-based granular activated carbon, the carbon layer is 2.0 m thick, and there is a 0.3 m thick (effective particle size 0.95~1.35 mm) homogeneous quartz sand layer underneath. The bottom is a 0.06 m thick pebble support layer (2-4 mm).

The average backwash cycle of the filter tank is 3~5 d. The backwash method is air-water backwash. The backwash time is divided into 3 stages, namely: separate air washing (lasting 3 min) + small water washing (lasting 1 min) + large water washing (lasting 3.5 min) + small water wash (lasted 1 min).

Backwash intensity: air wash intensity 45-50 m/h, small wash intensity 14.4-18 m/h, large wash intensity 21.6-25.2 m/h.

1.4.4 Yangshupu waterworks in Shanghai

Shanghai Yangshupu Water Plant is a water plant under the Shanghai Municipal North Water Supply Company. The plant currently has a daily processing capacity of 1.48 million m^3. The raw water is taken from the Huangpu River and the Yangtze River. At present, the plant is using a French government loan to build an advanced water purification system with a water treatment scale of 360,000 m^3/d.

The main processing flow of the new system of Yangshupu Water Plant is:

Raw water—pre-ozone—conventional treatment (mechanical mixing + high-density clarification tank + "V" filter tank)—middle lifting pump house—main ozone—activated carbon filter—disinfection—factory

The main parameters of activated carbon filter are as follows:

The activated carbon pool type is an ordinary fast filter with a design filter speed of 9.9 m/h. The activated carbon filter material is crushed carbon. The designed thickness of the carbon layer is 2 m, and the effective particle size is 0.65~0.75 mm. There is no supporting layer at the bottom of the activated carbon. The top of the activated carbon layer is 1.0 m from the top of the filter backwashing (inlet) tank weir.

The filter tank is designed to have a backwashing cycle of 24 h, and the backwashing method is two-stage air-water backwashing, that is: first air washing, then water washing. Backwash intensity: air wash intensity 55 m/h, water wash intensity 25 m/h.

1.4.5 Shijiu waterworks in Jiaxing

Jiaxing Shijiuyang Water Plant is currently the largest water supply plant in Jiaxing City. The raw water is taken from the Beijing-Hangzhou Grand Canal. The original conventional treatment scale of the plant is 170,000 m^3/d, and the total treatment capacity is 250,000 m^3/d after advanced treatment transformation and new system expansion.

The water plant includes new and old systems. The old system has a designed daily processing capacity of 170,000 m^3/d. The new system has a designed daily processing capacity of 80,000 m^3/d, and was completed in July 2005 for water supply.

1) The main treatment process of the old system of Shijiuyang Water Plant is:

Raw water-biological contact oxidation-conventional treatment-intermediate lifting pump house-main ozone-activated carbon filter-disinfection-delivery.

The main parameters of activated carbon filter are as follows:

The activated carbon pool type adopts the "V" filter pool type, with a total of 7 units, with a single-cell filtration area of 98 m^2 and a filtration rate of 10.3 m/h. Backwash intensity: air wash intensity 50 m/h, water wash intensity 20~25 m/h.

2) The main treatment process of the new system of Shijiuyang Water Plant is:

Raw water—pretreatment—conventional treatment—middle lift pump house—main ozone—activated carbon filter—disinfection—factory.

The new system filter of Shijiuyang Water Plant uses a flap filter type with a double-layer filter material of quartz sand and activated carbon.

The main parameters of activated carbon filter are as follows:

The sand filter and activated carbon filter of the new system adopt a joint construction method. Both the sand filter and the carbon filter adopt the flap filter type, and the water and air distribution system adopts a bread-shaped water and air distribution pipe (commonly known as a bread pipe), which is directly fixed to the bottom plate, with a water distribution and air pipe gallery in the middle. The filtration area of the single-cell activated carbon pool is 96 m^2. Backwashing method is air-water backwashing.

1.4.6 Deep purification water plant of Qianguo Refinery in Jilin Province

The raw water treatment plant of Qianguo Oil Refinery in Songyuan City, Jilin Province serves a total equivalent population of 50,000 people and a total treatment capacity of 10,000 m^3/d. Traditional treatment techniques cannot effectively treat the contaminated Nenjiang water source. Therefore, the design of the deep purification of the filtered water after the conventional treatment was completed in May 1995, and it was completed in October 1995 and put into operation immediately. The operation of the deep water purification plant is stable, and the purification efficiency is high, and the effluent water quality is in full compliance with the national drinking water hygiene standards.

The main treatment process flow of Qianguo Refinery Deep Purification Water Plant is:

Raw water—conventional process—intermediate pool—lift pump house—first-level ozone contact tower—second-level ozone contact tower—upflow type biological activated carbon filter tank—downflow type wooden fish stone/quartz sand filter tank—disinfection—factory.

The main parameters are as follows:

The ozone contact reaction tower adopts a two-stage series connection. The first-stage contact tower has a diameter of 2.4 m and a height of 8.22 m. The second stage has a diameter of 2.4 m and a height of 7.77 m. The middle is filled with polyethylene polyhedral hollow spheres with a diameter of 50 mm. The height is 4.0 m, and the bottom of the tower is equipped with a disc-shaped microporous titanium plate diffuser. The contact time of the secondary contact tower is 12 min, and the ozone dosage is 3 mg/L.

There are 4 biological activated carbon filter tanks, operating in parallel. The diameter of the tank is 3.6 m and the height is 8.26 m. It is equipped with domestic granular activated carbon (ZJ215), the filling height is 3.3 m, the specific surface area is 945 m^2/g, and the upward flow rate is 10 m/h. 20 min contact time, aeration pipe installed at the bottom.

There are 4 downflow wooden fish stone/quartz sand filter tanks, which can be backwashed automatically. The diameter of the tank is 4.0 m, the height is 4.54 m, the grain size of Muyu stone is 1.2~2.2 mm, and the filling height is 0.9 m. The supporting layer is 0.3 m high quartz sand (1~1.5 mm).

These successful examples all illustrate from a certain perspective that this joint technology has its unique advantages, which are manifested in the following aspects:

(1) Can effectively remove dissolved organic matter;

(2) Ozone can increase the adsorption capacity of biological activated carbon and prolong the service life of activated carbon;

(3) The amount of ammonia nitrogen is reduced by biological conversion, which reduces the formation of organic chlorides during chlorination at the later breaking point;

(4) The total amount of ozone used is less than when used alone, which is cheaper and more effective than using ozone or activated carbon alone;

(5) After treatment, the water quality can be comprehensively improved, and the effluent is stable and management is convenient. Just add a small amount of disinfectant to ensure the complete sanitation of the entire water distribution system.

Domestic and foreign scientists' research on ozone oxidation-biological activated carbon technology and the increasing number of engineering applications of this process all show that it has received attention and attention. Therefore, water treatment experts predict that with the increasing pollution of drinking water sources and the improvement of drinking water quality standards, O_3/BAC technology will become a common treatment method commonly used in drinking water purification plants.

1.5 Drinking water treatment process

1.5.1 Conventional treatment process

Conventional treatment processes, namely coagulation, sedimentation or clarification, filtration, and disinfection, were formed at the end of the 19th century and the beginning of the 20th century, and are still used by most water plants in the world, and my country is no exception. The flow chart is shown in Fig. 1-2. The raw water is first treated by coagulation. By adding coagulant, the suspended solids and colloidal substances in the water are aggregated into large particles. Then, after sedimentation treatment, the sludge discharge system is additionally disposed. The effluent is filtered. Through the retention capacity of sand and gravel, the pollutants in the water are removed again. Finally, the effluent is disinfected to ensure that the microorganism of water quality meets the standard. At present, due to its strong oxidation and economy, liquid chlorine is commonly used at home and abroad. However, conventional processes can only effectively remove large particulate matter such as suspended solids and colloids in water, and have extremely limited removal of soluble pollutants in water, especially for trace organic pollution and ammonia nitrogen pollution in my country’s water sources. The results of the current research in the field of water supply treatment show that the removal efficiency of organic matter in water by conventional processes is only 20% to 30%, and in the presence of dissolved organic matter, the stability of colloids in water is destroyed, making conventional coagulation processes. It is difficult to exert its due efficiency, resulting in a significant decrease in the ability to remove turbidity, and the removal efficiency is only 50% to 60%. In actual production, increasing the dosage of coagulant can improve the coagulation effect to a certain extent, but it will cause the production costs of water purification plants increase, and bring the risk of excessive metal ions such as aluminum ions. The problem of ammonia nitrogen in the water source water can be dealt with by chlorination at breakpoints. Although the excessive ammonia nitrogen can be controlled to a certain extent, this method will increase the risk of the generation of halogenated disinfection by-products in the factory water and cause corresponding water quality toxicological problems. As the quality of raw water is getting worse and worse, conventional treatment can no longer meet the requirements of the current sanitary standards for drinking water. Conventional processes need to be modified and upgraded to further improve drinking water quality [100, 101].

The enhanced conventional water treatment process is an emerging process that has emerged in recent years. It does not change the existing conventional water treatment structures and treatment processes. At the same time, through the enhancement and upgrading of the existing conventional processes such as coagulation and filtration, it also enhances the treatment of turbidity and removal of organic matter. Enhanced coagulation can achieve the optimal effect of coagulation by optimizing coagulants and improving coagulation conditions, and improve the removal efficiency of pollutants in water, especially organic components such as natural organic matter. In the winter of northern China, the water quality of the source water generally has the obvious characteristics of low temperature and low turbidity, which makes it difficult for the conventional coagulation process to exert its effective performance under the conditions of the winter water quality. Even if the raw water chemical dosage is increased, it cannot be guaranteed the effluent water quality. In view of the further deterioration of water quality or the sudden pollution of water quality, the addition of powdered activated carbon is a very effective method. Under the conditions that the existing process conditions are difficult to achieve the effect, the use of enhanced coagulation to improve the coagulation effect can effectively improve the water treatment. The removal ability of organic matter and other pollutants improves the quality of process effluent. Relevant studies have shown that adjusting the pH value of raw water, optimizing the dosage and method of coagulant addition, and using polymer agents to aid coagulation are effective means to improve the coagulation effect. The above methods can further enhance the coagulation effect and improve the turbidity of the raw water. Removal efficiency of key pollutants such as degree, color, TOC, oxygen consumption and algae. Enhanced filtration is achieved by optimizing filter parameters, adopting new types of filter materials, and bioenhancing existing common filter materials. The research results of Li et al. [102] showed that for the contaminated water, the modified quartz sand filter material is used for filtration treatment, and the removal efficiency is significantly improved compared with the traditional ordinary quartz sand filter material.

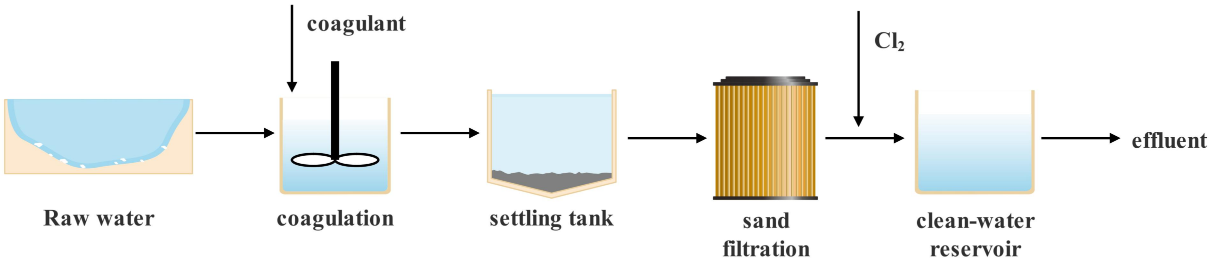

Fig. 1-2 Conventional process flow chart

1.5.2 Ozone-activated carbon advanced treatment process

Aiming at the more polluted source water, the advanced ozone-activated carbon treatment process is currently the most widely studied treatment method. The ozone-biological activated carbon process is an organic combination of ozone contact oxidation, activated carbon adsorption and biodegradation. It has become increasingly common in the field of water supply treatment in the world and has become a representative second-generation water treatment process. The flow chart is shown in Fig. 1-3. After coagulation sedimentation and filtration, most of the suspended solids, colloidal substances and some organic matters can be removed. The effluent enters the ozone contact tank. Under the strong oxidation of ozone, most of the organic matter is oxidized into small molecular substances or degraded into inorganic substances. After the subsequent treatment of biological activated carbon, the organic content in the water can be further purified. First of all, ozone can degrade the macromolecular substances in the raw water through oxidation treatment and become an intermediate product that is conducive to the adsorption of activated carbon. On the other hand, the self-degradation product oxygen of ozone can also provide an oxygen source for activated carbon, thereby improving the activity of aerobic microorganisms. And biological regeneration capacity to form biochar, thereby further enhancing the removal of water pollutants. As the most commonly used pre-oxidation agent in the water supply treatment process, ozone has a good removal effect on chroma, dissolved organic matter (DOM) and odor in water, and can destroy the molecular structure of existing organic matter through its strong oxidizing property. And it quickly react with most organics in the water, but the ozone oxidation alone also has a certain degree of deficiency. Although it has a better removal effect on aromatic compounds containing unsaturated double bonds, its oxidizing ability alone cannot effectively act on aromatic compounds containing unsaturated double bonds in water. But for those organic pollutants (persistent organics, endocrine disruptors, and "three causes") that have complex chemical structures and are difficult to be biodegraded, the pollution will be removed limited ability. Biological activated carbon has obvious removal effect on trace organic pollutants, disinfection by-products and precursor substances, and ozonation by-products in water. Usually combined with biological activated carbon after ozone, it can effectively remove natural organic matter (NOM) [103, 104].

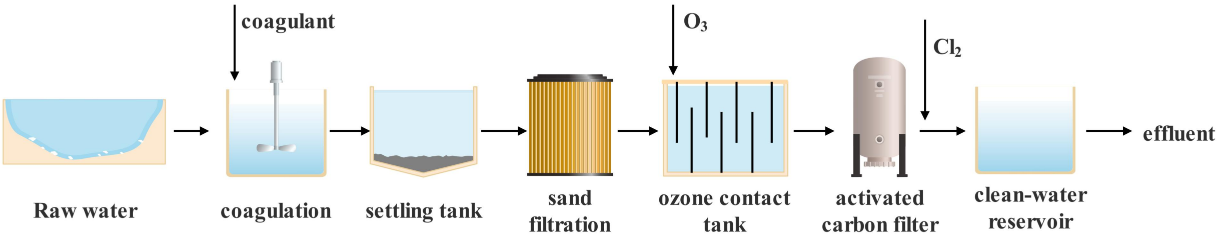

Fig. 1-3 O_3/BAC advanced treatment process flow chart

1.6 Review of water quality assessment method

Water is the source of life related to people's health and urban development. In recent years, many scholars at home and abroad have done a lot of research on surface water, source water and even groundwater, exploring the characteristics of water quality and temporal and spatial changes, controlling the change characteristics of water quality, and providing data support for water purification [105, 106].

Hou et al. [107] evaluate the water quality of reservoirs in lower reaches of Yellow River using the water quality index (WQI) method and try to compare water quality and main contaminations of mountain and Yellow River reservoirs. Results showed that mercury was the main contaminations in both of mountain and Yellow River reservoirs, while TP and SO_4^{2-} were another main contaminations in mountain and Yellow River reservoirs, because of runoff and atmospheric sedimentation. Hasan et al. [108] applied different water quality indices to assess the spatiotemporal variations of Dhaleshwari river through WQI and Pearson’s correlation coefficient. The results indicated that water quality deteriorated in the winter season in terms of time, while junction and downstream side showed more pollution in terms of space. Hybrid fuzzy-GIS-based water quality index was utilized to assess groundwater quality for drinking water supply by Jha et al. [109]. They concluded that the concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{2-} in groundwater were found within the

WHO desirable limits for drinking water throughout the year, while the concentrations of seven parameters (TDS, NO_3^--N, Na^+, Cl^-, K^+, F^- and Hardness) exceeded their permissible limits during pre-monsoon and post-monsoon seasons. Yotova et al. [110] carried out a water quality assessment of the Mesta River catchment by the composite water quality index and self-organizing maps. The results showed that deviations from the good quality requirements in Mesta river catchment were due to untreated domestic wastewaters. Meanwhile, they proved that a combination of a multivariate approach like SOM with WQI factors used for index calculation was a proper strategy for river basin water quality assessment.

A holistic assessment of water quality condition and spatiotemporal patterns in impounded lakes along the eastern route of China's South-to-North water diversion project was investigated by Qu et al. [111]. They identified three groups with distinct water quality characteristics: upstream Gaoyou Lake and Hongze Lake showing relatively higher nutrients, turbidity, and total suspended solids; downstream Dongping lake and Donghu Lake showing higher conductivity, total hardness, and chloride; and Luoma Lake and Nansi Lake intermediate between the two former groups via principal components analysis and analysis of variances. Liu et al. [112] studied the characterisation of spatial variability in water quality in the Great Barrier Reef catchments using multivariate statistical analysis. They found that different catchment characteristics influenced the magnitude of concentration in varying ways in the Great Barrier Reef catchments. Noori et al. [113] explored the temporal trend of thermal stratification in the Karkheh Dam Reservoir (KDR) and its interrelationship with water quality parameters based on the measured data. Results showed that a strong thermal stability in the KDR during late May until early December, followed by weak mixing until the early spring, and the concentrations of pollutant in the surface (due to nitrification) was higher than deep layers (due to denitrification) according to the depth profiles of nitrate.

Jiang et al. [114] applied the fuzzy neural network based on T-S model to evaluate and analyze the water quality characteristics of Liuxi river Irrigation District, Guangzhou. The results showed that the water quality evaluation results of the upstream Da’ao monitoring section were better than that of the downstream Liyuan monitoring section. The water quality in the South-to-North Water Diversion Project of China was evaluated by Nong et al. [115] using the water quality index (WQI) method. The results demonstrated that the water quality status of the Middle-Route (MR) of the South-to-North Water Diversion Project of China had been steadily maintained at an “excellent” level during the monitoring period, with an overall average WQI value of 90.39 and twelve seasonal mean WQI values ranging from 87.67 to 91.82. Wang et al. [116] applied multivariate statistical method to evaluate dissolved trace elements and a water quality assessment in the middle reaches of Huaihe River, Anhui, China. The results showed that Zn, Cd and Pb were identified as the dominant pollutants in the water body and approximately 96% of the waters in the Huaihe River were unsuitable for drinking. Xin et al. [117] also evaluated the water quality in the Danjiangkou

Reservoir of China. The results showed that the main indices influencing the water quality in the Danjiangkou Reservoir were total phosphorus (TP), permanganate index (COD_{Mn}), dissolved oxygen (DO), and five-day biochemical oxygen demand (BOD_5). But only the concentrations of TP, BOD_5, ammonia nitrogen (NH_3-N), COD_{Mn}, DO, and anionic surfactant (Surfa) did not reach the specified standard levels in the tributaries.

1.7 Current Situation of water supply in Harbin

Harbin is the capital of Heilongjiang Province, a national-level historical and cultural city, and the central city of economy, politics, trade, science and technology and cultural undertakings in the northeast of China. With the deepening of reform and opening up, urban construction and various social undertakings have developed rapidly, the gross national product has increased year by year, the urban population has continued to increase, and the people's living standards and quality of life have been significantly improved. It is moving towards the goal of becoming an important international economic and trade city.

Due to the major nitrobenzene pollution incident in the Songhuajiang River in 2005, most of the water used in the urban area of Harbin was taken from the Mopanshan Reservoir in Wuchang City. However, with the continuous advancement of urbanization, the water supply capacity of urban water supply facilities can no longer meet the increasing demand for water consumption. Insufficient water supply capacity of existing facilities, poor water source quality, and single main water source constraints have greatly reduced the safety of water supply in Harbin. It has become a constraint on local economic growth, improvement of investment environment, implementation of housing projects, and construction of two civilizations.

According to the current situation of urban water supply and available water resources in Harbin, as well as the spirit of the State Council's national document on strengthening urban water supply and water pollution prevention and control, in order to increase the capacity of water storage and strengthen the optimal allocation of water resources. The comprehensive water supply system with water sources and multi-channels complements each other to improve the safety of urban water supply. Harbin City decided to re-use Songhuajiang River water. In order to make Harbin get rid of the long-term restriction of Songhuajiang River's single water source on Harbin's urban water supply, and form a pattern of combined water supply from Songhuajiang River and Mopanshan Reservoir, greatly improving the safety of water supply.

According to the forecast of water demand, the highest daily water demand in Harbin City is 1.4227 million m^3/d in 2010 and 1,741,100 m^3/d in 2020. The water purification plant of Mopanshan Water Supply Project provides 900,000 m^3/d of water, and most of the remaining water can be provided by the water purification plant using Songhuajiang River as its water source. Since it is difficult for the existing treatment facilities of these water plants to make the effluent water quality meet the requirements of the "Urban Water Supply Quality Standard" (CJ/T206-2005), if the corresponding engineering measures are not taken in time, the following problems will occur in the joint water supply of the two water sources:

①The quality of urban water supply is a major issue related to the health of the people and a prerequisite for creating a harmonious society. Unsafe water quality will have long-term potential impacts on people’s lives.

②The water quality of the same water distribution network is different. Some of the water supply meets the water quality standards of the city, while the other part is of poor water quality. This will trigger citizens' dissatisfaction with the relevant departments and increase social instability.

③Unable to demarcate the dividing lines of the pipe network with different water supply quality, which caused insurmountable troubles to the normal operation of the local water supply and drainage group limited liability company.

In order to avoid the above-mentioned problems, effective measures must be taken to transform the existing treatment process of the water plant to ensure that the effluent quality meets the requirements of the urban water supply water quality standard. For this reason, Harbin City decided to start an emergency renovation project of a water purification plant at the source of the Songhuajiang River in Harbin, and carry out advanced treatment technical transformation of the existing Songhuajiang River source water purification plant to improve the quality of water supply in Harbin and further improve the safety of urban water supply.

1.8 Research objectives and purposes

Through the above review, different evaluation methods are used to analyze and study the source water in detail at home and abroad, and many treatment methods are adopted to alleviate the water quality problems in the water source area. As a special area in the northernmost part of China, in order to ensure the safety of drinking water for Harbin people, and to meet the situation of large increase in water demand caused by urban population increase and future urban development in Harbin, we conduct a comprehensive analysis on the water quality of Mopanshan Reservoir and Songhuajiang River in Harbin, to determine their characteristic pollutants and pollution causes, and to macroscopically control the change law of water quality in the two water sources of Harbin. At the same time, the water quality characteristics of the two water sources treated by the conventional process and advanced treatment process are compared and analyzed, and the process operation of advanced treatment process is studied in detail. The corresponding effective water supply countermeasures are put forward for the development of Harbin city.

1.9 Organization of Thesis

This thesis has eight chapters. The structural of the thesis is showed in Fig. 1-4.

1.9.1 Chapter 1. Introduction

In the chapter, background, previous research, purposes, and configuration of the thesis are described.

1.9.2 Chapter 2. Theory of urban safe water supply and Water purification renovation method

In the chapter, the involved theories of urban safe water supply, material, research method, and process overview are presented.

1.9.3 Chapter 3. Comparison of water quality between the Mopanshan Reservoir and Songhuajiang River

In the chapter, we compared the water quality between the Mopanshan Reservoir and Songhuajiang River and applied WQI method to evaluate the water quality of the two drinking water sources.

1.9.4 Chapter 4. Pollution source analysis and comparison of the finished water quality of the Mopanshan Reservoir and Songhuajiang River

In the chapter, the characteristic pollutants and pollution sources of the two drinking water sources are analyzed. Meanwhile, the finished water quality of the two drinking water sources are also carried out.

1.9.5 Chapter 5. Pilot study on the enhanced conventional process in a waterworks of Harbin

In the chapter, the enhanced conventional process in a waterworks of Harbin was researched.

1.9.6 Chapter 6. Pilot study on the advanced treatment in a waterworks of Harbin

In the chapter, we studied the advanced treatment in a waterworks of Harbin and analyzed the operating parameter of each treatment unit.

1.9.7 Chapter 7. Engineering economic analysis

In the chapter, the engineering economic of the O_3/BAC process was analyzed.

1.9.8 Chapter 8. Conclusions

In the chapter 8, the results of the thesis are summarized.

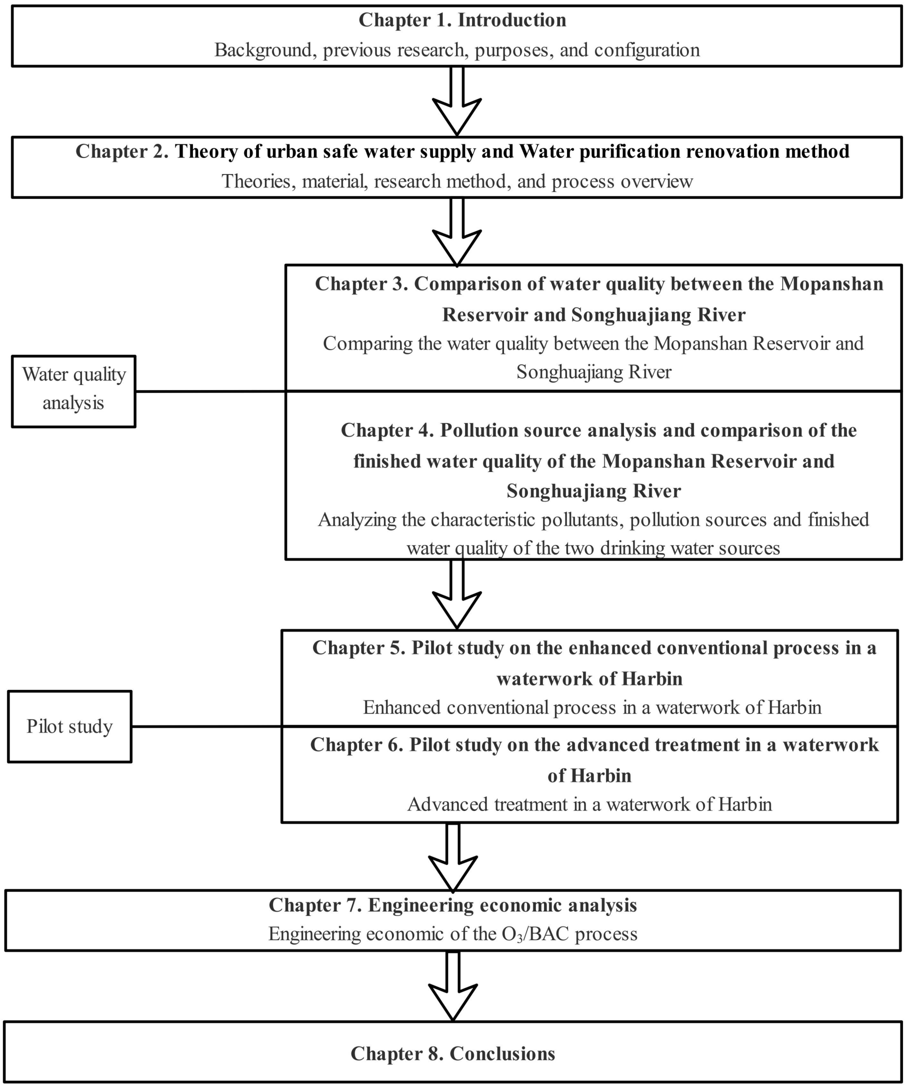

Fig. 1-4 The structural of the thesis

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Chapter 2. Theory of urban safe water supply and water purification renovation method

2.1 Theoretical analysis of urban water supply safety

2.1.1 Policy of the urban water supply safety at home and abroad

With the development of economic society and the continuous improvement of urban construction process, the public security problem caused by urban water supply security is a very common phenomenon in the world. The research on the content and scope of urban water supply security has gradually extended from micro to macro. As early as the early 1970s, some developed countries in Europe and the United States have taken urban water supply environmental pollution and its harm as the key research direction of urban water supply security, and carried out a series of studies on water environmental pollution. In 1997, at the 19th special session of the general assembly of the United Nations and the Commission on sustainable development of the United Nations, the relevant strategic experts of the United Nations pointed out that the importance of rational development and utilization of water resources should be further emphasized, and a series of plans and measures should be put forward to protect the existing water resources by using the ecosystem and other methods. Since the novel coronavirus pneumonia outbreak in 2020, the UN's world water development report, pointed out that the current outbreak of the new crown pneumonia outbreak has further intensified the billions of people in the world in urgent need of clean drinking water. In the course of decades of development, many countries at home and abroad have carried out water quality control, government intervention and management measures in different degrees [1-3].

There are great differences in the distribution of water resources among the states in the United States, and there are different management modes in the urban water supply system. But generally speaking, the United States attaches great importance to the integrated and unified management of water resources, the key management of river basins and the comprehensive utilization of water resources. It not only pays attention to the overall coordination between economic development and water resources development and utilization, but also pays attention to the overall coordination between the development and utilization of water resources and the development of ecological environment. Among the numerous studies in the United States, the most representative is the Tennessee River Basin. It is the world's first comprehensive development and management of the basin, but also the most successful basin. In order to realize the comprehensive management and overall coordination of the river basin, the United States has issued a series of corresponding policies, and established the Basin Management Bureau by legislation of Congress to ensure the effectiveness and unity of the management work. The Tennessee basin authority undertakes the development and management of the entire Tennessee basin. On the one hand, it is responsible for the development and utilization of water resources and special resources, on the other hand, it has to shoulder the responsibility of protecting the ecological environment [4, 5]. However, the research on water resources in Europe has experienced a transformation from traditional single basin water resources management to sustainable integrated management. The successful management cases of Thames

River Basin and Rhine River Basin reflect the research results of European urban water supply. The successful management of Thames River basin only depends on some conventional water supply technology, and does not use the world's advanced technology and technology. However, it has carried out bold system reform and scientific management method innovation in water supply management, which is known as "a great revolution of water industry management". The government has innovatively merged more than 200 water supply authorities located in the Thames River basin to form a new management agency of the Thames River water authority, with a clear division of labor and strict implementation. Through the unified management of aquaculture, transportation, livestock and poultry, water treatment, irrigation, flood control and other related businesses, the government has realized the comprehensive management of water supply system. This not only effectively and rationally develops and protects the water resources, but also eliminates the waste and damage of water resources. On the other hand, it fully reflects the social functions of the management institutions and fully mobilizes the enthusiasm of the management departments. The management of the Rhine basin began in July 1950, when a protection committee was set up in Switzerland to achieve the goal of comprehensive and unified management of the Rhine River Basin and to seek solutions. In view of the problems existing in the Rhine River, many researchers use different evaluation methods to comprehensively evaluate the water quality, and adopt advanced treatment technology to solve the pollution problems faced by the river. [6, 7]

In China, the exploration and research of water supply safety is also showing a gradual deepening process. In 2011, the No. 1 central document proposed that water conservancy should be regarded as a priority area for national infrastructure construction, and that strict water resources management should be taken as a strategic measure to accelerate the transformation of economic development mode. The 12th Five year plan also emphasizes the need to "attach great importance to water security, build a water-saving society, improve the water resources allocation system, strengthen the management and paid use of water resources, increase the prevention and control of water pollution in key river basins, and strengthen the construction of water conservancy infrastructure". It can be seen that as a major strategic project. Water resources security has been brought into the focus of government work. China's research on water supply safety protection has expanded from basic pollution monitoring and registration investigation to unified planning of water environment and establishment of various laws and regulations and management systems. The Ministry of water resources of the people's Republic of China took the lead in organizing the compilation of water resources protection planning basin in 1990. The State Environmental Protection Administration has also formulated the “Environmental Quality Standards for Surface Water”, “Standards for drinking water quality”, and “Environmental Assessment Standards for River Basin Planning” and other policies and regulations, and started to actively promote the construction of pollutant discharge permit system in 1998. In addition, many researchers in China have also carried out a lot of research in the field of water supply safety, water quality monitoring, basin pollution control and so on. In 2001, the Minister of water resources also put forward the idea of building a safe and reliable water supply source as the goal of urban water environment system, so as to form an integrated urban water supply and drainage network in the city [8-10].

From the perspective of urban water supply management in China, the research on urban water supply safety is not much more. In contrast, foreign countries attach great importance to the construction of urban water supply safety system, and take a series of restoration technologies and measures to improve the security guarantee ability of urban water supply. In recent years, only because of the water pollution gradually began to affect the normal production and life, the quality of life of urban residents is declining, only gradually began to pay attention to the safety of urban water supply. Therefore, based on the current national water environment standards, it is of great significance to monitor the water quality of the river basins, especially the water source areas, and improve the treatment measures.

2.1.2 Drinking water quality standards at home and abroad

Drinking water quality is an important standard for evaluating the safety of drinking water. Therefore, it is necessary to evaluate the extent to which China’s drinking water quality standards are in line with international standards from the comparison of domestic and international drinking water quality standards. At present, the World Health Organization (WHO) "Drinking Water Quality Guidelines", the European Union (EU) "Drinking Water Quality Directives", and the United States Environmental Protection Agency (USEPA) "National Drinking Water Quality Standards" are internationally authoritative and Three representative drinking water quality standards. Most of the drinking water quality standards of other countries or regions use them as a basis or reference to formulate their own national or regional standards [11, 12]. The current representative water quality standards are shown in Table 2-1.

Table 2-1 The drinking water quality standards in China with the international three standards

Dependency	Standard Title	Indicator total/item	Fixed number of years for final version	Notes
world health organization (WHO)	Potable water quality criteria	124	2011	Six revisions and supplements. The current standard is the fourth edition
European Union (EU)	Potable Water Quality Directive	52	1998	It was published in 1963 and has been revised three times. The current standard is 98/83/EC

environmental protection agency in USA (USEPA)	National standard for drinking Water quality	108	2004	Issued in March 2001 as "Drinking Water Standards and Health Consultants 2004"
China (jointly issued by the National Standards Commission and the Ministry of Health)	Standards for drinking water quality	106	2006	It was promulgated in 1955 and came into effect on July 1, 2007. Among them, there are 42 conventional indicators and 64 unconventional indicators.

It can be seen from Table 1-1 that the drinking water standards of international organizations and developed countries are relatively complete, which are mainly manifested in the following aspects: ①Standards are in line with laws and regulations and have strong enforcement. ②The standards are constantly reviewed and revised, close to reality, advanced and practical. According to the development of science and technology and the continuous improvement of people's quality of life, developed countries usually review the original standards after a period of implementation. For example, the United States reviews national standards every five years. ③Complete supporting measures. To ensure effective implementation of the standards, developed countries have established supporting measures that match the standards. The measures are mainly manifested in the establishment of a complete drinking water quality standard implementation guarantee system, such as the implementation of uniform standards, inspection methods, inspection instruments and training of inspectors across the country.

China's first drinking water quality standard was promulgated in 1955 and included 16 water quality indicators. After three revisions in 1976, 1985, and 2006, the water quality indicators increased to 106. The current drinking water quality standard implemented in China is "Standards for drinking water quality" (GB5749-2006), which will be implemented on July 1, 2007. This standard is based on international water quality standards. The total number of indicators is 106, of which 42 are conventional indicators and 64 are unconventional indicators. Although the detection rate of unconventional indicators is relatively low, in the evaluation of drinking water quality, unconventional indicators have the same effect as conventional indicators and belong to mandatory implementation items. The comparison between the current "Standards for drinking water quality" (GB5749-2006) in China and the three major international water quality standards is shown in Table 2-2.

Table 2-2 Comparison of indicators in the drinking water quality standards in China with the international three standards

Water quality index	China	Japan	EU	USA
pH	6.5-8.5	5.8-8.6	6.5-9.5	6.5-8.5
Chromaticity (PCU)	15	5	Acceptable and no odor	15
Turbidity (NTU)	1	1	Acceptable and no odor	N/A
COD_{Mn} (mg/L)	3	3 (1)	5	/
NH_3-N	0.5	/	/	/
Trichloromethane (mg/L)	0.06	0.1	0.1	0.1
Chloral	0.1	/	/	/

From Table 1-2, it can be seen that China's "Standards for drinking water quality" are similar to Japan's "Drinking Water Quality Guidelines" and "U.S. Drinking Water Quality Standards", and the index setting is relatively comprehensive. Considering the differences in the life and eating habits of Chinese residents. The requirements for certain specific water quality indicators are also different.

2.2 Study area

2.2.1 Mopanshan Reservoir

The Mopanshan Reservoir is located in the upper of the mainstream of the Lalin River, Wuchang City, Heilongjiang Province, which is about 180 km away from the urban area of Harbin City (Fig. 2-1). The longitude and latitude of the reservoir are 127°41′20″ E, 44°23′40″ N, respectively. The drainage area above the reservoir dam site is 1151 km^2, with a total storage capacity of 5.23 billion m^3. The normal water storage of the reservoir is 318 m, which has a total water storage capacity of 3.56 billion m^3. And the reservoir has a dead water level of 304.5 m and a dead storage capacity of 0.91 billion m^3. Meanwhile, the annual average runoff amount of the reservoir is 5.61 billion m^3/a. The inflow mainly depends on three inflow streams and surface runoff in catchment areas, which is greatly affected by the natural precipitation. Among its outflows, the yield as the water source is 3.37 billion m^3/a, and as the annual average environmental water supply is 0.13 billion m^3/a. The rest of the outflows are agricultural compensation water supply in irrigated areas, water-use for environment, and irrigation water, which mainly concentrate from May to September every year. The Songhuajiang River Basin, located between 41°42′~51°38′ N and 119°52′~132°31′ E, is at the northernmost end of the seven major river basins in China. It has an interval catchment area of 18.64 ten thousand km^2. And the annual average runoff amount is 321.8 billion m^3.

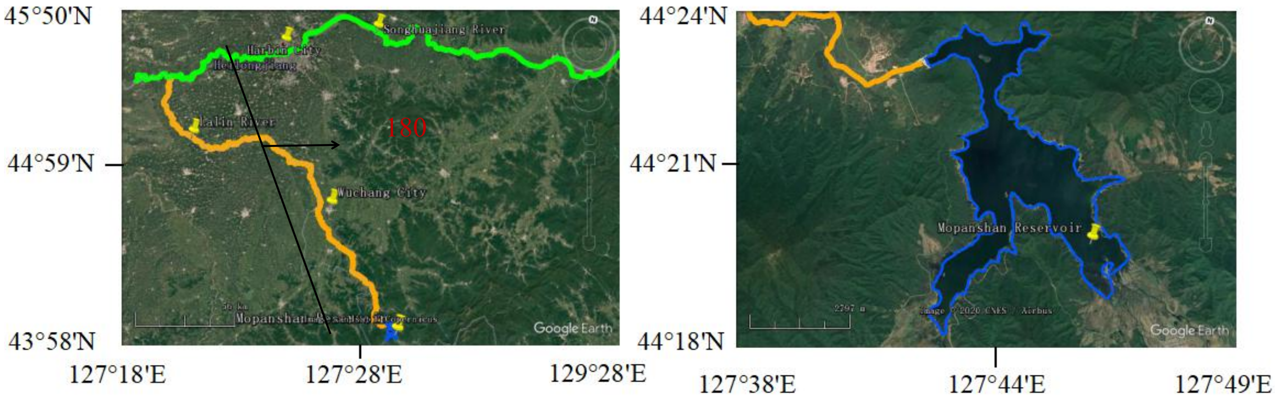

Fig. 2-1 Location map of Mopanshan Reservoir

2.2.2 Songhuajiang River

The Songhuajiang River Basin is located between 41°42′~51°38′N and 119°52′~132°31′E. It is at the northernmost end of the seven major river basins in China (Fig. 2-2). It has two major fountainheads. The north one is the Nen River, which originates from the Ilehuli Mountain and Daxing' an Mountains. Meanwhile, the south one is the second Songhuajiang River, which originates from the Heavenly Lake in Changbaishan. The two rivers converge at the Sancha River, known as the Songhuajiang River. The Songhuajiang River's mainstream is nearly one thousand kilometers long, with an interval catchment area of 18.64 ten thousand km^2. The annual average runoff amount is 321.8 billion m^3.

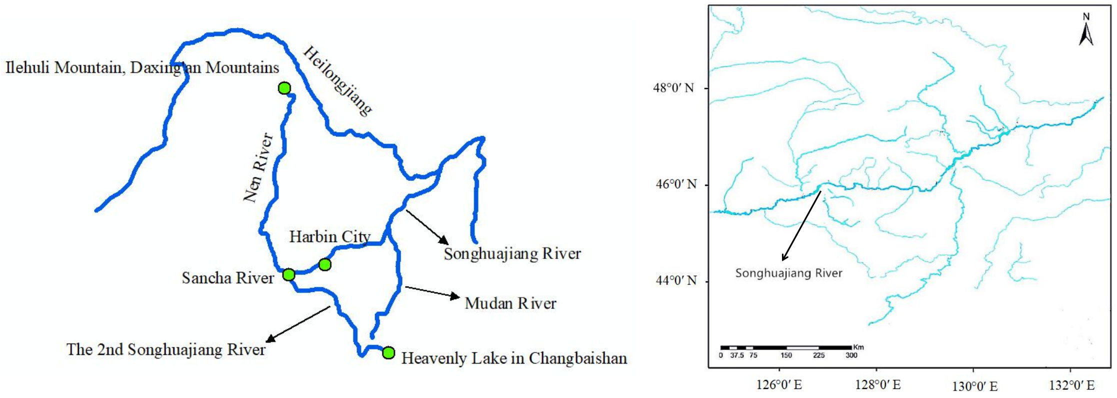

Fig. 2-2 Location map of Songhuajiang River

2.3 Waterworks profiles of Harbin

2.3.1 Profiles of the conventional process

The water plant takes the Mopanshan Reservoir and Songhuajiang River as the water source, and the daily water supply capacity is 350000 m^3/d. The treatment unit includes coagulation tank, sedimentation tank, sand filter and clean water tank. The process flow chart is shown in Fig. 1-2.

2.3.2 Profiles of the advanced treatment process

The pilot-scale plant, using the Songhuajiang River as the source water, was located at a water purification plant in Harbin City. The conventional treatment process used in this work consisted of coagulation, precipitation, filtration, and sterilization. To improve the effluent water quality, an advanced treatment-O_3/BAC process was utilized, with a pre-ozonation tank added before the coagulation tank and a main ozonation treatment unit attached after the sand filtration tank. The bacterial activated carbon (BAC) filtration unit was behind the main ozonation contact tank. The schematic process is illustrated in Fig. 2-3. The pilot plant scale was 5.0 t/h. Among these processing units, composite aluminum ferric was used as a coagulant to strengthen the coagulation effect. The height, diameter, and valid volume of the two ozone contact tanks, which were made of stainless steel, were 2.5 m, 800 mm, and 2.0 m^3, respectively. The hydraulic retention time of the pre-ozonation tank was five minutes, while it was ten minutes for the main ozonation contact tank. For the two ozonation schemes, air was applied as the feed gas to produce ozone by an ozone generator (WH-H-Y3, Nanjing Wohuan Technology Co., China). Then, the ozone was bubbled into the contact tank by water ejector. The ozonation off-gas was recovered to increase the ozone absorption rate as well as the coagulation, reaction, and precipitation effect in the water.

Furthermore, the conventional filtration was based on quartz sand, while the BAC filtration mainly relied on the loaded microorganism, granular active carbon (GAC), and cobble. The washing scheme of the conventional filtration was 2 min of air washing, 3 min of air-water backwashing, and 5 min of water washing with a washing intensity of 12.5 L/(m^2•s). The backwashing intensity of the BAC filtration (height 3.3 m, ID 1 m), which applied the air-water backwashing technique, was set as 11.5 L/(m^2•s) for ten minutes.

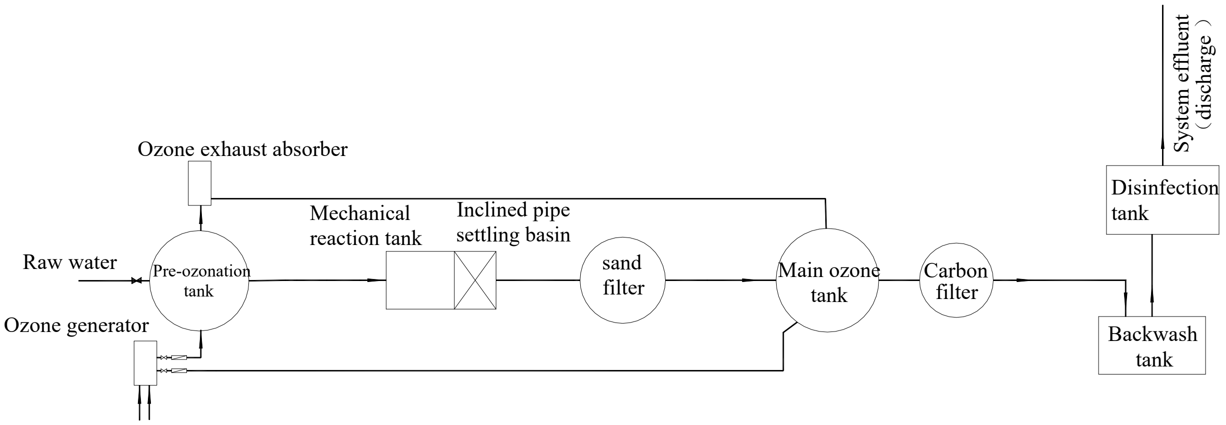

Fig. 2-3 Advanced treatment process flow chart

2.4 Methods of monitoring water quality

2.4.1 Experimental reagents and equipment

2.4.1.1 Experimental reagents

The main reagents involved in this study are shown in Table 2-3.

Table 2-3 List of main reagents

Reagent	Grade	Manufacturer
Activated carbon $1^{\#}$	Crushed carbon	Activated carbon factory, China
Activated carbon $2^{\#}$	Granular carbon	Activated carbon factory, China
Sulfuric acid	Analytical reagent	Alfa Aesar
Potassium permanganate (COD_{Mn})	Analytical reagent	Alfa Aesar
Anhydrous sodium sulphite	Analytical reagent	Alfa Aesar
Potassium dichromate (COD_{Cr})	Analytical reagent	Alfa Aesar
Ammonium chloride	Analytical reagent	Alfa Aesar
Salicylic acid	Analytical reagent	Alfa Aesar
Sodium potassium tartrate tetrahydrate	Analytical reagent	Alfa Aesar
Sodium hypochlorite	Analytical reagent	Alfa Aesar
Sodium bromate	Analytical reagent	Alfa Aesar
diatomite	Technical pure	Aladdin
Polyaluminum chloride	Technical pure	Aladdin
Polymeric aluminum ferric-calcium (PAFC)	Technical pure	Aladdin
Liquid chlorine	Technical pure	Aladdin

2.4.1.2 Experimental equipment

The main equipment involved in this study are shown in Table 2-4.

Table 2-4 List of main equipment

Equipment name	Equipment type	Equipment manufacturer
Portable pH meter	PHBJ-260F	Electronic Scientific Instrument Co., LTD, China
Turbidimeter	HACH2100N	HACH, USA
Ultraviolet specrophotometer	UV-1800	Shimadzu, Japan
Inductively coupled plasma source mass spectrometer	ICP-MS-6000	PerkinElmer, USA
Gas chromatography	6890B	Agilent, USA
Gas chromatograph-mass spectrometer	GCMS-TQ8040 NX	Shimadzu, Japan
Ion chromatograph	IC-S-3000	Dionex, USA
Residual chlorine portable	PCII	HACH, USA

detector		
Electro- thermostatic blast oven	BGZ-140	Spectrum Run Biotechnology Co., LTD, China
Ultrasonic cleaner	PL-S100TX	Kangshijie Ultrasonic Technology Co. LTD, China
Ozone generator	COM-AD-01	Anthross Environmental Protection LTD, China
Electronic balance	AL204	Mettler Tokodo Instruments Co., LTD, China
Six-unit coagulant agitator	MY3000-6J	Zhongke Road Instrument Testing Instrument Co. LTD, China
Microscope	CX31-12C03	Olympus, Japan

2.4.2 Sampling method of drinking water source and water treatment plant

The sampling, storage, analysis and monitoring methods of samples were carried out in accordance with "water and wastewater monitoring and analysis methods". The detection frequency of water samples in Mopanshan Reservoir and Songhuajiang River Basin is twice a month. The sampling site of the Mopanshan Reservoir is at the center of the lake. The sampling site of the Songhuajiang River is at the Zhushuntun monitoring section. All water samples were monthly obtained below 0.5 m from the surface water over 3 years (2016-2018). A 5 L acid-treated high-density polyethylene bottle was applied to collect water samples at the time interval. The samples were transported and stored for further analysis after the field parameters were determined (pH, temperature, etc.) [13, 14].

The detection frequency of water samples from conventional and advanced treatment units is twice a month. Each time according to the conventional process: source water - coagulation - sedimentation - sand filtration - disinfection - effluent; ozone - activated carbon treatment process: source water - preozonation - coagulation - sedimentation - sand filtration - post ozone - activated carbon - disinfection - effluent. A series of water quality index testing experiments were carried out by using low temperature incubator to transport to the laboratory。

The experimental water was prepared by Millipore Milli-Q pure water system (resistivity ≥ 18.2 MΩ·cm). The glassware used in the experiment was washed with ultrasonic wave for 10 minutes, then washed with tap water, washed with ultrapure water for 3 times, and finally dried at 120 ℃ for 24 hours.

2.4.3 Conventional water quality index detection methods

The main water quality index detection methods involved in the study are shown in Table 2-5.

Table 2-5 Main water quality index detection methods

Water quality index	Detection method
COD_{Cr}	Potassium dichromate method, GB/T 15456-2008
Total nitrogen (TN)	Alkaline potassium persulfate digestion-UV spectrophotometry, GB 11894-1989
Total phosphorus (TP)	Ammonium molybdate spectrophotometric method, GB 11893-1989
NH_4^+-N	Salicylic acid-hypochlorite salt photometric method, GB 7481-1987
COD_{Mn}	Permanganate index method, GB 11892-1989
SD	Saybolt disk method
Chla	Spectrophotometric method
Turbidity	Turbidimeter analysis
Chroma	Platinum cobalt colorimetry, ISO 7887-1985
UV_{254}	Ultraviolet spectrophotometry
Bromate	Ion chromatography
Fecal coliform	Membrane filtration
Alga	Microcounting method
Metal ion	Inductively coupled plasma-mass spectrometry, ICP-MS

2.4.4 Unconventional water quality index detection methods

2.4.4.1 Organic matter detection method

The main organic matters involved in water quality monitoring are disinfection by-products. According to EPA 525.2, the qualitative analysis of organic matter in water samples was carried out by gas chromatography-mass spectrometry. The operating conditions of GC/MS are as follows: carrier gas flow control: pressure control; carrier gas is high-purity nitrogen; sample volume:1 L; concentration ratio: 2000; injection volume: 1 μL; injection mode: separation and injection, oxygen ratio:1:2; column temperature: 45-270°C; injection port temperature: 250°C; transfer line temperature: 270°C; ion source: EI source; electronic energy:70 eV; scanning mass range: 30-200 m/z; detection mode Formula: full scan detection and selective ion scanning; heating program: initial temperature is 30°C, holding for 10min, heating to 72°C at the rate of 7°C/min, holding for 1 min, and then heating to 220°C at the rate of 40°C/min for 1 min.

2.4.4.2 Determination method of ozone concentration in water

The concentration of ozone O_3 in water is determined by ultraviolet absorption method, and the ultraviolet absorbance of water sample is measured at 258 nm. The calculation formula is shown in formula 2-1.

$$[O_3] = (A_0 - A_1) \times 48 \times 10^3 / (\varepsilon \times L) \qquad (2\text{-}1)$$

where，$[O_3]$: concentration of ozone water, mg/L;

A_0, A_1: the absorbance value of the solution before and after adding ozone;

48×10^3: molar mass of ozone，mg/mol;

ε: molar absorbance value of ozone, L/(mol•cm);

L: optical path (thickness of colorimetric dish), cm.

The molar absorptivity of ozone was calculated by iodometric titration. In this test, ε = 2900 L/(mol•cm). This method can determine the concentration of O_3 quickly and conveniently.

2.4.5 Water Quality Indicator (WQI) analysis

There are many methods to evaluate the water quality, such as the fuzzy mathematical evaluation method, the single factor index evaluation method and the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (CCME-WQI) [15, 16]. However, an improved Water Quality Indicator (WQI) method, raised by Xu et al. [17], was applied regarding the water quality characteristics of reservoirs in China. This method is different from simple weighting and superposition, in which the worst index is highlighted to make the evaluation result more objective. The formula is listed in Eq. 2-2.

$$\mathrm{WQI} = \sqrt{\frac{1}{n}\sum I_i \times I_i(\max)} \qquad (2\text{-}2)$$

Where WQI is the water quality indicator; I_i is the single factor index; $I_i(\max)$ is the maximum value among the single factor index; and n is the total number of the studied parameter.

The scoring criteria is indicated in Table 2-6. The higher the number, the worse the water quality.

Table 2-6 The scoring criteria of the WQI

Value of WQI	Classification
WQI < 0.5	Excellent
0.5 < WQI < 1	Good
1 < WQI < 1.5	Acceptable
1.5 < WQI < 2	Bad
WQI > 2	Poor

2.4.6 Eutrophication analysis

At present, there are many evaluation methods of eutrophication state of water quality, such as Carson index, modified Carson index, comprehensive nutrition state index, fuzzy mathematics evaluation method and grey analysis evaluation method. Although the trend of water environment eutrophication has been developing, there is no unified method to evaluate water eutrophication in China. Moreover, the single evaluation method has one sidedness in the selection of evaluation criteria and indicators, which may lead to the evaluation results unable to reflect the real situation of water eutrophication [18, 19]. Therefore, in this study, modified Carson index method and comprehensive nutrition state index method were used to evaluate the eutrophication status of Mopanshan Reservoir.

2.4.6.1 The amended Carlson trophic state index

Based on the previous studies, an amended Carlson trophic state index (TSIM), mainly focusing on the concentration of chlorophyll a (Chl-a), was proposed by a Japanese scholar [20, 21]. It overcomes the one-sidedness of single factor evaluation of eutrophication. The index includes transparency (SD), Chl-a and phosphorus (TP). The relevant formulas are presented in Table 2-7. The relationship between the TSIM and eutrophication is listed in Table 2-8.

Table 2-7 The formulas of the amended Carlson trophic state index

Index	Formula
TSIM (Chla)	$\text{TSIM (Chla)} = 10\,(2.46 + \ln \text{Chla} / \ln 2.5)$
TSIM (SD)	$\text{TSIM (SD)} = 10\,[2.46 + (3.69 - 1.53 \ln \text{SD}) / \ln 2.5]$
TSIM (TP)	$\text{TSIM (TP)} = 10\,[2.46 + (6.71 + 1.151 \ln \text{TP}) / \ln 2.5]$
TSIM	$\text{TSIM} = [\text{TSIM (Chla)} + \text{TSIM (SD)} + \text{TSIM (TP)}] / 3$

Where, the unit of Chl-a is μg/L, the unit of SD is m, and the unit of TP is mg/L.

Table 2-8 The relationship between the TSIM and eutrophication

Value of TSIM	Eutrophic state
< 30	Oligotrophic
30~50	Mesotropher
50~100	Eutropher

2.4.6.2 The comprehensive trophic level index

The comprehensive trophic level index (TLI) is another method to appraise the eutrophic state of the water body, which contains COD_{Mn}, SD, Chl-a, TN and TP [22-24]. The involved formulas are shown in Table 2-9.

Table 2-9 The formulas of the comprehensive trophic level index

Index	Formula
TLI (Chla)	$\text{TLI (Chla)} = 10\,(2.5 + 1.086 \ln \text{Chla})$
TLI (SD)	$\text{TLI (SD)} = 10\,(5.118 - 1.94 \ln \text{SD})$
TLI (TP)	$\text{TLI (TP)} = 10\,(9.436 + 1.624 \ln \text{TP})$
TLI (TN)	$\text{TLI (TN)} = 10\,(5.453 + 1.694 \ln \text{TN})$
TLI (COD_{Mn})	$\text{TLI } (COD_{Mn}) = 10\,(0.109 + 2.661 \ln COD_{Mn})$

The calculation of TLI is shown as in formula Eq. 2-3.

$$\text{TLI }(\sum) = \sum W_j \cdot \text{TLI (j)} \qquad (2\text{-}3)$$

Where TLI (∑) stands for the comprehensive trophic level index; W_j stands for the correlation weight of eutrophic state index of the j parameter; and TLI (j) stands for the eutrophic state index of the j parameter.

With Chl-a as the reference parameter, the formula of the normalized correlation weight of the j parameter is shown in Eq. 2-4.

$$W_j = \frac{r_{ij}^2}{\sum m_{j=1}^{m} r_{ij}^2} \qquad (2\text{-}4)$$

Where r_{ij} stands for the correlation coefficient between the j parameter and Chl-a; and m is the number of evaluation parameters. The correlation between Chl-a of Chinese reservoirs and other parameters (r_{ij}, r_{ij}^2 and W_j) is shown in Table 2-10.

Table 2-10 The correlation between Chl-a of Chinese reservoirs and other parameters (r_{ij}, r_{ij}^2 and W_j)

Parameter	Chla	TP	TN	SD	COD_{Mn}
r_{ij}	1	0.84	0.82	-0.83	0.83
r_{ij}^2	1	0.7056	0.6724	0.6889	0.6889
W_j	0.2663	0.1879	0.1790	0.1834	0.1834

A series of consecutive numbers from 0 to 100 are used to grade the eutrophic state of water bodies. And the relationship between the TLI and eutrophication is presented in Table 2-11. In the same nutritional state, the higher the index value is, the more serious the eutrophication is.

Table 2-11 The relationship between the TLI and eutrophication

Value of TLI	Eutrophic state
TLI (∑) < 30	Oligotrophic
30 ≤ TLI (∑) ≤ 50	Mesotropher
TLI (∑) > 50	Eutropher
50 < TLI (∑) ≤ 60	Light eutropher
60 < TLI (∑) ≤ 70	Middle eutropher
TLI (∑) > 70	Hyper eutropher

2.4.7 Export coefficient model

In order to study the non-point source pollution load of Mopanshan Reservoir, the output coefficient model is used for analysis, and the equation is shown in equation 2-5 [25].

$$L = \sum_{i=1}^{n} E_i \left[A_i (l_i)\right] + P \qquad (2\text{-}5)$$

Where, L ——The amount of nutrients lost (kg/a);

A_i ——Area of land use type i or number of livestock or population of type i;

E_i ——The output coefficient of the i th nutrient source;

P ——Nutrient load of rainfall input (kg/a);

l_i ——Nutrient input of i nutrient source (kg/a).

In the formula, the output coefficient Ei represents the difference of nutrient output among different land use types in the watershed. Among the population factors, the output coefficient can represent the discharge and treatment of domestic sewage, the use of phosphorus containing detergent and the nutritional status of diet. For livestock, the output coefficient shows the proportion of livestock waste entering the river network.

The annual output of nitrogen and phosphorus of the population is shown in the following formula.

$$E_h = D_{ca} \times H \times 365 \times M \times B \times R_s \times C \qquad (2\text{-}6)$$

Where, E_h ——Annual output of nitrogen and phosphorus of population (kg/a);

H ——Population in the basin (cap);

M ——Removal coefficient of nutrients in wastewater treatment process;

D_{ca} ——Daily output of nutrients per person (kg/d);

R_s ——Nutrient retention coefficient of filter layer;

B ——Biological removal coefficient of nutrients in wastewater treatment process;

C ——Phosphorus removal coefficient with desorption.

2.4.8 Determination of velocity gradient

In the coagulation experiment, the calculation formula of velocity gradient is shown as follows.

$$G\,(s^{-1}) = (P/V \cdot \mu)^{1/2} \qquad (2\text{-}7)$$

$$P\,(W) = 9.8 \cdot f \cdot N_P A d^{5-2m} n^{3-m} \rho^{1-m} \mu^{m} \qquad (2\text{-}8)$$

$$f=(D/3d)^{1.1}(H/D)^{0.6}(4h/d)^{0.3} \qquad (2\text{-}9)$$

where，n—rotation rate (rps)；

ρ—density of water；

A，m—coefficient，when $Re=100\sim5\times10^4$，$A=14.35$，$m=0.31$；

ν—dynamic viscosity of water, $\nu=\mu/\rho$(As 2-12)。

Table 2-12 The kinematic viscosity coefficient of water at different temperatures

T (°C)	20	22	24	30
N (m^2/s)	1.01×10^{-6}	0.99×10^{-6}	0.92×10^{-6}	0.88×10^{-6}

V—reactor volume；

f—correction coefficient。

When the blade and beaker size conform to the following relation，D：d=2.5-4，H：D=0.6-1.1，h：d=0.2-0.33，f=1；Otherwise，$f=(D/3d)^{1.1}(H/D)^{0.6}(4h/d)^{0.3}$

In this test, the blade size of the six-link agitator is：h=4 cm，d=5 cm；the size of beaker: H=12 cm，D=11 cm，V=1L=10^{-3} m^3；so f=0.54。

Therefore, the following formula and the corresponding speed can be obtained (n):

$$n^{2.69}=(0.00010\sim0.00011)G^2 \qquad (2\text{-}10)$$

2.4.9 Orthogonal experiment

In order to determine the mixing speed and mixing time in the enhanced coagulation experiment and reduce the experimental amount, the orthogonal experiment is used to design the experiment, so as to obtain better effect with the minimum experimental amount. The velocity gradient of fast mixing is G_0 and the mixing time is T_0. The flocculation process is divided into three stages. The velocity gradient and stirring time of each stage are represented by G_1, T_1, G_2, T_2, G_3 and T_3 respectively. The experiment is designed by using the orthogonal test table L18 (2×3^7) (the first factor is two levels). The factor level table is shown in Table 2-13, and each level is arranged according to the principle of randomness.

Table 2-13 Factor level table

Factor	G_0 (s^{-1})	T_0 min	G_1 (s^{-1})	T_1 min	G_2 (s^{-1})	T_2 min	G_3 (s^{-1})	T_3 min
Level 1	340	1.5	199	3.5	253	4	58	8
Level 2	441	2	220	3	147	5	39	9
Level 3	/	1	226	2	100	6	78	10

The results of orthogonal test were analyzed by visual method. The average values of the test results of each factor and level were calculated, expressed by K1, K2 and K3, and their average yields were expressed by $\overline{K1}$, $\overline{K2}$ and $\overline{K3}$. The range of test results reflects the influence of the change of factor level on the test results, and determines the primary and secondary factors in the test. In the study, R is used to represent the range of each factor.

2.4.10 Evaluation method for water quality of pipe network

2.4.10.1 Larson ratio (LR)

Larson ratio often used to characterize the corrosiveness of water to iron pipes. The LR value of water body is calculated by the ratio of the sum of SO_4^{2-} and Cl^- equivalent and HCO_3^- equivalent. The higher the LR value, the stronger the corrosion. When LR is less than 0.3, it can be considered that water is basically non corrosive. When 0.3 < LR < 0.7, water has weak corrosivity. When LR > 0.7, the corrosivity of water is strong. The calculation formula is shown in formula 2-11.

$$LR = \frac{[Cl^-] + 2[SO_4^{2-}]}{[HCO_3^-]} \tag{2-11}$$

2.4.10.2 Water quality causticity ratio (WQCR)

Larson ratio (LR) can basically judge the corrosion and scaling tendency of pipe network to a certain extent. The traditional method to judge the chemical stability of water quality is mainly based on the equilibrium relationship of carbonate system in water, which is helpful to judge the tendency of water quality stability. However, because it is based on the dissolution equilibrium of single calcium carbonate, it has some limitations in judging the corrosivity of water quality. Therefore, we introduce the water quality causticity ratio (WQCR) here, so as to comprehensively consider the influence of sulfate, chloride and oxidant in water. The calculation formula is shown in formula

2-12.

$$\mathrm{WQCR} = \frac{\left[\mathrm{Cl^-}\right]+\left[\mathrm{SO_4^{2-}}\right]+\left[\mathrm{NO_3^-}\right]}{\left[\mathrm{alkalinity}\right]\left[\mathrm{DO}+\mathrm{residual\ chlorine}\right]} \qquad (2\text{-}12)$$

The concentration of each ion is calculated in mol/L. When WQCR>1, the scale of the original pipe section is unstable, and the risk of yellow water after water source switching is greater. When WQCR<1, the original pipe scale is stable, and the risk of yellow water after water source switching is small.

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Chapter 3. Comparison of water quality between the Mopanshan Reservoir and Songhuajiang River

3.1 Introduction

Harbin is located in the northernmost region of China. Here, water is equipped with a low-temperature feature. This develops other complex water quality characteristics, such as turbidity, potassium permanganate index (COD_{Mn}), and ammonia nitrogen (NH_4^+-N) [1]. However, high-quality drinking water safeguards people's lives and health [2,3]. In China, lake reservoirs and river reservoirs are major water sources for domestic drinking water in urban areas [4,5]. Therefore, appraising the water quality diversity between the lake reservoirs and river reservoirs is vital for the health and economic development of humans.

For Harbin City, the typical lake reservoir is the Mopanshan Reservoir. Meanwhile, the typical river reservoir is the Songhuajiang River. Among them, the Songhuajiang River was originally the main water source for production and living. However, a nitrobenzene pollution event occurred in 2005. Consequently, the Mopanshan Reservoir became the main water supply for Harbin City in 2007 [6,7]. Until 2010, water from the Mopanshan Reservoir has supplied the entire south urban area of Harbin City. Meanwhile, the Songhuajiang River was withdrawn as a water source for Harbin City. Currently, the city’s drinking water is mainly drawn from the Mopanshan Reservoir. However, the disadvantages of the Mopanshan Reservoir as Harbin City’s only water source have become increasingly clear. Li et al. [8] showed that the Mopanshan Reservoir has a seasonal variability of the organic pollution. Liu. et al. [9] found the similar results. On the one hand, the Mopanshan Reservoir’s water quality has suffered eutrophication. On the other hand, as the Mopanshan Reservoir is far away (180 km) from the urban area of Harbin City. Therefore, two gravity pipelines are used for water transport. Any failure of these pipelines will affect the water supply necessary for maintaining the life and productivity of residents and enterprises in Harbin City. This would adversely impact society. The government of Harbin decided to reinstate the Songhuajiang River as a water source for the city in 2015. The water source project of the Songhuajiang River came into operation. Therefore, evaluating the water quality of the Mopanshan Reservoir and the Songhuajiang River is crucial to carry out the government's decisions.

In this study, the water body classification and water quality of raw water of the Mopanshan Reservoir and the Songhuajiang River were compared and analyzed. The researchers monitored data over three years (2016-2018). Ultimately, this research will lead to the development of both effective management and conservation strategies for the two drinking water sources of the Harbin City.

This chapter is organized as the following. In Chapter 3.2 the body classification comparative analysis of the two drinking water sources are compared and discussed. The comparative water quality analysis of raw water is presented in Chapter 3.3. And the Chapter 3.4 is the summary.

3.2 Comparative analysis of the water body classification

The “Environmental Quality Standards for Surface Water” (GB3838-2002) suggest that the surface water body is divided into five categories. They are labeled as Case I, Case II, Case III, Case

IV, and Case V. Among them, Case I, Case II, and Case III water body are suitable for the drinking water. In this section, the water body classification of the Mopanshan Reservoir and the Songhuajiang River in 2014-2018 are analyzed to reveal the water overview preliminarily.

3.2.1 Water body classification of the Mopanshan Reservoir

The water body classification of the Mopanshan Reservoir from 2014 to 2018 is listed in Table 3-1. It can be seen that the rates of reaching the Case III standard are 83.33%, 91.67%, 100%, 58.33%, and 83.33% from 2014 to 2018. Especially in 2016, the Mopanshan Reservoir's water all can entirely reach the Case III, exhibiting a preferable water quality. However, the water was presented as poor in 2017, especially in the summer. The abundant rainfall caused the organic maters flowing into the reservoir through the surface water run off. Meanwhile, several researchers showed the reservoir had a trend of eutrophication in the summer, which was another reason for the worsened water quality [10, 11]. On the whole, the water quality presented poor from May to July compared to the other months. Also, it was poor in 2017 and 2018 compared to the previous years. Therefore, some enhanced measures should be applied to ensure the water supply security, especially in the summer.

Table 3-1 Water body classification of the Mopanshan Reservoir

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2014	III	III	III	III	IV	IV	III	III	III	III	III	III
2015	III	III	III	III	III	III	III	III	III	IV	III	III
2016	III	III	III	III	III	III	III	III	III	III	III	III
2017	III	III	III	IV	III	IV	IV	III	III	III	IV	IV
2018	III	III	III	III	III	IV	IV	III	III	III	III	III

3.2.2 Water body classification of the Songhuajiang River

Table 3-2 shows the water body classification of the Songhuajiang River. The rate of reaching the Case III standard accounted for 50%, 58.33%, 91.67%, 91.67%, and 100% from 2014 to 2018. The water quality demonstrated an improving trend year by year. Therefore, the Songhuajiang River Harbin section has consistently realized the Case III water quality standards after a series of protection measures were implemented since the nitrobenzene pollution event in 2005. Interestingly, the water quality exhibited poor from November to June. This is mainly due to the enclosed environment in the icebound season (Nov.-Apr.) and surface water run off in the rainy season (May-June). However, the rate of reaching the Case III standard can reach up to 100% in 2018. This implies that the Songhuajiang River water is suitable for the drinking water at present.

Table 3-2 Water body classification of the Songhuajiang River

Year	Month

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2014	V	IV	III	IV	III	IV	III	III	III	III	IV	IV
2015	IV	III	IV	IV	IV	III	III	III	III	III	IV	III
2016	III	III	III	IV	III	III	III	III	III	III	III	III
2017	III	IV	III	III	III	III	III	III	III	III	III	III
2018	III	III	III	III	III	III	III	III	III	III	III	III

The water quality of the Songhuajiang River was shown as preferable to that of the Mopanshan Reservoir through the analysis of the water body classification. The Songhuajiang River increases its water quality year by year. Meanwhile, the Mopanshan Reservoir has a trend of deterioration year by year.

3.3 Comparative water quality analysis of raw water

Both the Mopanshan Reservoir and the Songhuajiang River water source are located in the high latitude zone of China's cold regions. Due to their similar geographic location, soil structure, and precipitation conditions, they belong to the same surface water source. Based on "Environmental Quality Standards for Surface Water" (GB3838-2002) and "Standards for drinking water quality" (GB5749-2006), this paper conducts a comprehensive comparative analysis of the raw water quality of the two water sources.

3.3.1 Sensory traits and physical indicators

3.3.1.1 Chroma and turbidity

Chroma and turbidity are the most basic sensory indicators for the performance of water quality. The sensory changes of them mainly caused by dissolved and suspended substances in the water. Based on the "Standards for drinking water quality" (GB5749-2006), the threshold value of chroma and turbidity are 15 PCU and 1 NTU, respectively. Variation of the two water quality indexes of the the Mopanshan Reservoir and the Songhuajiang River in 2016-2018 is depicted in Fig. 3-1. The chroma of the Mopanshan Reservoir reduced from 28 PCU to 17 PCU. As a lake-reservoir-type water body, the Mopanshan Reservoir water has a high chroma, which exceeds the standard limit (15 NTU). It is due to the reservoir is rich in vegetation. A large amount of humus in the soil enters into the water body with surface runoff, which results in the higher chroma. As a whole, the chroma of the Mopanshan Reservoir shows a trend of decreasing year by year. The turbidity of the reservoir is also relatively low, but the change is not significant, with an average of 1.89 NTU. The main reason is that it is a slow-flowing water body, and the suspended matter is deposited in the bottom mud under the action of gravity, which caused the low turbidity.

The Songhuajiang River has a wide runoff area and a high flow rate. It has obvious effects on the dissolution and scouring of substances in the soil and river channels. A large amount of soluble matter and suspended sand are washed into the water body, resulting in higher chroma and turbidity of the Songhuajiang River. Obtained from Fig. 3-1, the chroma of the Songhuajiang River reduced from 164 PCU to 44 PCU, while the turbidity reduced from126.4 NTU to 90.3 NTU. However, after years of treatment of the Songhuajiang River, the chroma and turbidity of the water body have clearly shown a downward trend year by year.

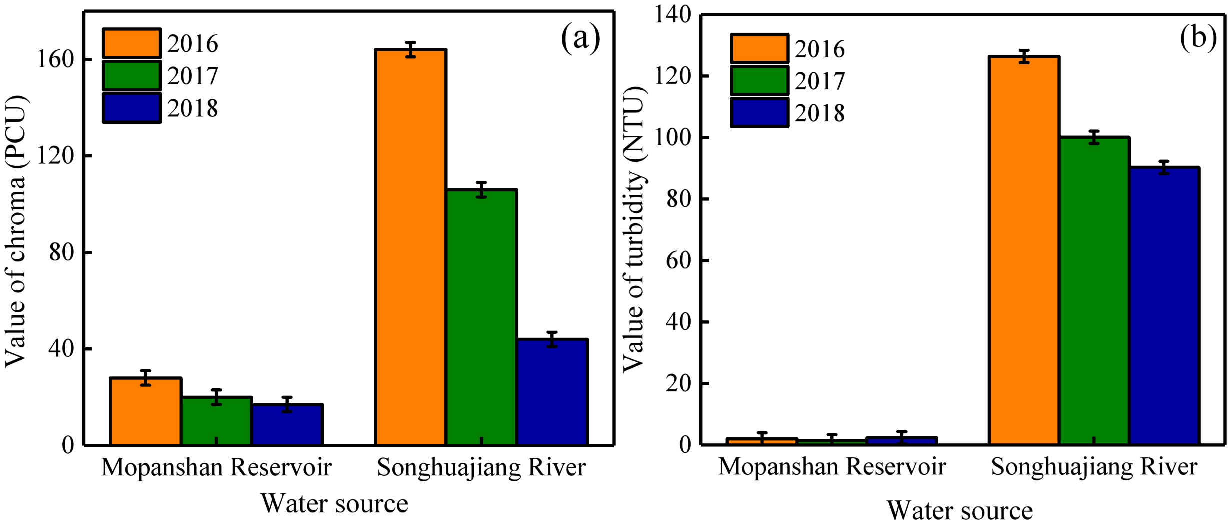


Fig. 3-1 Variation of chroma and turbidity in the Mopanshan Reservoir and Songhuajiang River. (a) chroma, (b) turbidity

3.3.1.2 pH

The value of pH reflects the acidity and alkalinity of the water body. The pH regulation of the “Environmental Quality Standards for Surface Water” (GB3838-2002) is in the range of 6~9. Variation of pH of the Mopanshan Reservoir and Songhuajiang River in 2016~2018 is shown in Fig. 3-2.

Obtained from Fig. 3-2, the pH difference between the Mopanshan Reservoir and Songhuajiang River water is obvious. The average pH value of the Mopanshan Reservoir is basically less than 7.0, while the average pH value of Songhuajiang River water is greater than 7.0. The pH value of Songhuajiang River water is generally higher than that of Mopanshan Reservoir. The pH value of the raw water of Mopanshan Reservoir is different from that of the Songhuajiang River. The one reason is that the raw water of the reservoir contains a lot of acidic natural substances, such as humic acid and fulvic acid due to the rich vegetation in the basin. The second one is that the temperature of Mopanshan Reservoir is relatively low. The solubility of carbon dioxide in water increases, so the pH of the water body is less than 7.0. The Songhuajiang River has a long runoff area, rich dissolved oxygen content, and strong water self-purification, so the water pH is greater than 7.0. In the water purification process of the water plant, the raw water of Mopanshan Reservoir needs to be adjusted to 7.0 by alkali, while the raw water of Songhuajiang River does not require additional alkali. Considering economic costs, Songhuajiang River water saves the cost of alkali injection compared with that of the Mopanshan Reservoir.

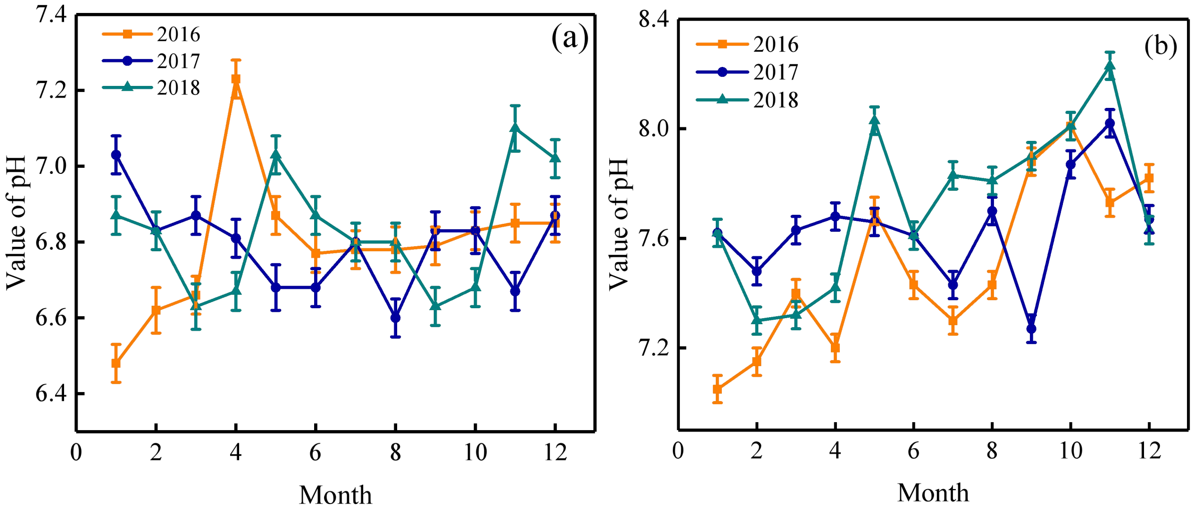


Fig. 3-2 Variation of pH in the Mopanshan Reservoir and Songhuajiang River. (a) Mopanshan Reservoir, (b) Songhuajiang River

3.3.1.3 Total hardness

The total hardness refers to the total concentration of calcium and magnesium ions in water, which reflects the soft and hard degree of water. The total hardness (in $CaCO_3$) regulation of the "Standards for drinking water quality" (GB5749-2006) is 450 mg/L. The variation of total hardness of the Mopanshan Reservoir and Songhuajiang River in 2016-2018 is showed in Fig. 3-3. The mean total hardness of the Mopanshan Reservoir was 38 mg/L. The mean total hardness of Songhuajiang River was 82 mg/L, close to 100 mg/L, which was higher than that of the reservoir. on the whole, the change of total hardness was more stable than that of the Mopanshan Reservoir. According to the World Health Organization for high-quality drinking water, the total hardness of water should be between 30 and 200 mg/L, and the pH value should be neutral or slightly alkaline. In terms of pH and total hardness, the Songhuajiang River water is more suitable for drinking.

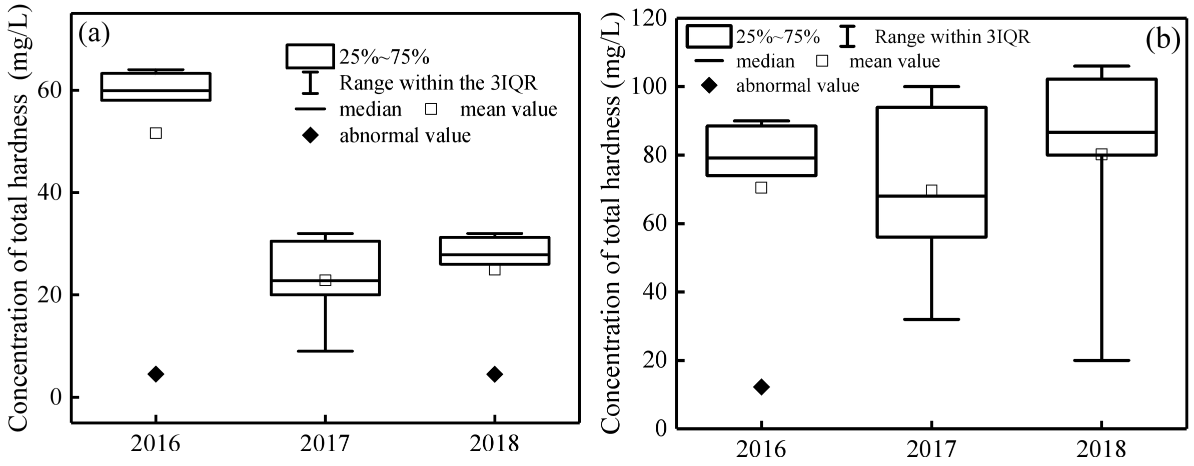


Fig. 3-3 Variation of total hardness in the Mopanshan Reservoir and Songhuajiang River. (a) Mopanshan Reservoir, (b) Songhuajiang River

3.3.1.4 Dissolved oxygen (DO)

The portion of molecular oxygen in air dissolved in water is called dissolved oxygen, which is a water quality index reflecting the self-purification ability of water body. The greater the DO, the stronger the self-purification capacity of the water is. When the water body is polluted by organic matter, oxygen consumption will increase, which will lead to the decrease of DO in the water body. The DO threshold value in the Case III of the "Environmental Quality Standards for Surface Water" (GB3838-2002) is 5 mg/L. The variation of DO of the Mopanshan Reservoir and Songhuajiang River in 2016-2018 is showed in Fig. 3-4.

The average DO in the raw water of the Mopanshan Reservoir was 6.3 mg/L. The average DO in the raw water of the Songhuajiang River was 8.5 mg/L, which was higher than that of the reservoir. This is mainly because Songhuajiang River is a river-type water body with high flow velocity and strong fluidity. With the flow of water body, more DO enters into the water body, resulting in higher content of DO and self-purification capacity of the Songhuajiang River water body than that of the Mopanshan Reservoir.

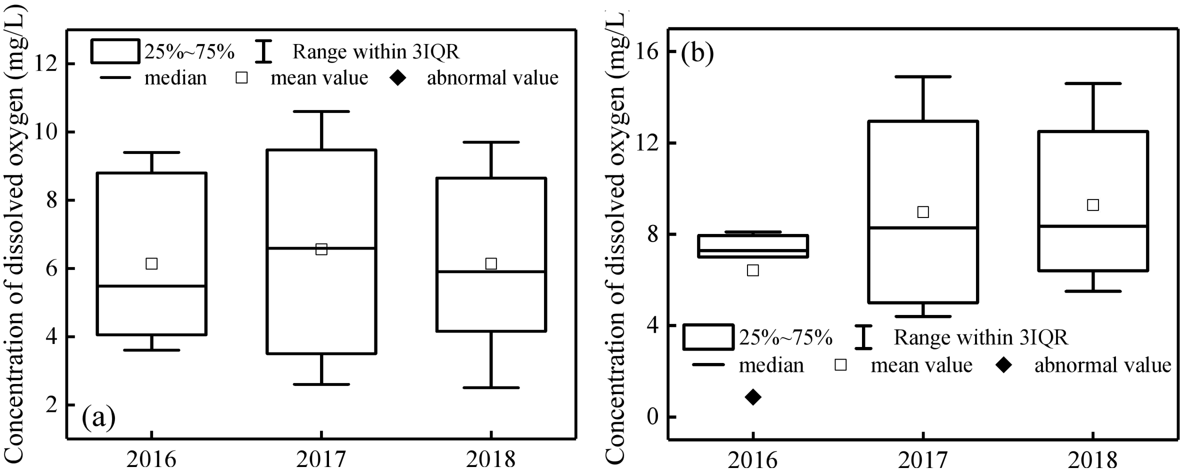


Fig. 3-4 Variation of dissolved oxygen in the Mopanshan Reservoir and Songhuajiang River. (a) Mopanshan Reservoir, (b) Songhuajiang River

3.3.2 Inorganic non-metallic index

The involved inorganic non-metallic indexes in the "Environmental Quality Standards for Surface Water" (GB3838-2002) are ammonia nitrogen (NH_4^+-N), total phosphorus (TP), total nitrogen (TN), fluoride, sulfate, chloride, nitrate, sulfide, cyanide, volatile phenols, and anion synthetic detergent. Since TN is not used as an indicator for the evaluation of surface water-type drinking water sources, other items are analyzed.

3.3.2.1 Ammonia nitrogen

Ammonia nitrogen is an important index to evaluate the degree of water pollution. It mainly exists in water in the form of free ammonia or ammonium salts, and mainly comes from domestic sewage containing nitrogen, industrial wastewater, and pesticide irrigation. The NH_4^+-N threshold value in the Case III of the “Environmental Quality Standards for Surface Water” (GB3838-2002) is 1 mg/L, and in the Case II is 0.5 mg/L。The variation of NH_4^+-N of the Mopanshan Reservoir and Songhuajiang River in 2016-2018 is showed in Fig. 3-5.

It can be seen from the figure that from 2016 to 2018, the ammonia nitrogen content of raw water in Mopanshan was under 0.5 mg/l, meeting the requirements of Case II water body, but there was a trend of increasing year by year, with the risk of eutrophication. In the same period, the maximum value of Songhuajiang River raw water was more than 1.0 mg/L, which exceeded the requirements of Case III water body. The ammonia nitrogen content of Songhuajiang River raw water exceeded the standard in some periods. However, after years of treatment, the ammonia nitrogen in Songhuajiang River water has a gradual downward trend.

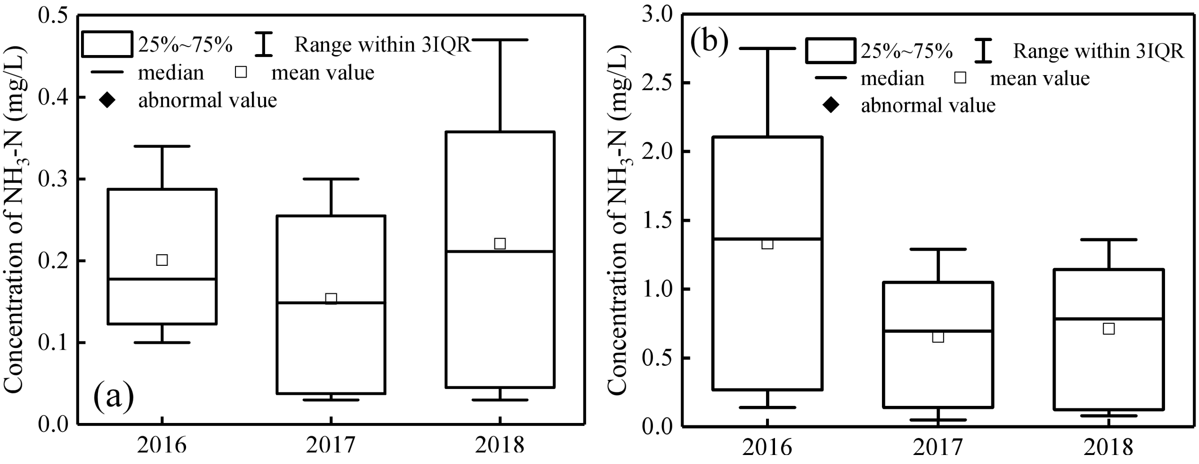


Fig. 3-5 Variation of NH_3-N in the Mopanshan Reservoir and Songhuajiang River. (a) Mopanshan Reservoir, (b) Songhuajiang River

3.3.2.2 Total phosphorus

The total phosphorus in water mainly comes from domestic sewage, chemical fertilizer, organophosphorus pesticide and phosphate detergent used in modern detergent. Phosphorus in water is a key element for algae growth, but excessive phosphorus is the main reason for the pollution and odor of water body and eutrophication of lakes. The “Environmental Quality Standards for Surface Water” (G3838-2002) stipulates that the Case III standard limit of total phosphorus is 0.2 mg/L (Lake and reservoir 0.05 mg/L). Fig. 3-6 shows the changes of total phosphorus content in Mopanshan raw water and Songhuajiang River raw water from 2016 to 2018.

It can be seen from Fig. 3-6 that the total phosphorus content of Mopanshan raw water exceeded the standard in 2017 and 2018, with the maximum of 0.09 mg/L, and the water body has the trend of eutrophication. However, the total phosphorus content of Songhuajiang River raw water is less than 0.2 mg/L, which meets the requirements of Case III water body standard, and after treatment, there is a downward trend year by year.

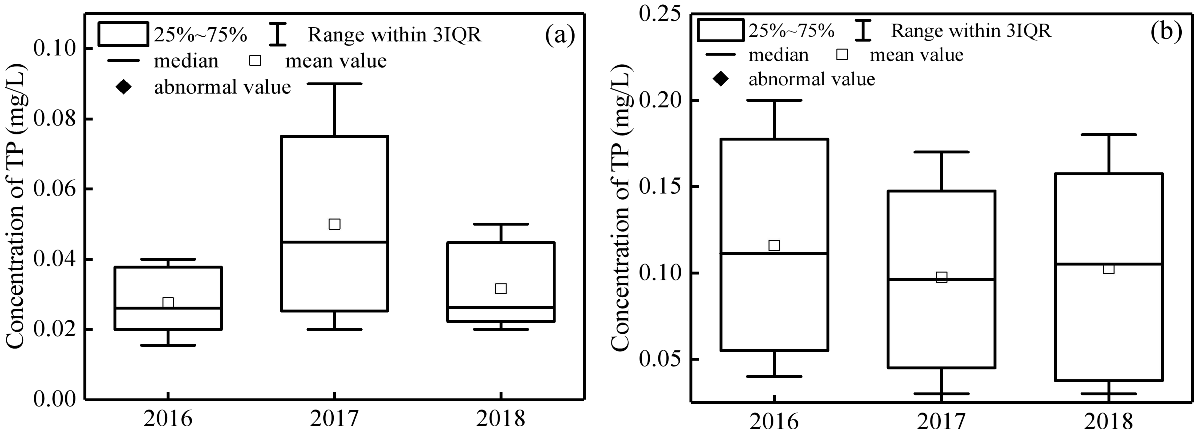


Fig. 3-6 Variation of TP in the Mopanshan Reservoir and Songhuajiang River. (a) Mopanshan Reservoir, (b) Songhuajiang River

3.3.2.3 Fluoride, sulfate, chloride and nitrate

The four projects represent the situation of anions in water. The standard limits of sulfate and chloride, nitrate and fluoride are 250 mg/L, 10 mg/L and 1.0 mg/L respectively. The anion changes of Mopanshan raw water and Songhuajiang River raw water from 2016 to 2018 are shown in Table 3-3.

From the median values in Table 3-3, it can be seen that the four anions content of Songhuajiang River raw water is higher than that of Mopanshan raw water, but the content is low compared with the standard limit value. The content of fluoride in the raw water of Songhuajiang River and Mopanshan Reservoir accords with the environmental quality standard of surface water, but the content of fluoride in the raw water of Songhuajiang River is higher than that of Mopanshan Reservoir, which can provide more fluorine for human body, so it is more suitable for drinking water.

In addition, the contents of sulfide, cyanide, volatile phenol and anionic synthetic detergent in Mopanshan Reservoir raw water and Songhuajiang River raw water were lower than the detection limit, and were not detected.

Table 3-3 Variation of anion in the Mopanshan Reservoir and Songhuajiang River

Water source	Year	Type	Water quality index (mg/L)			
			Sulfate	Chloride	Fluoride	Nitrate
Mopanshan Reservoir	2016	Interval value	6.54-8.71	0.80-1.63	0.08-0.34	0.70-1.05
		Mean value	7.70	1.23	0.22	0.90
	2017	Interval value	6.89-14.75	1.16-7.25	0.06-0.33	0.80-1.83
		Mean value	9.29	2.66	0.20	1.22
	2018	Interval value	7.86-10.12	1.82-3.28	0.02-0.18	1.13-1.81

		Mean value	9.41	2.35	0.06	1.43
Songhuajiang River	2016	Interval value	11.36-22.68	4.1-13.04	0.22-0.44	0.98-2.09
		Mean value	16.85	8.95	0.29	1.49
	2017	Interval value	2.16-26.48	5.45-17.24	0.15-0.66	0.97-3.68
		Mean value	16.48	9.88	0.35	1.47
	2018	Interval value	13.29-35.05	5.12-19.61	0.08-0.55	0.29-1.84
		Mean value	20.62	1.29	0.31	1.15

3.3.3 Metal index, selenium and arsenic

3.3.3.1 Iron and manganese

Iron and manganese are indispensable trace elements in human body, which are mainly absorbed by food and water. However, the excessive content of iron and manganese has a great impact on human body, and also affects the water purification process and effluent quality. According to the "Environmental Quality Standards for Surface Water" (G3838-2002), the standard limits of iron and manganese are 0.3 mg/L and 0.1mg/L respectively. Table 3-4 shows the changes of iron and manganese content in Mopanshan Reservoir raw water and Songhuajiang River raw water from 2016 to 2018.

It can be seen from Table 3-4 that there is a big difference in iron content between Mopanshan Reservoir raw water and Songhuajiang River raw water, but there is little difference in manganese content. However, the content of Fe and Mn in the raw water of Songhuajiang River is higher than that of Mopanshan Reservoir raw water. The main reason is that the river course of Songhuajiang River is longer and iron and manganese and other minerals in soil dissolve in water during runoff. However, the raw water channel of Mopanshan Reservoir is relatively short and has no significant contribution to the content of iron and manganese. Generally speaking, the iron and manganese contents in Mopanshan Reservoir and waters are not over the standard. For the Songhuajiang River water, the manganese content in the water is basically not over the standard, and the iron content is obviously over the standard, but through the water purification process, the iron can be removed effectively.

Table 3-4 Variation of Fe and Mn in the Mopanshan Reservoir and Songhuajiang River

Water source	Year	Type	Water quality (mg/L)	
			Fe	Mn
Mopanshan Reservoir	2016	Interval value	<0.002-0.161	<0.002-0.044
		Mean value	0.048	0.011
	2017	Interval value	<0.002-0.173	<0.002-0.085
		Mean value	0.057	0.020
	2018	Interval value	<0.002-0.210	<0.002-0.050

		Mean value	0.020	0.010
Songhuajiang River	2016	Interval value	0.044-5.402	0.006-0.13
		Mean value	1.687	0.047
	2017	Interval value	0.172-5.346	0.009-0.098
		Mean value	1.434	0.036
	2018	Interval value	0.010-4.832	0.003-0.091
		Mean value	0.727	0.041

In addition, through monitoring, it is found that the manganese content in Mopanshan Reservoir water is likely to exceed the standard in April. For two consecutive years in 2017 and 2018, the highest manganese content in water reached 0.3 mg/L in April, lasting for 4-6 days, as shown in Table 3-5. The phenomenon of excessive manganese in raw water of Mopanshan Reservoir is mainly due to the rise of water level and the increase of storage capacity after the end of ice sealing period in April. The cold and hot convection occurs in the upper and lower layers of the reservoir, which results in the desorption of manganese adsorbed by the sediment and release into the surface and middle layers of the reservoir, resulting in the manganese content of raw water taken from the intake exceeding the standard.

Table 3-5 Variation of Mn in April of 2017 and 2018 of the Mopanshan Reservoir

Year	Content of Mn (mg/L)					
2017	24th	25th	26th	27th	28th	29th
	0.035-0.069	0.034-0.220	0.076-0.232	0.106-0.190	0.154-0.263	0.128-0.199
2018	8th	9th	10th	11th	12th	13th
	0.058-0.127	0.079-0.158	0.104-0.166	0.045-0.096	0.011-0.015	0.084-0.139

3.3.3.2 Other heavy metals, selenium and arsenic

According to the “Environmental Quality Standards for Surface Water” (G3838-2002), heavy metals in class III water include copper, zinc, mercury, cadmium, chromium, lead and silver. The standard limits are 1.0 mg/L, 1.0 mg/L, 0.0001 mg/L, 0.005 mg/L, 0.05 mg/L, 0.05 mg/L and 0.05 mg/L respectively. The standard limits of selenium and arsenic are 0.01 mg/L and 0.05 mg/L. The contents of heavy metal cations, selenium and arsenic in raw water of Mopanshan Reservoir and Songhuajiang River are shown in Table 3-6. From the data in the table, it can be seen that the water quality indexes detected are all less than the standard limits in the environmental quality standard for surface water (G3838-2002).

Table 3-6 Variation of heavy metal, Se and As in the Mopanshan Reservoir and Songhuajiang River

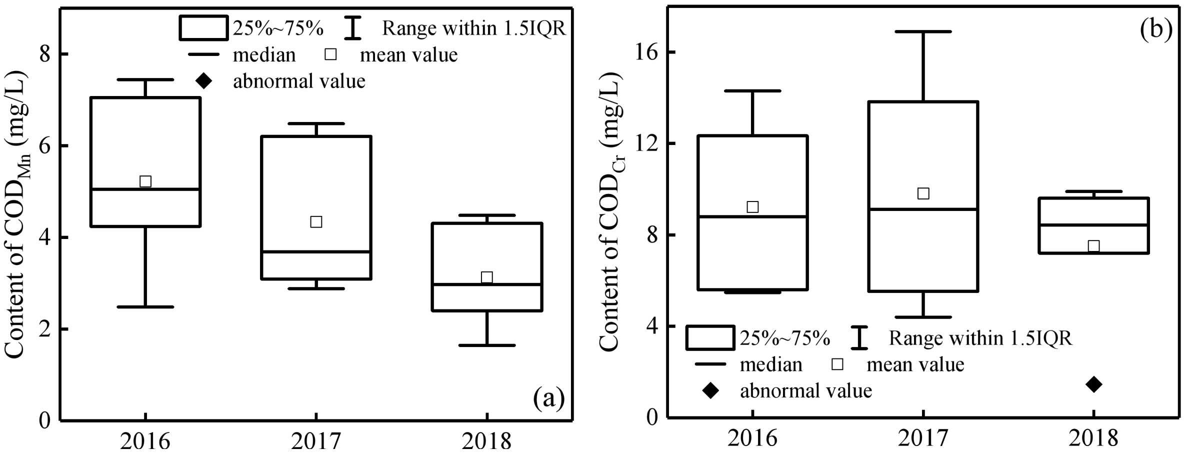
Water source	Year	Water quality index (mg/L)								
		Cu	Zn	Hg	Cd	Cr	Pb	Ag	Se	As
Mopanshan	2013	0.004	0.011	<0.00002	<0.	<0.	<0.	<0.	<0.	<0.002

Reservoir					002	004	002	002	0002	
	2014	0.004	0.038	<0.00002	<0.002	<0.004	<0.002	<0.002	<0.0002	0.0002
	2015	0.004	0.045	<0.00002	<0.002	<0.004	<0.002	<0.002	<0.0002	<0.0002
Songhuajiang River	2013	0.002	0.006	<0.00002	<0.002	<0.004	<0.002	<0.002	<0.0002	0.0003
	2014	0.003	0.021	<0.00002	<0.002	<0.004	<0.002	<0.002	<0.0002	0.0003
	2015	<0.002	0.006	<0.00002	<0.002	<0.004	<0.002	<0.002	<0.0002	0.0003

3.3.4 Comprehensive organic contaminant index

3.3.4.1 Permanganate index (COD_{Mn}) and chemical oxygen demand (COD_{Cr})

Permanganate index (COD_{Mn}) and chemical oxygen demand (COD_{Cr}) indirectly indicate the content of organic pollutants in water. The standard limits of COD_{Mn} and COD_{Cr} in Case III water of the "Environmental Quality Standards for Surface Water" (GB3838-2002) are 6 mg/L and 20 mg/L respectively. The changes of COD_{Mn} and COD_{Cr} contents in Mopanshan Reservoir raw water and Songhuajiang River raw water from 2016 to 2018 are shown in Fig. 3-7. From the data analysis, the COD_{Mn} and COD_{Cr} contents of raw water of Mopanshan Reservoir and Songhuajiang River showed a decreasing trend year by year. The COD_{Cr} content of Songhuajiang River is slightly higher than that of Mopanshan Reservoir raw water, which is mainly due to the industrial, agricultural and human activities around the Songhuajiang River Basin. In addition, the maximum content of COD_{Mn} in Mopanshan Reservoir and Songhuajiang rivers exceeded 6mg/L, which indicated that the water was polluted by organic pollutants to some extent.



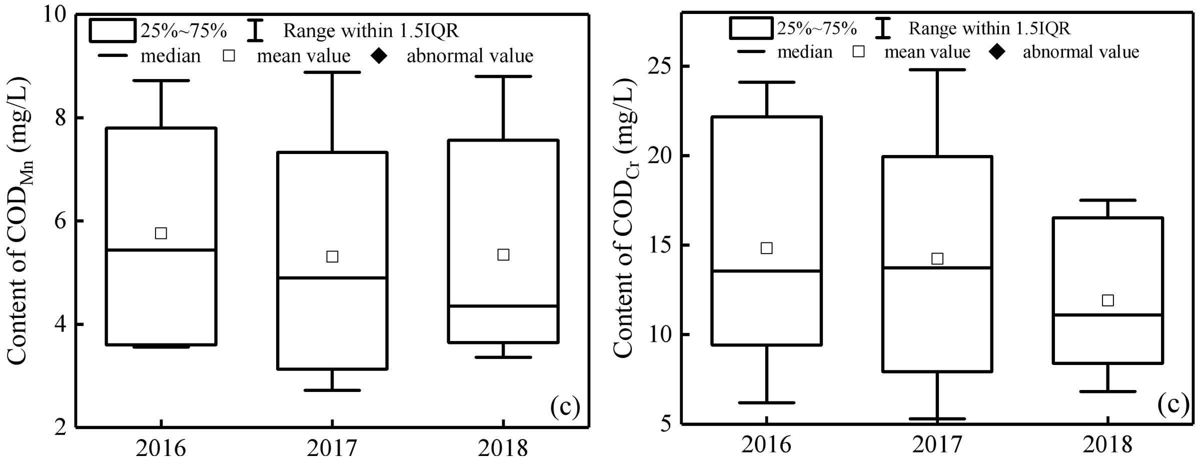


Fig. 3-7 Variation of COD_{Mn} and COD_{Cr} in the Mopanshan Reservoir and Songhuajiang River. (a) COD_{Mn} in the Mopanshan Reservoir, (b) COD_{Cr} in the Mopanshan Reservoir, (c) COD_{Mn} in the Songhuajiang River, (d) COD_{Cr} in the Songhuajiang River

Both COD_{Cr} and COD_{Mn} can indicate the degree of water pollution by organic and reducing substances, so there is a certain quantitative relationship between them (as shown in Fig. 3-8 and Fig. 3-9). The COD_{Cr} and COD_{Mn} of Mopanshan Reservoir and Songhuajiang River were regressed, the regression equations are as follows $Y=1.597x^2 - 11.64x + 32.01$ 和 $Y=0.378x^3 - 3.554x^2 + 11.16x - 0.942$ 。 When the value of COD_{Mn} increases, COD_{Cr} also shows an increasing trend, which is consistent with the changing law of monitoring data.

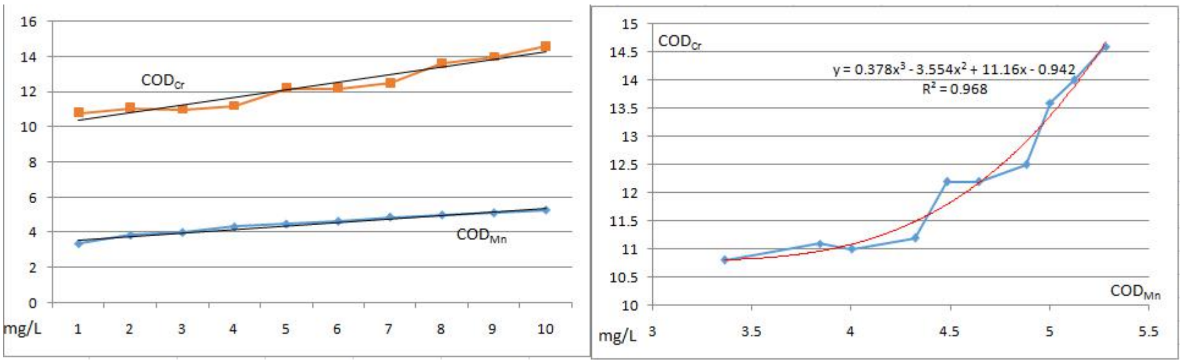


Fig. 3-8 The variation trend and regression of COD_{Cr} with COD_{Mn} in the Mopanshan Reservoir

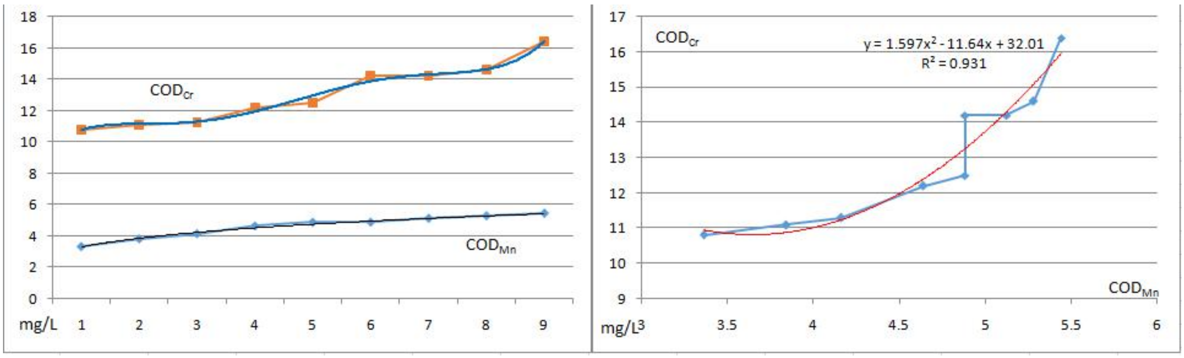


Fig. 3-9 The variation trend and regression of COD_{Cr} with COD_{Mn} in the Songhuajiang River

3.3.4.2 Five days' biochemical oxygen demand (BOD_5)

Five day biochemical oxygen demand (BOD_5) refers to the amount of some oxidizable substances in a certain volume of water decomposed by microorganisms in a certain period of time. In particular, the amount of dissolved oxygen consumed by organic matter is a comprehensive indicator reflecting the content of organic pollutants in water. According to the “Environmental Quality Standards for Surface Water” (GB3838-2002), the standard limit of BOD_5 in Case III water is 4 mg/L. BOD_5 content changes of Mopanshan Reservoir raw water and Songhuajiang River raw water from 2016 to 2018 are shown in Fig. 3-10. As can be seen from the figure, except for the poor water quality in Mopanshan Reservoir in 2017 and the phenomenon of BOD_5 exceeding the standard, other detection values can meet the requirements of Case III water body standard. However, the level of BOD_5 in Songhuajiang River is more serious than that in Mopanshan Reservoir, but there is still a trend of decreasing year by year. Since BOD_5 and COD_{Mn} are both comprehensive indicators of organic pollution in water body, the reason for exceeding the standard is consistent with that of COD_{Mn} seasonally.

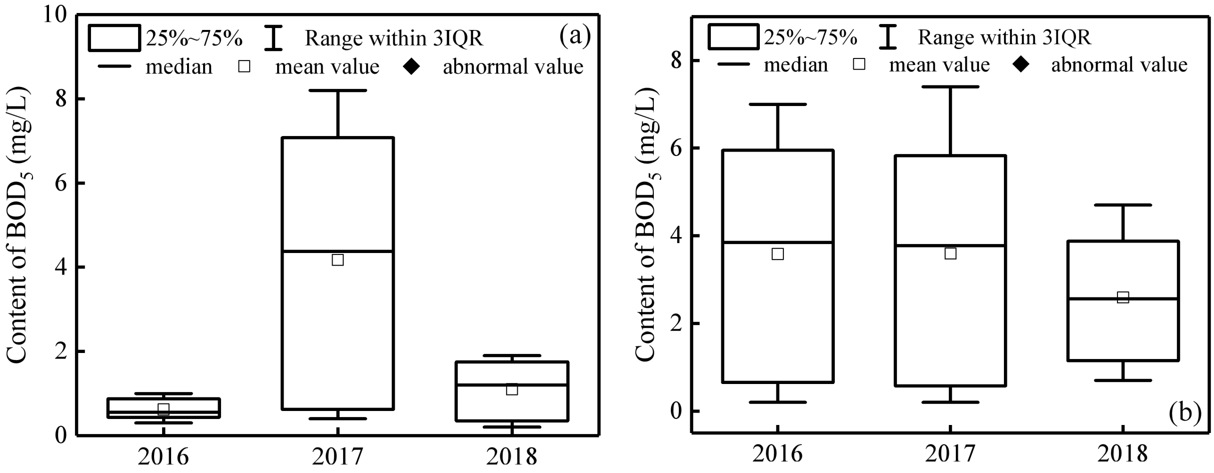


Fig. 3-10 Variation of BOD_5 in the Mopanshan Reservoir and Songhuajiang River. (a) Mopanshan Reservoir, (b) Songhuajiang River

3.3.5 Biological index

3.3.5.1 Fecal coliform

Fecal coliform is a group of intestinal bacteria that grow in the intestines of animals and enter the water body with the excretion of feces. Coliforms are not used as the evaluation basis in the environmental quality assessment method of surface water, but can reflect the degree of water affected by human activities. According to the “Environmental Quality Standards for Surface Water” (GB3838-2002), the standard limit of fecal coliform in Case III water is 10000 cells/L. Table 3-7 shows the average annual fecal coliform content changes in Mopanshan Reservoir raw water and Songhuajiang River raw water from 2016 to 2018.

It can be seen from the table that the number of fecal coliforms in Songhuajiang raw water is significantly higher than that in Mopanshan Reservoir raw water. The reason is that there are point source and non-point source pollution along the Songhuajiang River, such as the discharge of domestic sewage and human living activities. However, the ecological protection around Mopanshan Reservoir is better and less affected by human activities.

Table 3-7 Variation of fecal coliform in the raw water of the Mopanshan Reservoir and Songhuajiang River

Year / Water source		2016	2017	2018
Mopanshan Reservoir	Interval value (A/L)	0-280	0-6402	0-4757
	Mean value (A/L)	48	41	49
Songhuajiang River	Interval value (A/L)	100-54000	40-96000	20-54000
	Mean value (A/L)	6945	12443	8105

3.3.5.2 Algae

Algae refers to a group of autotrophic microorganisms that live in the water in a floating way and can carry out photosynthesis. There are many kinds of algae, which do not require strict environmental conditions and have strong adaptability. However, the existence of a large number of algae will not only destroy the balance and stability of the water ecosystem, but also release microcystins when there are Microcystis, which will have adverse effects on water quality and water purification process. Table 3-8 shows the change of algae quantity in Mopanshan Reservoir from 2016 to 2018.

It can be concluded from the table that the order of magnitude of algae in Mopanshan Reservoir is not large, and the total number of algae decreases with the increase of water depth. The main reason is that the light intensity in the surface layer is higher than that in the bottom layer, which leads to the decrease of the vertical distribution. When the water temperature rises, the number of algae increases, which indicates that the change of algae quantity has seasonal variation. In general, the total number of algae in Mopanshan Reservoir is low, and the time limit in summer is short, and the temperature is not high, so the risk of large-scale algae outbreak is small.

Table 3-8 Variation of alga in the Mopanshan Reservoir

Month	Number of alga (A/L)		
	middle-level in 2016	Surface-level in 2017	Surface-level in 2018
1	1.3×10^6	1.8×10^6	1.5×10^6
2	2.4×10^6	2.9×10^6	2.2×10^6
3	4.7×10^6	5.3×10^6	6.3×10^6
4	5.6×10^6	5.8×10^6	5.9×10^6

5	$5.9.\times10^{6}$	6.1×10^{6}	1.2×10^{7}
6	3.3×10^{6}	4.7×10^{7}	1.4×10^{7}
7	1.1×10^{6}	8.7×10^{7}	9.2×10^{7}
8	7.3×10^{6}	8.2×10^{7}	9.4×10^{6}
9	1.2×10^{6}	5.9×10^{7}	5.3×10^{6}
10	1.6×10^{6}	4.3×10^{6}	1.2×10^{6}
11	1.5×10^{6}	2.3×10^{6}	1.5×10^{6}
12	1.7×10^{6}	3.0×10^{6}	2.0×10^{6}

3.3.6 Assessment of the Water Quality Indicator (WQI)

Since the 1960s, dozens of water quality indexes have been put forward to evaluate water pollution, such as single factor index method, Nemerow index method, brown water quality index method, comprehensive pollution index method, fuzzy mathematics evaluation method, principal component analysis method, grey cluster analysis method and artificial neural network method. For the above methods, domestic scholars have done a lot of research and improvement work, which has a certain theoretical value, but due to the limitations of various conditions, it has not been widely used in practice, so it is lack of practical significance. Among them, the comprehensive water quality index with ten parameters proposed by Horton in 1965 has been gradually favored by researchers, and has been improved to comprehensively and systematically evaluate the water pollution. In particular, the Canadian water quality index method is widely used to evaluate the quality of drinking water in the world [12, 13].

Based on the water quality data of Mopanshan Reservoir and Songhuajiang River from 2016 to 2018, based on nine indicators including ammonia nitrogen, COD_{Mn}, total phosphorus, turbidity, chroma, dissolved oxygen, total hardness, biochemical oxygen demand and fecal coliform bacteria, and based on the environmental quality standard of surface water, CCME WQI method was used to evaluate the water pollution status of these two water sources. The evaluation results are shown in Table 3-9. It can be seen from the data that the CCME WQI scores of Mopanshan Reservoir from 2016 to 2018 are 76, 68 and 64, respectively. The pollution situation has a downward trend year by year, and the water level has also changed from medium to poor. This may be related to the frequent human and agricultural activities around Mopanshan Reservoir in recent two years. After years of treatment, the water quality of Songhuajiang River has been improved. The CCME WQI score increased from 54 to 65, and the water quality changed from poor to medium, indicating that the water quality of Songhuajiang River has been significantly improved after years of government treatment.

Table 3-9 Evaluation result of the CCME WQI

Drinking water source	Year	Score of CCME WQI	Rank of CCME WQI

Mopanshan Reservoir	2016	76	Acceptable
	2017	68	Acceptable
	2018	64	Poor
Songhuajiang River	2016	54	Poor
	2017	59	Poor
	2018	65	Acceptable

3.4 Summary

This chapter makes a comparative analysis of the water types and quality of Mopanshan Reservoir water and Songhuajiang River water, and the following three results can be obtained.

(1) The rates of reaching the Case III standard in the Mopanshan Reservoir are 83.33%, 91.67%, 100%, 58.33%, and 83.33% from 2014 to 2018. The rate of reaching the Case III standard in the Songhuajiang River accounted for 50%, 58.33%, 91.67%, 91.67%, and 100% from 2014 to 2018. Results showed that the Mopanshan Reservoir and the Songhuajiang River water both could reach the Case III standard.

(2) The pH value of Mopanshan Reservoir raw water is less than 7.0, and that of Songhuajiang River is more than 7.0. The total hardness of Mopanshan Reservoir raw water is lower than that of Songhuajiang River water, but the total phosphorus of Mopanshan Reservoir water exceeds the standard. The contents of dissolved oxygen, ammonia nitrogen, fluoride, sulfate, chloride, nitrate, iron and fecal coliform in raw water of Songhuajiang River were higher than those in Mopanshan Reservoir raw water. The potassium permanganate index and chemical oxygen demand of the raw water of Mopanshan Reservoir and Songhuajiang River decreased year by year, but the organic matter comprehensive index of Songhuajiang River was still higher than that of Mopanshan Reservoir raw water.

(3) The CCME WQI scores of Mopanshan Reservoir from 2016 to 2018 are 76, 68 and 64, respectively, and the pollution situation has an increasing trend year by year. After years of treatment, the water quality of Songhuajiang River has been improved. The CCME WQI score increased from 54 to 65, indicating that the water quality of Songhuajiang River has been significantly improved after years of treatment by the government.

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Chapter 4. Pollution source analysis and comparison of the finished water quality of the Mopanshan Reservoir and Songhuajiang River

4.1 Introduction

In the third chapter, the water types and water quality of Mopanshan Reservoir and Songhuajiang River are compared and analyzed comprehensively. However, the water source is an important factor for the sustainable development of regional ecological environment. Climate, topography, human activities, industrial and agricultural production will have a certain impact on the water quality of the water source area. Therefore, it is necessary to study the distribution of characteristic pollutants and pollution sources in water sources. The Songhuajiang River and Mopanshan Reservoir studied in this project are two important water sources in Harbin, which have far-reaching significance for the development and planning of Harbin city. In this chapter, through the comparative study of the change trend of characteristic pollutants in the two water sources, and the distribution of pollution sources, we can have a more comprehensive and profound understanding of the water quality of the two water sources in Harbin. In addition, this chapter also uses the traditional water purification process (coagulation-sedimentation-filtration-disinfection) to treat Mopanshan Reservoir water and Songhuajiang River water. Taking the "Standards for drinking water quality" (GB5749-2006) as the evaluation standard, this chapter compares and analyzes the effluent quality of the two water sources after traditional treatment, and provides reference for the subsequent process upgrading and transformation.

This chapter is organized as the following. In Chapter 4.2 the analysis of characteristic pollutants of the two drinking water sources are compared and discussed. The distribution analysis of pollution sources is presented in Chapter 4.3. And the comparison analysis of the finished water quality is presented in Chapter 4.4. The Chapter 4.5 is the summary.

4.2 Comparison analysis of the characteristic pollutants

4.2.1 Analysis of characteristic pollutants of the Mopanshan Reservoir

According to the “Environmental Quality Standards for Surface Water” (GB3838-2002), 109 indices were measured to evaluate the water quality of the Mopanshan Reservoir. The majority of the indices were undetected or close to the limit of detection (LOD) for years, aside from the permanganate index (COD_{Mn}), total nitrogen (TN), and total phosphorus (TP). Thus, the COD_{Mn}, TN, and TP were considered as the characteristic pollutants in the Mopanshan Reservoir. A detailed analysis is shown in Fig. 4-1.

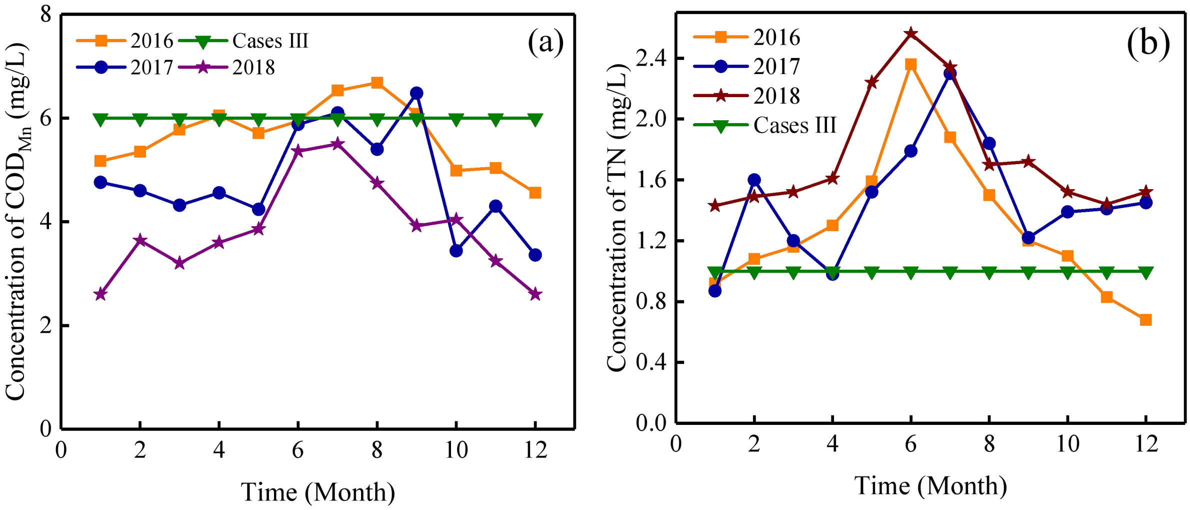
Fig. 4-1 (a) showed that the value of COD_{Mn} exceeded the Case III standard (6 mg/L) in July-September of 2016 and September of 2017. It accorded with the Case III standard for the rest of the monitoring period. Moreover, the COD_{Mn} value has a characteristics of seasonal variation. There are higher values of COD_{Mn} in the rainy season and lower values in the icebound season. It is probably because surface runoff carries organic pollutants from soils into the reservoir with increased precipitation in summer and autumn. This results in the increase of COD_{Mn}. In contrast, the reservoir is enclosed in the icebound season, which reduces the exogenous input of pollutants.

Generally speaking, the concentration of COD_{Mn} declined year by year. Especially in 2018, the COD_{Mn} value was controlled effectively for all the monitoring ones being below the Case III standard.

The variation of TN in the Mopanshan Reservoir from 2016 to 2018 was presented in Fig. 4-1 (b). The value of TN in the Mopanshan Reservoir exceeded the Case III standard (1.0 mg/L) and was even higher than the inferior Case V standard (2.0 mg/L). Specifically, the value of TN was at a high level from April to September every year and reached a peak during June and July (2.5 mg/L). The agricultural production period usually occurs from April to September. Therefore, the value of TN increased with the nitrogen-containing fertilizers entering into the reservoir through surface runoff. In general, there exist a potential risk of water eutrophication in the Mopanshan Reservoir for the increasing of TN value year by year. Furthermore, the TN variation also has a characteristic of seasonal variation, with higher values in the rainy season and lower values in the icebound season.

The variation of TP in the Mopanshan Reservoir from 2016 to 2018 is illustrated in Fig. 4-1 (c). The value of TP was lower than 0.05 mg/L in 2018. Meanwhile, it exceeded the Case III standard (0.05 mg/L) in March and June of 2016 and April and May of 2017. The value of TP was close to the Case III standard in the monitoring years, implying a risk of eutrophication. Meanwhile, the high value of TP and TN both occurred in the agricultural production period. The value of TP increased sharply in June probably due to the phosphorus fertilizer used in agricultural production entering the reservoir along with the surface runoff.

In general, the characteristic pollutants in the Mopanshan Reservoir all have a characteristic of seasonal variation. The COD_{Mn}, TN, and TP are the crucial control indicators to guarantee the water quality of the reservoir, especially in the rainy season.



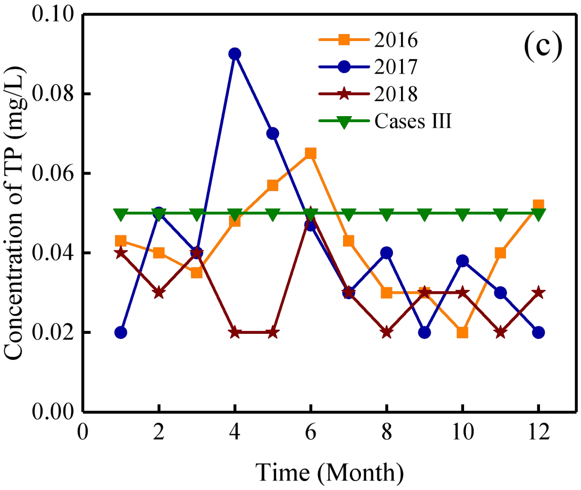


Fig. 4-1 Variation of COD_{Mn}, TN and TP in the Mopanshan Reservoir from 2016 to 2018. a) COD_{Mn}, b) TN, c) TP

4.2.2 Analysis of characteristic pollutants of the Songhuajiang River

The majority of the referred 109 indices in the Songhuajiang River were all similar to that in the Mopanshan Reservoir. They all can accorded with the Case III standard, aside from the COD_{Mn}, COD_{cr}, and ammonia nitrogen (NH_4^+-N). Thus, the COD_{Mn}, COD_{cr}, and NH_4^+-N were considered the characteristic pollutants in the Songhuajiang River. Since the nitrobenzene pollution event in 2005, the Songhuajiang River has suffered a serious defeat and undergone a series of repairs. Some special years (2005, 2006, 2010, 2015 and 2017) are selected to monitor the variation of COD_{Mn} and NH_4^+-N roundly. The detailed results are shown in Fig. 4-2.

Fig. 4-2 (a) showed the variation trend of COD_{Mn} in the Songhuajiang River in the special years. Evidently, the variation of COD_{Mn} also has a characteristic of seasonal variation. In the rainy season, the COD_{Mn} has a high value with an average of 7.03 mg/L. It mainly because the increase of precipitation causing the surface water run off carrying organic pollutants into the river. Meanwhile, there are many enterprises on both sides of the river. They discharge large quantities of sewage into the river. Thus, the Songhuajiang River carries a huge pollution load in the rainy season. This was the primary reason for the COD_{Mn} exceeding the standard. However, the COD_{Mn} value declined in the icebound season. It is mainly due to a decreased input of exogenous pollutants for the frozen river. The contribution of the COD_{Mn} value mainly depends on the release of the bottom sludge. Furthermore, the content of COD_{Mn} declined year by year over a decade of governance. Especially in 2017, the COD_{Mn} values are all below the Case III standard, with an average of 5.28 mg/L. This reveals that the Songhuajiang River possessed reduced organic contamination after treatment in the past decade.

The variation of NH_4^+-N in the Songhuajiang River is presented in Fig. 4-2 (b). Evidence shows that the variation of NH_4^+-N also has a characteristic of seasonal variation. However, the variation is different from that of COD_{Mn}. The content of NH_4^+-N has a high value in the icebound season, while it dramatically declines in the rainy season. The average values of NH_4^+-N in the icebound season of 2005, 2006, 2010, 2015 and 2017 are 2.14 mg/L, 1.81 mg/L, 1.27 mg/L, 1.18 mg/L and 0.88 mg/L, respectively. They are 0.37 mg/L, 0.32 mg/L, 0.28 mg/L, 0.17 mg/L and 0.26 mg/L in the rainy season, respectively. This may be due to several factors in the icebound season, including low water temperature and precipitation in winter, a relaxed standard of NH_4^+-N standard discharge from the municipal sewage treatment plant, the poor activity of the bacteria and the reduced self-purification capacity of the water. However, the content of NH_4^+-N can be reduced in the rainy season for the dilution of precipitation and increase of the self-purification capacity. Furthermore, the content of NH_4^+-N in the Songhuajiang River has declined over the recent ten years for its continuous expansion of management. For example, in 2005, the content of ammonia nitrogen reached 3.44 mg/L, which far exceeded the poor level V (2 mg/L). However, in 2017, the highest content of NH_4^+-N was observed from January to April. It measured lower than 1 mg/L, meeting the Case III standard.

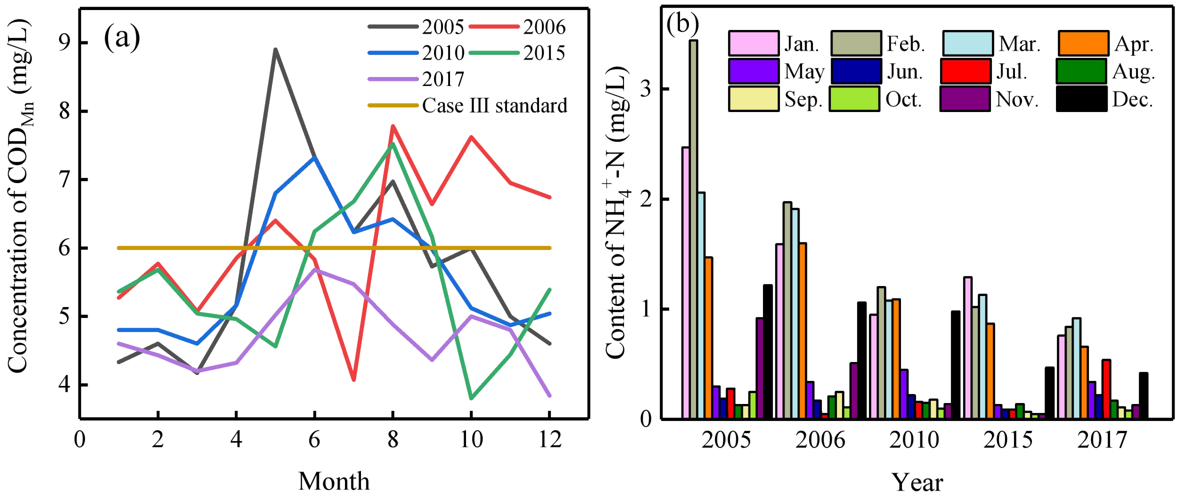


Fig. 4-2 Variation of COD_{Mn} and NH_4^+-N in the Songhuajiang River. a) COD_{Mn}, b) NH_4^+-N

The variation of COD_{Cr} from 2016 to 2018 was presented in Fig. 4-3. In 2016 and 2017, the value of COD_{Cr} in the Songhuajiang River reached a maximum of 24.1 mg/L and 24.8 mg/L, respectively, which were higher than the Case III standard (20 mg/L). In 2018, the value of COD_{Cr} met the level III standard, indicating that the water quality of the Songhuajiang River tended to improve.

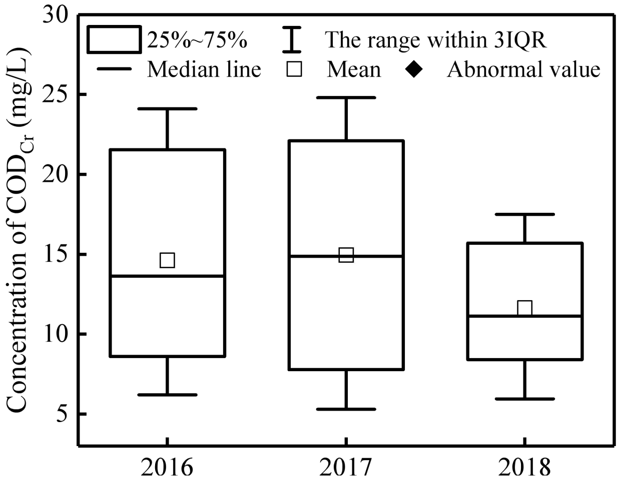


Fig. 4-3 Variation of COD_{Cr} in the Songhuajiang river

The above results showed that the characteristic pollutants of the Mopanshan Reservoir are the COD_{Mn}, TN, and TP. Meanwhile, they are COD_{Mn}, COD_{Cr}, and NH_4^+-N in the Songhuajiang River. These characteristic pollutants all have a characteristic of seasonal variation. However, the water quality of the Mopanshan Reservoir and Songhuajiang River both reached the Case III standard in 2017. The types of characteristic pollutants are not exactly the same. The only common one was the COD_{Mn}. The above analysis indicated that the value of COD_{Mn} in the Songhuajiang River was higher than that in the Mopanshan Reservoir. However, the referred pollutants can be removed excellently through water purification treatment. Meanwhile, the content of NH_4^+-N in the Songhuajiang River has decreased gradually year by year, while the Mopanshan Reservoir has a trend of eutrophication. The water quality of the Songhuajiang River can meet the Case III water standard, which indicates that the water can reach the requirements for drinking water sources.

4.3 Comparative study on the distribution of pollution sources

4.3.1 Pollution source analysis of the Mopanshan reservoir

4.3.1.1 Pollution source analysis of the Mopanshan reservoir

(1) The source of non-point source pollution in the reservoir area. There are tens of thousands of residents in the first and second grade protection areas of Mopanshan Reservoir. The nitrogen and phosphorus loads in rural domestic sewage consumed by residents' daily life are relatively high, most of which are caused by residents' excreta and synthetic detergent. In addition, the rural urban population is relatively scattered. Most of the rural areas have no designated garbage storage sites and special garbage collection, transportation, landfill and treatment systems. In addition, some farmers have a weak awareness of environmental protection, and the generated rural domestic waste is often scattered and stacked at will. In case of rain, garbage will be washed into the river by surface runoff.

(2) Pesticide and chemical fertilizer pollution accounted for a large proportion of the area pollution. There are 82300 mu of cultivated land in the upstream of Mopanshan Reservoir, and the

cultivated land above the dam site accounts for 4.8% of the total catchment area. According to statistics, 9.72 tons of pesticides and 810.61 tons of chemical fertilizers are used every year. The results showed that the utilization rate of nitrogen fertilizer was only 20%~35%. Due to the strong fixation of phosphorus by soil, the utilization rate of phosphate fertilizer is 10%~20%. As a result, a large number of fertilizer which has not been absorbed by plants will enter the water body of Mopanshan Reservoir with soil erosion and surface runoff under the effect of rainfall runoff.

(3) Tree cutting in the upper reaches affects the sustainable water supply capacity of water sources. There are seven forest farms in shanhetun Forestry Bureau in the upper reaches of Mopanshan Reservoir. The tree cutting activities seriously threaten the sustainable water supply capacity of water source, and the forest vegetation and wetland in the water source area are destroyed. The water conservation capacity of the reservoir is greatly reduced and soil erosion is caused, which has a significant impact on the water quality and water quantity of Mopanshan Reservoir.

4.3.1.2 Eutrophication trend analysis of the Mopanshan Reservoir

The evaluation of eutrophic state index is usually used to study the eutrophication trend of water quality in the reservoir. It mainly involves in five eutrophication indicators: TN, TP, COD_{Mn}, SD and Chl-a [1, 2]. According to the water quality analysis of the Mopanshan Reservoir, TN and TP exceed the Cases III standard. It implied the reservoir existed the risk of eutrophication. In this work, the amended Carlson trophic state index (TSIM) and the comprehensive trophic level index (TLI) were applied to evaluate the eutrophication of the Mopanshan Reservoir. The value of the eutrophication indicators of the reservoir from 2016 to 2018 are listed in Table 4-1. It was obvious that the value of COD_{Mn} decreased year by year, while the value of TN increased year by year. The value of Chl-a was also increasing by years, which caused the transparency of the reservoir reduced every year.

Table 4-1 The value of the eutrophication indicators of the Mopanshan Reservoir from 2016 to 2018

Year	Eutrophication indicator				
	TP (mg/L)	TN (mg/L)	COD_{Mn} (mg/L)	Chla (μg/L)	SD (m)
2016	0.028	1.22	5.53	16.34	0.5
2017	0.05	1.87	4.26	25.63	0.4
2018	0.034	2.34	3.28	37.41	0.3

The TSIM was calculated based on the formulas in Table 2-6. The results are presented in Table 4-2. In general, the higher the Carson index at the same nourishment state, the more severe the eutrophication is. The Carson index of the Mopanshan Reservoir from 2016 to 2018 were 61.49, 66.79 and 68.15, respectively. The Carson index increased by years. The reservoir showed a state of eutropher. Compared to the Carson index, the TLI take TN and COD_{Mn} into account, which could comprehensively appraise the eutrophication of the reservoir. The results about the TLI are listed in Table 4-3. In general, the higher the TLI value at the same nourishment state, the worse the eutrophication is. It can be seen that the TLI of the Mopanshan Reservoir from 2016 to 2018 were 52.32, 56.21, and 56.55, respectively. The TLI also increased by years, while the reservoir showed a state of light eutropher. In a word, the Mopanshan Reservoir exhibited a characteristic of eutrophication in recent years, no matter what the evaluation method is. The eutrophication not only can produce algal toxin, but also can induce the generation of trichloromethane, which reduce the safety of drinking water [3].

As a whole, the water quality of the Mopanshan Reservoir is still suitable for drinking water in recent years. However, the existing of some seasonal-exceeding parameters and trend of eutrophication increased the difficulty in water treatment and safety risk of drinking water. Thus, it is necessary to dispose the water of the reservoir to improve the water quality of the drinking water source.

Table 4-2 The amended Carlson trophic state index of the reservoir

Year	Eutrophication indicator			The Carlson Index-TSIM	Eutrophic state
	TSIM (TP)	TSIM (Chla)	TSIM (SD)		
2016	52.92	55.09	76.45	61.49	Eutropher
2017	60.20	60.00	80.17	66.79	Eutropher
2018	55.35	64.13	84.97	68.15	Eutropher

Table 4-3 The comprehensive trophic level index of the reservoir

Year	Eutrophication indicator					Comprehensive trophic level index-TLI	Eutrophic state
	TLI (TP)	TLI (TN)	TLI (COD_{Mn})	TLI (Chla)	TLI (SD)		
2016	36.29	57.90	46.60	55.34	64.63	52.32	Light eutropher
2017	45.71	65.13	39.66	60.23	68.96	56.21	Light eutropher
2018	39.45	68.93	32.70	64.33	74.54	56.55	Light eutropher

The comparison of the two evaluation methods is shown in Fig. 4-4. Generally speaking, when TN and TP exceed 0.2 mg/L and 0.02 mg/L respectively, the water body will be in eutrophication state, which may cause water bloom. However, the main pollutants in Mopanshan Reservoir are total nitrogen and total phosphorus, with the maximum values of 2.56 mg/L and 0.09 mg/L, respectively. It can be clearly seen from the figure that the eutrophication degree of Mopanshan Reservoir is increasing year by year. The comprehensive nutritional status index was lower than that of Casson index, which was mainly due to the neglect of total nitrogen and COD_{Mn}, and more emphasis on the effect of total phosphorus.

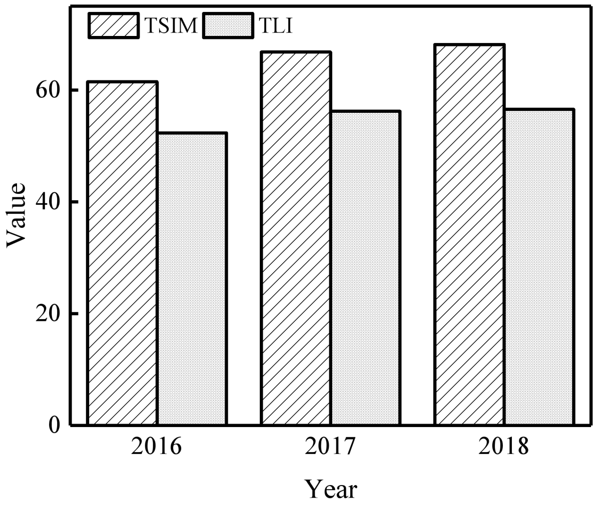


Fig. 4-4 Comparison diagram of the TSIM and TLI

Generally speaking, the eutrophication status of Mopanshan Reservoir is increasing year by year through the analysis of Carson index and comprehensive trophic state index.

4.3.1.3 Pollutant balance accounting and pollutant source distribution of the Mopanshan Reservoir

(1) Pollutant balance accounting

A large number of data show that the water eutrophication in China is becoming more and more serious. The survey from 1978 to 1980 showed that eutrophic lakes only accounted for 5% of the total investigated area. By 2005, it had reached 60%. Up to now, eutrophication has occurred in water bodies from south to North in China. In 1992, a large-scale toxic cyanobacteria bloom occurred in Dianchi Lake for the first time, and the Third Waterworks was closed for this reason. In 1997, due to the serious eutrophication of Guanting reservoir, it was forced to withdraw from the domestic water source of Beijing. In 1998 and 1999, a large area of cyanobacteria blooms occurred in Qiandao Lake. In late February 2005, pseudopolydinium blooms occurred in the bay of Gaolan river. In 2005 and 2006, algal blooms occurred continuously in Xiangxihe reservoir of the Three Gorges Reservoir in spring. In May 2007, Taihu Lake blooms broke out earlier than in previous years, which caused the public drinking water crisis. In early March 2008, a water bloom broke out in Songzi River, a tributary of the South Bank of Gezhouba downstream of the Yangtze River. In July 2008, cyanobacteria bloom occurred in Xuanwu Lake of Nanjing for the first time. It can be seen that the eutrophication of Mopanshan Reservoir is not an example. If we do not protect it, control it, and do not carry out ecological construction, the eutrophication trend of Mopanshan Reservoir will increase day by day.

In addition, Mopanshan Reservoir is lack of liquidity, low storage capacity, and there is no industrial area upstream, so there is no centralized discharge of industrial pollution. Therefore, the eutrophication trend of Mopanshan Reservoir is mainly caused by organic matter carried by natural factors.

Based on the hydrological and water quality data of the lake and reservoir in recent years, the input-output balance relationship is established. The water balance and pollutant input balance in Mopanshan Reservoir are shown in Fig. 4-5. The water source reservoir is sensitive to the data of external confluence and pollutants, and its tolerance to pollutants is low. Once the pollutants are imported excessively, it will cause serious water pollution and even lose the function of water source. Relevant studies show that the excessive input of pollutants, the depletion of upstream resources, the deposition of pollutants in lakes and reservoirs, and the pollution of surrounding catchment areas all affect the reservoir function. This section uses the output coefficient method model to calculate the total amount of pollutants in Mopanshan Reservoir, and analyzes the concentration transmission and change of water pollutants in the reservoir area. The model mainly includes two aspects: upstream input and pollution in catchment area. The water pollution of Mopanshan Reservoir is greatly affected by upstream input. Even if the pollutants generated during rainfall are rapidly imported, they mainly enter the reservoir through three inflow rivers (Dasha River, Sasha River and Lalin River). Turbidity, chroma and dissolved organic carbon (DOC) were used as the main control indexes. The turbidity material mainly includes suspended solids and colloids, and the color forming substances are mainly small particle colloids (1-10 nm). Soluble organic carbon (DOC) contains not only natural organic colloids, but also a small amount of man-made organic pollution. Therefore, the related water quality state variables controlling the mass balance equation in Mopanshan Reservoir can be expressed as follows.

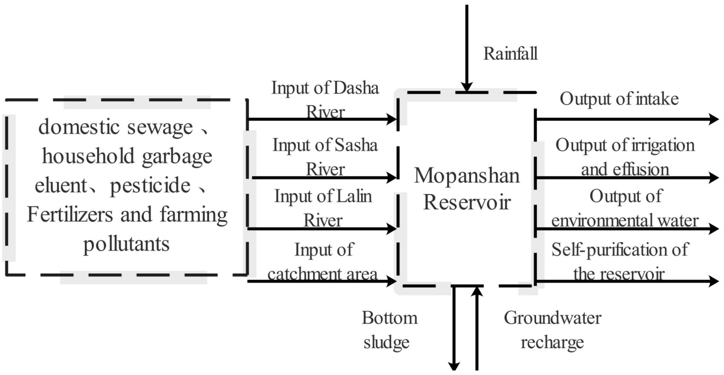


Fig. 4-5 Diagram of water and pollutant balance of the Mopanshan Reservoir

$$\frac{\partial}{\partial t}(m_x m_y HC)+\frac{\partial}{\partial x}(m_y H\mu C)+\frac{\partial}{\partial y}(m_x H v C)+\frac{\partial}{\partial c}(m_x m_y \omega C)$$

$$=\frac{\partial}{\partial x}\left(\frac{m_y HA_x}{m_x}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{m_x HA_y}{m_y}\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial y}\left(m_x m_y \frac{A_z}{H}\frac{\partial C}{\partial c}\right)+m_x m_y HS_c \qquad (4\text{-}1)$$

Where, C--Concentration of each water quality state variable (mg/L);

S_c--Internal and external source and sink terms per unit volume;

μ,v,w--They are the velocity components in x, y, z directions in the curve σ coordinates;

$m_x m_y$--Scale factor in x, y, z direction of horizontal curve coordinates;

A_x,A_y,A_z--They are the turbulent diffusion coefficients in x, y, z directions;

H--Water depth (m).

where $\frac{\partial}{\partial x}(\frac{m_y H A_x}{m_x}\frac{\partial C}{\partial x}),\frac{\partial}{\partial y}(\frac{m_x H A_y}{m_y}\frac{\partial C}{\partial y}),\frac{\partial}{\partial y}(m_x m_y \frac{A_z}{H}\frac{\partial C}{\partial c})$ represents advection transmission process，

$\frac{\partial}{\partial x}(m_y H\nu C),\frac{\partial}{\partial y}(m_x H\mu C),\frac{\partial}{\partial c}(m_x m_y \omega C)$ represents the process of diffusion transmission. The physical transmission processes of the above six items are similar, and their numerical solutions are basically the same. In addition, where $m_x m_y HS_C$ represents the hydrodynamic process and external load of each water quality variable. Therefore, when solving the formula, the dynamic term can be reduced from the physical transmission term in the model to simplify the implementation.

$$\frac{\partial}{\partial t_p}(m_x m_y HC)+\frac{\partial}{\partial x}(m_y H\mu C)+\frac{\partial}{\partial y}(m_x H\nu C)+\frac{\partial}{\partial c}(m_x m_y \omega C)$$

$$=\frac{\partial}{\partial x}(\frac{m_y H A_x}{m_x}\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(\frac{m_x H A_y}{m_y}\frac{\partial C}{\partial y})+\frac{\partial}{\partial y}(m_x m_y \frac{A_z}{H}\frac{\partial C}{\partial c})+m_x m_y HS_{cp} \qquad (4\text{-}2)$$

$$\frac{\partial C}{\partial t_k}=S_{ck} \qquad (4\text{-}3)$$

$$\frac{\partial}{\partial t}(m_x m_y HC)=\frac{\partial}{\partial t_p}(m_x m_y HC)+(m_x m_y H)\frac{\partial C}{\partial t_k} \qquad (4\text{-}4)$$

From the formula (4-1) and (4-2), it can be found that the source and sink terms of the formula can be decomposed into the power source sink term and the physical source sink term related to the inflow and outflow. The dynamic equation (4-3) can further separate the reaction process from the internal source and sink term, and can eliminate the influence of water depth and scale factor.

$$\frac{\partial C_k}{\partial t}=KC+R \qquad (4\text{-}5)$$

where，K--Power rate；

R--Internal source and foreign exchange items.

When the values of K and R are basically the same at each point in the lake, the solution of both dynamic equation and physical transmission process is more accurate. According to the mass balance equation, hydraulic characteristics and pollutant distribution in Mopanshan Reservoir, there are some differences in the diffusion mode between the monitoring point at the estuary and the reservoir center or water intake. In the estuary of the inflow river, the upstream incoming water belongs to the advection transmission process, and after the reservoir enters the reservoir, it belongs to the typical diffusion transmission process. The water quality of the estuary is determined by the inflow and water quality of the upstream, which has a relatively large impact on the water quality, especially when the rainfall in summer and the flow in the dry season is insufficient. Therefore, it is not suitable to set water intake at the entrance of the river, and the reservoir can regulate and store the upstream river. There is a velocity difference before and after the storage, and the balance between the two ends of the formula can be reached only when the sedimentation and overturning effects are considered. The loss of nutrients in the water body caused by sedimentation is equal to the product of the flux and area of the sediment water interface in the region. Namely $M_{settling}=\nu\cdot c\cdot A_s\cdot dt$ ， the following formula can be used to explain the deposition, overturning and exchange between sediment and water according to the balance of matter.

$$\begin{aligned}&\partial_t(m_x m_y H S_j)+\partial_x(m_y H\mu S_j)+\partial_y(m_x H\nu S_j)+\partial_s(m_x m_y \omega S_j)\\&-\partial_s(m_x m_y \omega_{sj} S_j)=\partial_s(m_x m_y \frac{K_v}{H}\partial_s S_j)+Q_{sj}^E+Q_{sj}^I\end{aligned} \tag{4-6}$$

$$H^{n+1}S^* = H^n S^n + \frac{\theta}{m_x m_y}(Q_{sj}^E)^{n+1/2} - \frac{\theta}{m_x m_y} \tag{4-7}$$

The formula can be further written as

$$-\frac{K_v}{H}\partial_s S_j - w_s S = J_{j0} : s \approx 0$$

$$-\frac{K_v}{H}\partial_s S_j - w_{sj} S_j = 0 : s \approx 1$$

Finally, the precipitation, diffusion and overturning in the reservoir can be expressed by the following formula.

$$S^{n+1} - \frac{\theta}{H^{n+1}}\partial_s(w_s S^{n+1}) - \theta\partial_s\left[(\frac{K_y}{H^2})^{n+1}\partial_s S^{n+1}\right] = S^* \tag{4-8}$$

In the steady state, the total balance equation of the reservoir pollution load is

$$V\cdot\frac{dc}{dt} = W(t) - Q\cdot c - \nu\cdot c\cdot A_i \tag{4-9}$$

For Mopanshan Reservoir, due to the large discharge of Lalin River and Dasha River, the increase of sediment and the impact of sediment turning up in flood season on water quality should be considered at the entrance of the two rivers. This can also explain the reason why the turbidity increases rapidly in spring when there is little or no rainfall in spring, and the sediment in the reservoir is mainly concentrated in the estuary. For suspended solids such as sediment, the physical transport process is faster, so there is a more obvious gradient relationship in the reservoir, while for colloidal substances, the dynamic transmission process in the reservoir is slower than the physical transport process, so there is a certain gradient change in the lake reservoir. This gradient change shows obvious layer difference and the concentration between the reservoir and the reservoir center in dry season However, when the water is abundant, the water quality is relatively consistent. In order to ensure the safety of water quality, it is necessary to ensure that the organic pollutants imported from upstream will not accumulate in the lake and reservoir, and at the same time, it can play a role of regulating and storing in the rapid input (rainy season) to ensure the stability of water quality.

Due to the rapid renewal of water body of Mopanshan Reservoir, the water intake is the main outlet node in winter, and it still accounts for 30% of the outlet flow in summer. Therefore, considering the hydraulic characteristics of sediment migration and pollutant output, it is not suitable to set the water intake at the bottom of the reservoir. In practice, it is reasonable to set the water intake at 15 m below the water level. However, when the water level is low, the water layer above the water intake should not be less than 5 m to prevent algae outbreak. As another important way of lake reservoir output is irrigation and environmental water. Considering the output demand of the bottom pollutants and the better surface water quality, it is necessary to open the bottom gate to discharge water to accelerate the pollutant output in the reservoir. Especially when the pollutants accumulate rapidly, the opening of the bottom gate will accelerate the output of colloid and suspended solids in the reservoir with the circulation in the reservoir, which is beneficial to the control of water quality. In addition, due to the low water temperature and low concentration of pollutants in the reservoir, and the water body renewal is relatively fast, the water self-purification effect on the removal of pollutants in the reservoir, especially natural organic pollutants, is relatively small, which only has an impact on the rapid input of pollutants in rainy season.

Through the analysis of the input and output of pollutants in Mopanshan Reservoir, it is found that the industrial point source pollution of the upstream river is almost nonexistent, and the relevant characteristic pollutants are not detected in the reservoir water. Due to the objective existence of the upstream villages in the water source protection area, the input of domestic pollutants has become an important way of human pollution in the reservoir area. According to the calculation, the population of the surrounding area is about 3500 people, and the average daily sewage volume is about 200 L/d (including breeding and farming). The COD content of sewage is 300-500 mg/L, and the average value is 400 mg/L. According to the model calculation, if 100% of the generated pollutants enter into the reservoir area, the maximum domestic pollutant input of the first level protection zone is 102.2 t/a. The population of the secondary protection area is 6500, and the average daily sewage volume is about 200 L/d (including breeding and farming). The COD of sewage is 300-500 mg/L, and the average value is 400 mg/L. According to the calculation of the model, about 80% of the generated pollutants enter the reservoir area, and the maximum domestic pollutant input of the secondary protection zone is 151.8 t/a. In the calculation process, the amount of pesticide input into the reservoir area is relatively low and can be ignored. In addition, due to the rapid renewal of water body, the pollutant output in the process of reservoir formation can also be ignored after years of replacement.

From the output situation, the water supply of Mopanshan Reservoir to the downstream cities is more than 3×10^8 m^3/a, and the average total outflow is about 5.6×10^8 m^3/a. According to the detection, the average COD concentration in the urban water source is 13 mg/L, and the quality of irrigation and environmental water is similar, as shown in Fig. 4-6.

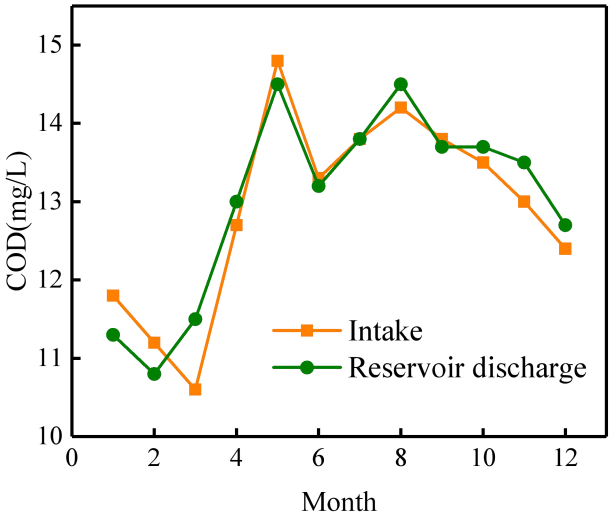


Fig. 4-6 COD variation at the outlet of the Mopanshan Reservoir

Based on this value, the annual output of pollutants is 7280 t/a (calculated by COD). According to the change of water quality of Mopanshan Reservoir in recent five years, the concentration of organic matter in the water has not changed significantly. Based on the average settlement and degradation amount in this reservoir is about 260 t/a, the input and output of organic matter in the reservoir is shown in Fig. 4-7. Fig. 4-7(a) shows the input of pollutants from the simulated reservoir. According to the calculation of the discharge of Mopanshan Reservoir, the annual input of pollutants is about 7800 t/a, of which three rivers account for more than 91.21%, among which the Lalin River accounts for 59.84%, while human factors account for only 3.4% of the total amount of pollutants in the water, and the influence of surrounding rainfall accounts for 5.39%. Fig. 4-7(b) shows the output of pollutants from the simulated reservoir. In terms of output, Mopanshan is mainly used for urban water supply and irrigation of surrounding farmland, accounting for 48.1% and 46% respectively, which is 8 times of other output.

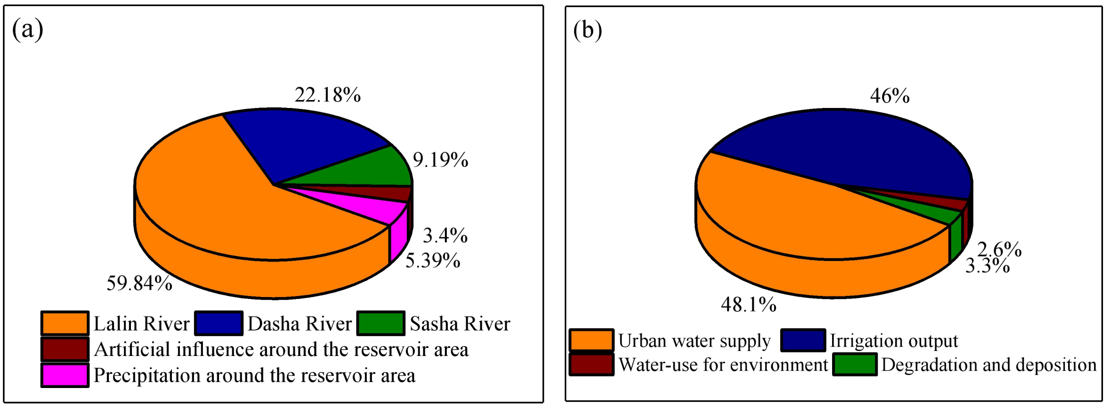


Fig. 4-7 Simulated calculation of organic matter. (a) input, (b) output

(1) Pollutant source distribution

According to the change characteristics of water quality in lake reservoir type water source reservoir in cold area, the characteristics of pollutant input and output in Mopanshan Reservoir in different hydrological periods are quite different, thus affecting the water quality in the reservoir. On the other hand, due to the special seasonal hydraulic changes and flow field distribution, the distribution of pollutants in the reservoir is not the same, which is also the reason for the difference of water quality in different sections of the reservoir. In fact, the annual water level and inflow and outflow of the reservoir are mainly affected by climate and hydrology, and then affect the output of organic matter. The organic matter in the reservoir is mostly natural organic pollutants, and the input and output of pollutants vary greatly in different hydrological periods. The pollutants are continuously exported in the ice covered period, and rapidly imported in the spring flood season, but there is a big difference between the dry year and the wet year in summer and Autumn. The accumulation of pollutants exists in the dry year, while the dynamic balance of pollutants is basically in the wet year. At the beginning of winter and the early period of ice cover, the pollutants continue to input due to the increase of water level, while the outflow is low, so the pollutants accumulate, as shown in Fig. 4-8.

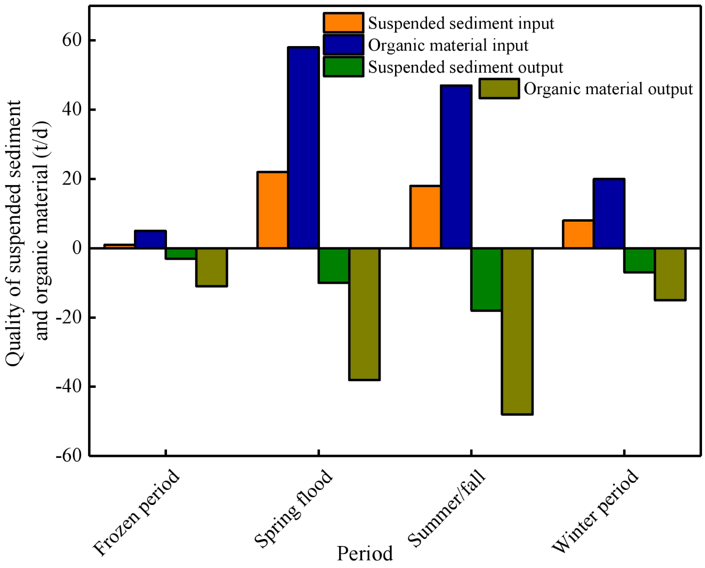


Fig. 4-8 Balance of suspended sediment and organic material in different seasons. Note: Suspended sediment is measured in SS, organic material is measured in COD

Based on the design operation data of Mopanshan Reservoir, the total input suspended load is 3.5×10^4 t/a, while the average turbidity in the outlet water is only 2 NTU. According to Cornwell formula, the SS is about 4 mg/L. According to the annual average discharge of about 5.6×10^8 m^3, the overhanging mass is only 2240 t/a. Most of the suspended sediment will form sediment, and the annual sediment increment is expected to exceed 3.25×10^4 t/a, and the sediment is relatively concentrated at the estuary, as shown in Fig. 4-9.

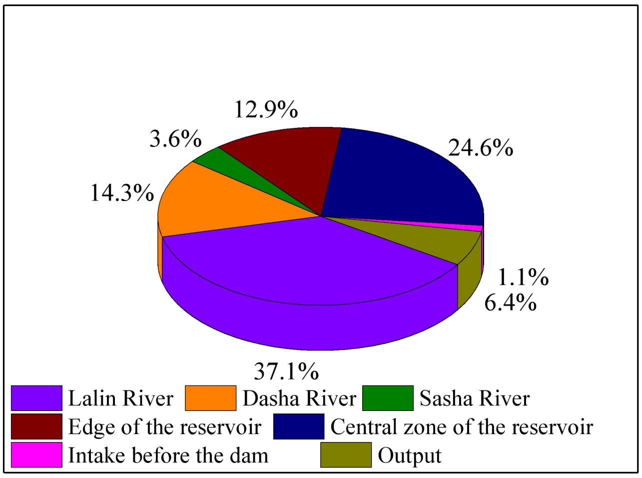


Fig. 4-9 Distribution proportion of the bottom sludge

According to the model calculation, the distribution density of sediment in the estuary is the largest. Among them, the sediment at the Lalin estuary accounts for 37.1% of the total sediment, i.e. 1.3×10^4 t/a, and its density is 7.5 times of the average density. The sediment density at the Dasha estuary is also close to 5000 t/a, which is 4 times of the average density. However, the sediment density at the edge and center of the reservoir is only about half of the average value, as shown in Fig. 4-10.

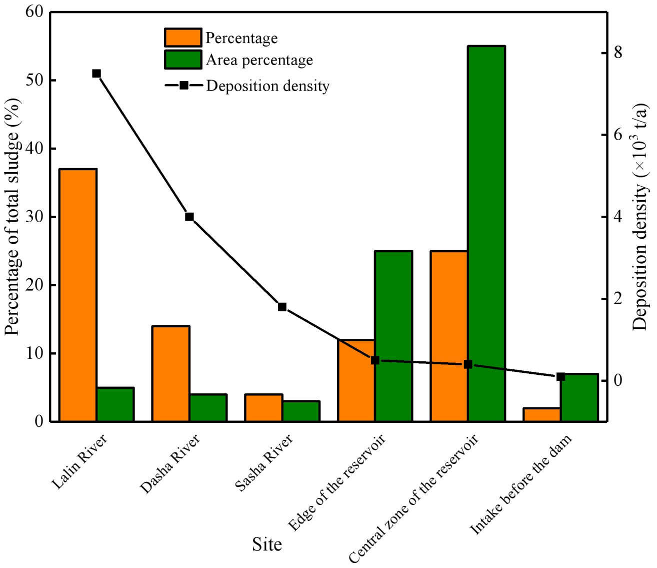


Fig. 4-10 Distribution density of the bottom sludge

In summary, the sedimentation density of the sediment at the intake in front of the dam is the lowest, which is very important to ensure the safety of water supply. But on the other hand, the annual net sedimentation volume at the water intake in front of the dam is still 400 tons. If the deposited sludge is concentrated under the water intake and cannot be exported, the water quality of the bottom water outlet will decrease significantly after 30 years. Especially at the entrances of the Lalin River and Dasha River, necessary manual cleaning and control are required to control the growth of sediment. In particular, controlling the growth of sediment at the entrance of the reservoir will be the key to the life of the reservoir. At the same time, the eutrophication degree of Mopanshan Reservoir is related to the treatment of non-point source pollution, the ecological environment protection around the reservoir area, and it is closely related to the forest, wetland and ecological protection of the quasi-protected area upstream of the water source. In order to better protect the water quality of Mopanshan Reservoir and slow down its eutrophication process. It is necessary to manually clean and control the bottom sludge at the entrance of Mopanshan Reservoir, while restraining the growth of bottom sludge at the entrance of the reservoir. Apply ecological engineering technology to rationally manage the ecology of the reservoir area, and absorb and remove nutrients in polluted water bodies by planting higher aquatic plants.

4.3.2 Pollution sources analysis of the Songhuajiang River

4.3.2.1 Distribution of the Songhuajiang River

Songhuajiang River Basin is located in the northernmost part of the seven major river basins in China and has two main sources. The northern source is Nenjiang River, which originates from yierhuli mountain in Daxing'an Mountains, and the second Songhuajiang River in the south, which originates from Tianchi of Changbai Mountain. After the confluence of Sancha River, the two rivers are called Songhuajiang River. They flow eastward to Tongjiang River and then enter Heilongjiang Province. The basin spans three provinces of Inner Mongolia, Heilongjiang and Jilin, with a total length of 1900 kilometers, a drainage area of 545600 square kilometers and a total runoff of 75.9 billion cubic meters. Nenjiang River is the North source of Songhuajiang River. It originates from the south side of the middle section of yilehuli mountain in Daxing'an Mountains. It is named Nanweng River (also known as Nanbei River) at an altitude of 1030 m. Nenjiang River flows southeast from the source of the river. It meets Ergen river about 1km south of the twelve station forest farm and turns to the south. It is called Nenjiang River. The total length of the main stream is 1370 km, and the drainage area is 297000 km^2. There are many tributaries on the right bank of Nenjiang River, but few on the left bank. The tributaries on both sides originate from the branches of Daxinganling and Xiaoxing'anling, facing Southeast or southwest main stream along the slopes of Daxinganling and Xiaoxinganling.

According to the landform and valley characteristics of Nenjiang River Basin, the main stream of Nenjiang River can be divided into upper, middle and lower reaches. That is to say, the upstream section from Heyuan to Nenjiang County is 661 km long. The river course in the Heyuan area is 172.2 km long, and the river source area is Daxinganling Mountain area. The river valley is narrow, the river slope is large, the current is turbulent, the water surface is 100-200 m wide, and the riverbed is composed of pebbles and gravel. From below the dobukur estuary, the river channel gradually widens and the water volume increases. The width of the river valley can reach 5-10 km. On the left bank of the upstream section, there are Wadu River, Gugu River, menlu River and Kolo

River, and on the right bank there are naduli River, big and small Guli River and dobukur river.

From Nenjiang County to Molidawa Daur banner is the middle reaches section, with a length of 122 km, which is the transition zone from mountainous area to plain area. There are many low mountains and hills on both sides of the river. The terrain is flatter than that of the upper reaches. The two sides are asymmetric, especially on the left bank. The river valley is very wide. There are few tributaries in this reach. Except for the larger tributary Gan River on the right bank, the rest are small tributaries and small mountain streams.

The downstream section from molidawadaor banner to Songyuan is 587 km long. The downstream section is a vast plain, with meandering river channels, many beaches, sandbanks and river branches. Most of the river channels are reticulated. The beaches on both sides of the river stretch very wide. The widest part can reach 10 km, and the maximum water depth is 5.5-7.4 m. On the right side, many tributaries converge and flood is concentrated. The density of the river network in the lower reaches increases and the tributaries increase. From the upper to the lower right bank, there are Nuomin River, Alen River, Yinhe River, Yalu River, Chuoer River, Taoer River and Huolin River, and on the left bank there are Nemoer River, Wuyuer River and Shuangyang River.

Nenjiang River mainly flows through Nenjiang County, Nierji town of Molidawa banner and Qiqihar City, with an average annual runoff of 22.73 billion m^3 and an average annual runoff depth of 79.6 mm.

The second branch of Songhuajiang River flows through 26 cities and counties in Jilin Province, including Antu, Dunhua, Jilin, Changchun and Fuyu, with a total length of 958 km and a drainage area of 73400 km^2. The main tributaries are toudao River, Huifa River, Aolong River and Yinma River. The topography of the whole basin is high in Southeast and low in northwest, and the river channel flows from southeast to northwest. The annual average precipitation of the basin is relatively abundant, and the water resources are rich, especially in the upstream mountainous areas, where the mountains are high and the rivers are steep, and the water resources are very rich. According to the landform of the second Songhuajiang River, it can be roughly divided into four sections, namely, the river source section, the upstream river section, the hilly river section and the downstream river section.

The two river mouth from the source to the junction of Erdaojiang and Toudao river is the source section. The river is 255.7 km long and the catchment area is 18000 km^2. The whole river section is located in Changbai Mountain. There are five major tributaries, namely, Baihe River, Gudong River and Toudao River in the Heyuan section.

From Liangjiangkou to Fengman Power Station dam site, it is the upstream section of the second Songhuajiang River, with a length of 208.1 km, and a catchment area of 25000 km^2, and the river valley is of "V" type. Jiaohe and Huifa River, a large tributary, have been built in this section, and Baishan, Hongshi and Fengman Hydropower Stations have been built. From Fengman Power Station dam site to Mushi river mouth, it is the hilly section of the second Songhuajiang River, with a length of 190.7 km and a catchment area of 9000 km^2. Wende River, Aolong River and muchI River, the major tributaries, are located on the left bank, showing asymmetric river network type, and the river valleys on both sides are wide.

From the Mushi River Estuary to the second Songhuajiang River Estuary, it is the downstream river section. The river channel is 170.9 km long, with a catchment area of 21000 km^3. The river channel is wide and there are many sand dunes along the river. There are many forked rivers, Chuangou and Jiangxinzhou island in the river channel. Willow weeds grow on the river island. There are few tributaries on the right bank except Yinma River on the left bank.

4.3.2.2 Main pollution source in the state-controlled section of the Songhuajiang River

Most of the industrial enterprises in Heilongjiang and Jilin provinces are located along the river. Many of them are energy and raw materials based industrial structure with high water consumption and high drainage. Due to the backward production technology and treatment equipment and facilities, it has become the main factor leading to water pollution. Most of the urban domestic sewage along the river is directly discharged without treatment, which has become an important source of pollution. Because the main stream of Songhuajiang River is the main drinking water source of cities along the river, and all of them take water directly from the river. At present, the water quality of the main stream of Songhuajiang River is seriously polluted, and about 70% of the drinking water is from Songhuajiang River. The annual monitoring results of the monitoring section in zhushuntun water source area of Harbin City show that the water quality of Songhuajiang River can not meet the class III standard of surface water in individual periods, mainly manifested as organic pollution. We know that the main pollutants in Songhuajiang River are cod, volatile phenol and petroleum pollution. From the pollution situation of the main stream of Songhuajiang River, when there is no sewage discharge, the water quality of the river is relatively good, which shows that point source pollution is the main pollution load.

Songhuajiang River Basin Jilin control area is mainly the second Songhuajiang River Basin, flowing through Jilin City, Changchun City, Songyuan City and other cities in Jilin Province. The industries of these cities in Jilin Province are relatively developed, mainly including chemical raw materials and chemical products manufacturing industry, petroleum processing, coking and nuclear fuel processing industry, paper and paper products industry, agricultural and sideline food processing industry, chemical fiber manufacturing industry, beverage manufacturing industry and other industries. In addition to the source of the basin, the urban domestic sewage and industrial production wastewater flowing through the second Songhuajiang River have caused it Pollution. Among them, Jilin industrial pollution sources mainly include: Jilin Chemical Industry Group Co., Ltd. and Jilin Ferroalloy Co., Ltd. Changchun mechanical energy industry mainly includes: China First Automobile Group Corporation, Changchun Gas Company. Songyuan chemical industry mainly includes: PetroChina Qianguo Petrochemical Company, Jilin Fuyu Chemical Co., Ltd.

Songhuajiang River Basin in Heilongjiang Province control area mainly includes Nenjiang River Basin and Songhuajiang River main stream basin. Nenjiang River mainly flows through Qiqihar city and mainly receives industrial wastewater and domestic sewage from Qiqihar city. Qiqihar city is a heavy industrial city, in which the chemical industry is dominated by Heihua group and Qihua group. Nenjiang River has a long line and a wide basin. Besides some large-scale industrial enterprises, there are also many small-scale chemical, pharmaceutical and mechanical processing enterprises.

4.3.2.3 Current management situation of the Songhuajiang River

The state has continuously incorporated the prevention and control of water pollution in the Songhuajiang River basin into the 11th Five Year Plan and the 12th Five Year Plan, and the state and coastal provinces have invested a lot of funds and treatment projects. During the 11th Five Year Plan period, Jilin City arranged 24 pollution control projects, including 15 industrial pollution source treatment projects, 6 urban sewage treatment and recycling facilities construction projects and 3 pollution prevention and control projects in key regions, with a total investment of 1.6 billion yuan. By the end of 2010, all 24 projects have been completed, and breakthroughs have been made in the construction of urban sewage treatment plants and supporting pipe networks. Sewage treatment plants have been built and put into operation in Jilin City and its counties (cities). The domestic sewage treatment capacity has reached 394000 tons/day, and the actual treatment capacity has reached 365000 tons/day, which can reduce the chemical oxygen demand by 30000 tons/year. The prevention and control of industrial water pollution has been deepened. All industrial treatment projects have been put into operation stably, and the cumulative reduction of COD emission is about 10000 tons/year. During the Eleventh Five Year Plan period, 98 sets of high energy consumption and high pollution production units, such as tryptophenol as, hydrogen acid and calcium carbide coking plant, were eliminated successively. The discharge of waste water and chemical oxygen demand were reduced by 13.54 million tons/year and 4500 tons/year respectively. The goal of increasing production and not increasing pollution was realized. According to the requirements of the 12th Five Year Plan for water pollution prevention and control in Songhuajiang River Basin of Jilin Province and the 12th Five Year Plan for water pollution prevention and control in Liaohe River Basin of Jilin Province, a total of 152 projects with a total investment of 9.787 billion yuan were included in the 12th Five Year Plan. The Liaohe River Basin has been listed into 74 projects with a total investment of 5.636 billion yuan. The number of projects and the amount of investment have doubled compared with the 11th Five Year Plan. At the same time, the comprehensive environmental improvement of important tributaries such as Dongliao River, Tiaozi River, Zhaosutai River, Yitong River and other important tributaries in Jilin Province will continue to deepen, requiring all localities to ensure that the water quality of centralized drinking water sources within their jurisdiction is 100% up to standard.

The environmental protection agency said that it would strive to prevent the occurrence of emergencies. Even if there was an incident, it would try every possible means to control the pollutants. Even if the pollution occurred, the pollutants could not spread to ensure that the pollutants would not enter the Songhuajiang River. In this regard, a series of supporting policies and measures have been formulated. In view of the high environmental risk of industrial layout in Songhuajiang River Basin, a three-level prevention and control system for key enterprises has been established, and emergency drills for environmental pollution accidents have been carried out, focusing on the prevention of natural disasters, safety accidents and emergencies. Special supervision actions were organized and carried out in special periods such as flood season and dry season, and the potential environmental safety hazards along the Songhuajiang River and the upstream of drinking water source areas were investigated by means of net work. The goal of "strive not to occur, occurrence can be controlled, pollution will not spread and ensure that it will not enter the river". According to the code for design of environmental protection of chemical construction projects (GB 50483-2009) issued by the Ministry of environmental protection in 2011, it is stipulated that "emergency accident pool shall be set up in chemical construction project" to ensure that the device drainage can be effectively accepted in case of accident, and the accident wastewater can not enter the water body to cause pollution. The construction of accident pool, even if sudden pollution incidents occur, the risk of pollutants directly discharged into Songhuajiang River Basin is completely controllable. According to the Journal of environmental and safety engineering, since the nitrobenzene incident in 2005, only one environmental pollution incident occurred in Yongji County, Jilin Province in 2010.

4.3.2.4 Water quality change analysis of the Songhuajiang River

Fig. 4-11 shows the changes of ammonia nitrogen and permanganate index of Songhuajiang River monitoring section in Jilin City. It can be seen from the figure that the water quality indicators of centralized drinking water sources in Jilin City from 2017 to 2018 meet the requirements of Case III standard in the “Environmental Quality Standards for Surface Water” (GB3838-2002), with the compliance rate of 100%. Among them, ammonia nitrogen is kept at 0.02-0.2 mg/L all year round, and permanganate index is between 3.0-5.0 mg/L. The water quality can meet the requirements of Case III water body in surface water source area all year round.

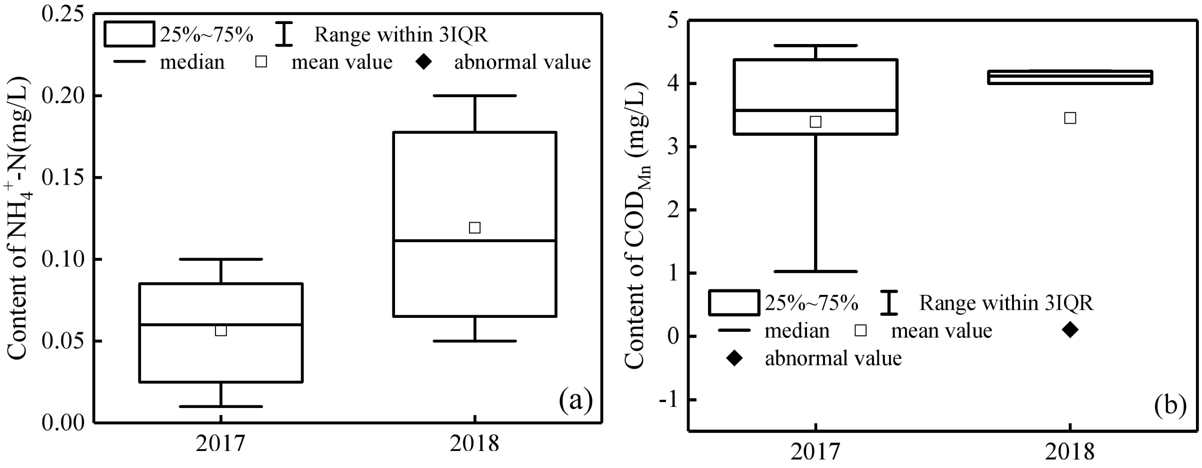


Fig. 4-11 Variation of NH_4^+-N and COD_{Mn} at the Jilin monitoring section. (a) NH_4^+-N, (b) COD_{Mn}

Fig. 4-12 shows the changes of ammonia nitrogen and permanganate index of Songhuajiang River monitoring section in Songyuan City. The water quality of centralized drinking water source in Songyuan City can meet the Case III water quality standard. In 2015, the highest ammonia nitrogen was 1.3 mg/L (exceeding the Case III water standard), and the permanganate index was basically maintained at 6 mg/L (meeting the Case III water standard). At the beginning of 2016, ammonia nitrogen was between 0.2-0.8 mg/L, and the water quality was significantly improved compared with previous years, which could meet the Case III surface water quality standard.

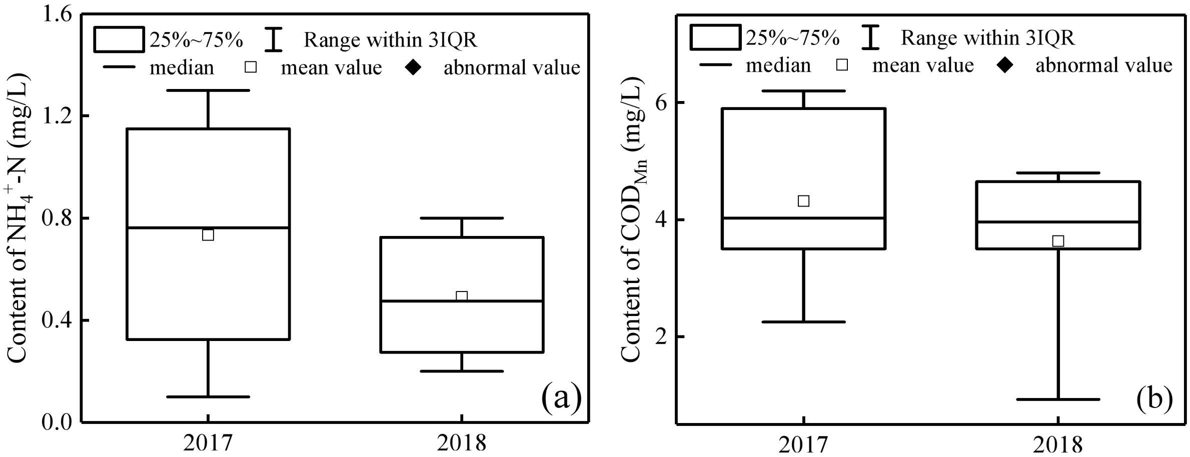


Fig. 4-12 Variation of NH_4^+-N and COD_{Mn} at the Songyuan monitoring section. (a) NH_4^+-N, (b) COD_{Mn}

Fig. 4-13 shows the changes of ammonia nitrogen and permanganate index of Songhuajiang River monitoring section in Qiqihar city. The water quality of centralized drinking water sources in Qiqihar city is excellent. The water quality of class I ~ III water quality section accounts for 100%. Compared with the same period of last year, the water quality has no obvious change. According to the data statistics of Nenjiang river monitoring section in the upper reaches of Songhuajiang River, the ammonia nitrogen index of Qiqihar monitoring section in recent years has reached the standard of Case III water body, and the content is low. The results show that the annual variation of permanganate index of Qiqihar monitoring section presents a downward trend as a whole, and it is higher in some months in summer, mainly due to a large amount of precipitation.

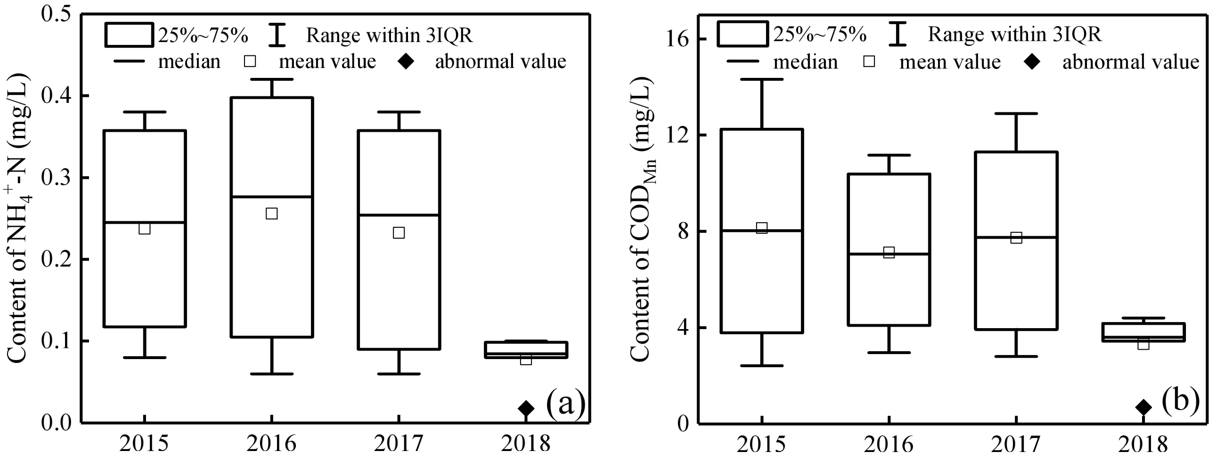


Fig. 4-13 Variation of NH_4^+-N and COD_{Mn} at the Qiqihaer monitoring section. (a) NH_4^+-N, (b) COD_{Mn}

Fig. 4-14 shows the changes of ammonia nitrogen and permanganate index on the monitoring section of Songhuajiang River in Zhaoyuan. It can be seen from the figure that the water quality in Zhaoyuan is improving year by year.

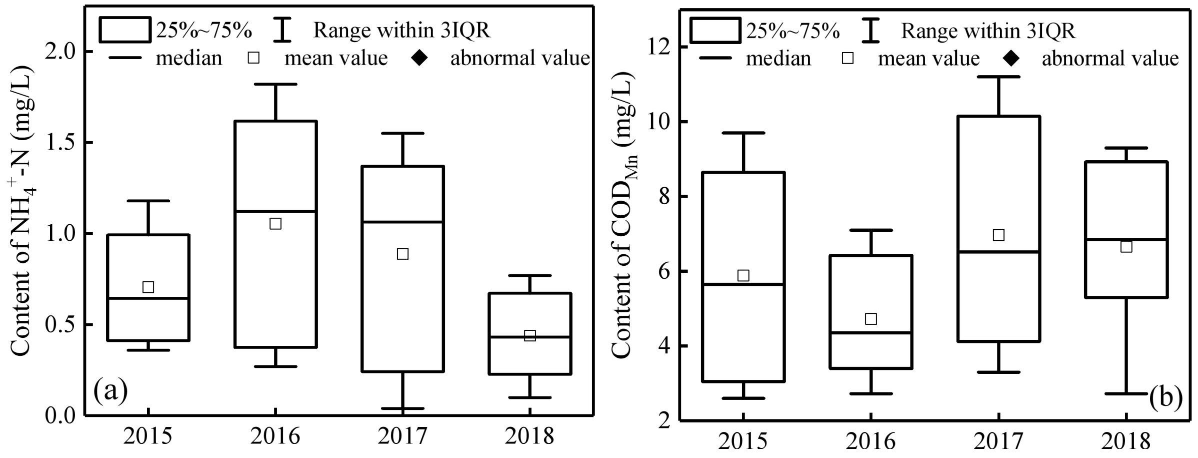


Fig. 4-14 Variation of NH_4^+-N and COD_{Mn} at the Zhaoyuan monitoring section. (a) NH_4^+-N, (b) COD_{Mn}

In order to further understand the comprehensive treatment of industrial pollution along the upper reaches of Harbin section of Songhuajiang River Basin and its impact on the raw water quality of Harbin section, through the analysis and comparison of ammonia nitrogen and permanganate index of zhushuntun section, it is found that although the ammonia nitrogen value of raw water in Songyuan City and permanganate index in Qiqihar in summer are high, the Songhuajiang River

Basin has strong self-purification The ammonia nitrogen in zhushuntun raw water in summer and permanganate index in winter can reach Case III standard of surface water. It can be seen that the water resources pollution in Songhuajiang River Basin has been well dealt with. The content of ammonia nitrogen in the basin is mainly affected by non-point source pollution and the discharge of urban sewage treatment plants. During the period of the Eleventh Five Year Plan and the twelfth five year plan, the state has made great efforts to prevent and control the water pollution in the Songhuajiang River Basin, so that the Songhuajiang River can "recuperate". During the past decade, six key tasks have been achieved in the prevention and control of water pollution in the river basin, including meeting the standards of drinking water sources, comprehensive treatment of priority control units, comprehensive prevention and control of industrial pollution, construction of sewage treatment facilities, demonstration of agricultural non-point source prevention and control, and construction of environmental supervision capacity. The overall goal is to consolidate the water quality of a number of control sections, improve the water quality of a number of control sections, eliminate the water quality of inferior five control sections, and significantly improve the water environment quality of Songhuajiang River. During the 11th Five Year Plan period, 70 new urban sewage treatment plants were built in Songhuajiang River Basin, with an additional sewage treatment capacity of 2.95 million tons/day. During the 12th Five Year Plan period, 79 new sewage treatment plants were built in Jilin Province and 212 in Heilongjiang Province, with an additional sewage treatment capacity of 2.03 million tons/day. After being intercepted and incorporated into the municipal sewage pipe network, the water quality of ammonia nitrogen has been significantly improved. Even if the ammonia nitrogen in the second Songhuajiang River and Nenjiang River basin can not meet the class III standard of surface water, it will not have a great impact on the ammonia nitrogen in the raw water of Harbin river section. However, due to the decrease of surface runoff during the dry season, the discharge is basically unchanged. In winter, the standard of ammonia nitrogen in the water body discharged into Songhuajiang River is relaxed by urban sewage treatment plant. Under the condition that the surface runoff is reduced and the standard is relaxed, the absolute content of ammonia nitrogen will increase. At the same time, the temperature of river water is low in winter, and the self-purification effect is weakened, resulting in the deterioration of water quality and the increase of ammonia nitrogen in water.

There are many reasons for the increase of permanganate index concentration in rivers, one of which is the content of organic matter in the soil of the basin. Songhuajiang River Basin belongs to the area of high organic matter soil. The high organic matter in the soil will flow into the river along with the surface runoff in the rainy season, so that the content of organic matter in the river increases and the concentration of permanganate index increases relatively.

Therefore, in order to strengthen the sewage treatment capacity of Songhuajiang River Basin and strengthen the stable discharge of pollution sources, enterprises with high total pollutant discharge but having achieved standard discharge should implement clean production, realize energy saving, consumption reduction, pollution reduction and efficiency increase, strengthen the resource utilization of sewage and encourage water recycling. Strictly implement the national industrial policies, prohibit the transfer or introduction of heavy pollution projects, and encourage the development of projects with low pollution, no pollution, water saving and comprehensive utilization of resources.

4.4 Finished water quality

Based on the above comparative analysis of the water quality, the main pollutants in the Mopanshan Reservoir were the COD_{Mn}, TN, and TP. Meanwhile, they were COD_{Mn} and NH_4^+-N in the Songhuajiang River. A conventional treatment (coagulation-precipitation-filtering-disinfection) was applied based on a water plant in Harbin City to analyze the finished water quality of the two drinking water sources. The water quality of the effluent was appraised by the “Standards for drinking water quality” (GB5749-2006).

4.4.1 Finished water quality in the Mopanshan Reservoir

The national drinking water standard involves 106 water quality indices. The major common water quality indices of the finished water from 2016 to 2018 are presented in Table 4-4, while the other indices are below the limit of detection. Clearly, the value of detectable indices all can reach or be inferior to the national standard. The point to make here is that the excessive COD_{Mn} and TN in raw water can be removed by the conventional treatment effectively. The effluent can completely meet the national drinking water standard. For example, the COD_{Mn} and TN value in 2018 averagely are 1.47 mg/L and 0.075 mg/L on average, which are evidently 51% and 85% inferior to the threshold value of the national drinking water standard.

Table 4-4 The major common water quality indices of the finished water in the Mopanshan Reservoir

Indice	Threshold value	2016		2017		2018	
		Rainy season	Icebound season	Rainy season	Icebound season	Rainy season	Icebound season
pH	6.5-8.5	7.0	7.0	6.8	6.81	6.80	6.83
Chloride (mg/L)	250	6.73	6.35	8.20	7.724	9.17	8.84
Sulfate (mg/L)	250	8.54	8.12	10.33	7.657	9.16	8.17
Total hardness (mg/L)	450	30	38	34	38	36	40
TN (mg/L)	0.5	<0.025	0.04	<0.025	0.03	0.07	0.08
Fluoride (mg/L)	1.0	0.05	0.02	0.08	0.017	0.02	0.01
COD_{Mn} (mg/L)	3	1.84	1.04	1.76	2.32	1.36	1.58

Due to the high content of natural macro-molecule organic matter in the Mopanshan Reservoir water, it is easy to cause the disinfection by-product exceeding the drinking water standard after the use of liquid chlorine disinfection [4-6]. Hence, a detailed statistical analysis of DBPs was performed. The sterilization indicators of the finished water from 2016 to 2018 are presented in Table 4-5. According to the qualitative analysis of organic pollutants in the effluent from the water plant, results showed ten types of DBPs, six of which could be detected. All of these DBPs met the drinking water standard, except for chloral. The average value of chloral was 0.012 mg/L, which exceeded 20% of the limit. Moreover, the content of chloral in the rainy season was evidently higher than that in the icebound season. It indicated that chloral was another crucial control indicator in the rainy season for the Mopanshan Reservoir, other than the COD_{Mn}, TN, and TP.

Table 4-5 Monitoring value of DBPs of the finished water in the Mopanshan Reservoir

Indice	Threshold value (mg/L)	2016		2017		2018	
		Rainy season	Icebound season	Rainy season	Icebound season	Rainy season	Icebound season
Trichloromethane	1	0.0253	0.0244	0.0207	0.0073	0.0052	0.0032
Chloral	0.01	0.021	0.011	0.005	0.016	0.012	0.006
Trichloroacetic acid	0.1	0.019	0.018	0.012	0.010	0.013	0.01
Dichloroacetic acid	0.05	0.011	0.006	0.004	<0.001	0.015	<0.001
Bromodichloromethane solution	0.06	0.0023	0.003	0.001	<0.001	<0.001	<0.001
Dichloromethane	0.02	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Tribromethane	0.1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dibromochloromethane	0.1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cyanochloride	0.07	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
2,4,6-Trichlorophenol	0.2	<0.02	<0.02	<0.02	<0.001	<0.001	<0.001

4.4.2 Finished water quality in the Songhuajiang River

The monitoring values in 2017 were collected to analyze the finished water quality of the Songhuajiang River after conventional treatment. The values of major common water quality indices are shown in Table 4-6. All the referred water quality indices meet the drinking water standard, except for the NH_4^+-N. The average value of NH_4^+-N was 1.01 mg/L, exceeding 2.02 times than the threshold value of the national drinking water standard. In the icebound season, the monitoring value of NH_4^+-N was 1.96 mg/L, exceeding 3.92 times than the limit value. It indicated that the conventional treatment was ineffective in eliminating NH_4^+-N in the icebound season. The average value of COD_{Mn} was 2.74 mg/L, which was 8.7% lower than the limit value. That is to say, the COD_{Mn} of the Songhuajiang River water after the conventional treatment can reach the national drinking water standard, while the NH_4^+-N cannot be eliminated efficiently. However, numerous researchers suggest that ozone/activated carbon process is effective to eliminate the NH_4^+-N [7, 8]. For example, Fan et al. [9] found that when the concentration of NH_4^+-N in raw water was 1 mg/L, the value in the effluent after the process of ozone/activated carbon was 0.3 mg/L, which distinctly reached the drinking water standard.

Table 4-6 The major common water quality indices of the finished water in the Songhuajiang River

Monitoring time	Indice						
	pH	COD_{Mn} (mg/L)	NH_4^+-N (mg/L)	Total hardness (mg/L)	Fluoride (mg/L)	Chloride (mg/L)	Sulfate (mg/L)
Rainy season	7.01	2.82	0.05	66.4	0.25	16.57	17.93
Icebound season	7.01	2.66	1.96	90.4	0.26	16.93	28.84

The sterilization indicators of the Songhuajiang River' finished water in 2017 are listed in Table 4-7. It can be seen that there were ten types of DBPs in the finished water, four of which were detected. All the detected DBPs met the drinking water standard. For example, the average value of chloral was 0.004 mg/L, which was obviously below the limit value. That is to say, the conventional treatment is effective in removing the DBPs of the Songhuajiang River water.

Table 4-7 Monitoring value of disinfection by-products of finished water in the Songhuajiang River in 2017

Indice	Threshold value (mg/L)	Monitoring value (mg/L)	
		Rainy season	Icebound season
Trichloromethane	1	0.0027	0.0072
Chloral	0.01	0.003	0.005
Trichloroacetic acid	0.1	0.002	0.011
Dichloroacetic acid	0.05	0.005	0.020
Bromodichloromethane solution	0.06	<0.001	<0.001
Dichloromethane	0.02	<0.0001	<0.0001
Tribromethane	0.1	<0.001	<0.001
Dibromochloromethane	0.1	<0.001	<0.001
Cyanochloride	0.07	<0.01	<0.01
2,4,6-Trichlorophenol	0.2	<0.001	<0.001

Given the comprehensive analysis of water quality indices, it can be concluded that the Mopanshan Reservoir water can reach the Case III standard. However, it has trends of deterioration and eutrophication. Importantly, the finished water of the reservoir existed the exceeding the Chinese national standard of chloral after the conventional treatment. This increases the difficulty of subsequent processing. However, after the Songhuajiang River undergoing over a decade of contamination remediation, the water also can reach the Case III standard. Further, the finished water all can meet the national drinking water standard after the conventional treatment, apart from the NH_4^+-N in the icebound season. Taken into the disadvantage of the Mopanshan Reservoir account, the Songhuajiang River water is more suitable for the drinking water at present.

4.5 Summary

This chapter mainly compares and analyzes the characteristic pollutants of Songhuajiang River Basin and Mopanshan Reservoir water, and analyzes the distribution and treatment status of pollution sources in Songhuajiang River Basin and Mopanshan Reservoir through investigation and analysis. The main conclusions are as follows.

(1) The characteristic pollutants of Mopanshan Reservoir water are permanganate index, total nitrogen and total phosphorus. Among them, the permanganate index showed the characteristics of seasonal over standard, the total nitrogen increased year by year, the water was slightly polluted, and there was a trend of eutrophication. The characteristic pollutants of Songhuajiang River raw water are permanganate index, chemical oxygen demand and ammonia nitrogen. Among them, permanganate index exceeded the standard in summer and ammonia nitrogen exceeded the standard in winter.

(2) The pollutants in Mopanshan Reservoir mainly come from agricultural non-point source pollution such as pesticide and chemical fertilizer, domestic sewage and surface runoff. The proportion of anthropogenic pollution is only 3.4%, while the input of rainfall into the river and its surrounding areas has a great impact. The trend of eutrophication in the reservoir area is mainly caused by natural factors. Both Casson index and comprehensive trophic state index showed that the eutrophication trend of Mopanshan Reservoir increased year by year. In order to better protect the water quality of Mopanshan Reservoir and slow down its eutrophication process, it is necessary to clean up and control the population at the entrance of Mopanshan Reservoir, and restrain the growth of sediment at the entrance.

(3) There are many industrial enterprises on both sides of Songhuajiang River, and point source pollution is the most important pollution load. At present, after a series of government control measures, the water quality of Songhuajiang River can meet the requirements of Case III surface water source.

(4) After the conventional treatment of raw water from the Mopanshan Reservoir, only the chloral could not meet the national standard, while all other water quality indices could reach the requirements of “Standards for drinking water quality” (GB5749-2006). For the Songhuajiang River, all the water quality indices and DBPs could meet the national standard after the conventional treatment, apart from the NH_4^+-N in the icebound season. Through contrast and analysis, the Songhuajiang River is more suitable for the drinking water at present.

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Chapter 5. Pilot study on the enhanced conventional process in a waterworks of Harbin

5.1 Introduction

Through the above study, the Mopanshan Reservoir has a characteristic of low temperature and low turbidity, high chroma, and the trend of eutrophication. There existed a trait of low temperature and organic pollution in the Songhuajiang River water. However, the effluent water quality of the two drinking water sources can not reach the requirement of the “Standards for drinking water quality” (GB5749-2006) after the conventional water purification process.

Coagulation is a process of aggregation of colloidal particles and micro suspended solids in water under the action of electric double layer and adsorption bridging by adding coagulant. Coagulants can be divided into two categories: ①inorganic salts, including aluminum salts (aluminum sulfate, aluminum potassium sulfate, potassium aluminate, etc.), iron salts (ferric chloride, ferrous sulfate, ferric sulfate, etc.) and magnesium carbonate;②polymer materials, such as polyaluminum chloride, polyacrylamide, etc. In the process of treatment, coagulant is added to the wastewater to eliminate or reduce the mutual repulsion force between colloidal particles in water, so that the colloidal particles in water are easy to collide and agglomerate to form larger particles or flocs, and then separate from the water. The enhanced coagulation is to further expand and improve the removal range and removal rate of organic matter by improving coagulation conditions. The method is mainly achieved by adjusting pH value, improving coagulant, improving hydraulic conditions, adding oxidant and coagulant aid. The relative molecular weight range of organics can be increased from more than 10000 to 3000 or even lower by strengthening coagulation and sedimentation [1-3].

Filtration is the most commonly used operation method for separating solution and precipitation, which mainly uses porous media to intercept solid particles in suspension and then separate solid and liquid. As the process goes on, the filter layer will gradually thicken, and the resistance of water flow will also increase, which will reduce the water flow. At this time, it is necessary to backwash the filter media with clean water to remove the solid material intercepted and remove the filter cake in time. Filter media are usually quartz sand, activated carbon, anthracite, ceramsite, etc. The enhanced filtration is mainly based on the traditional filter, which can not only remove turbidity, but also remove organic matter and ammonia nitrogen [4, 5].

Therefore, in this chapter, we focus on the strengthening treatment of conventional treatment process, in order to reduce investment and optimize operating conditions, so that the water quality can reach the standard and further purify the water source. In this paper, based on the original traditional treatment process of a water plant in Harbin, the Songhuajiang River is taken as the raw water, and the pilot test of enhanced coagulation and enhanced filtration is mainly studied to determine the optimal operation conditions of enhanced coagulation and enhanced filtration.

This chapter is organized as the following. In Chapter 5.2 the raw water and effluent water quality of the waterwork are analyzed. The study of the enhanced coagulation is presented in Chapter 5.3. And the study of the enhanced filtration is presented in Chapter 5.4. The Chapter 5.5 is the

Summary.

5.2 Raw water and effluent water quality of the waterworks

The relevant water quality parameters of the Songhuajiang River are listed in Table 5-1. The average contents of turbidity, COD_{Mn}, and NH_3-N were 57 NTU, 5.85 mg/L, and 1.07 mg/L, respectively. These values exceed the threshold value of “Standards for drinking water quality” (GB5749-2006), which states that their maximum values should be 1 NTU, 3 mg/L, and 0.5 mg/L, respectively. Thus, attention was mainly paid to the monthly monitoring of these three parameters in this study, as depicted in Fig. 5-1. It is interesting to note that the turbidity value of the Songhuajiang River was extremely high from April to November, while it sharply reduced from December to March. The turbidity in spring and summer was on average five-fold higher than that in autumn and winter. This is because the precipitation is plentiful from April to November in Harbin City, resulting in an increase in surface runoff and floating granules. In contrast, the river enters a frozen period from December to April, which is the main reason for low turbidity. Furthermore, the relatively high turbidity can directly influence the subsequent disinfection effect and increase the use of disinfectants. It can even increase the content of DBPs in water and decrease the effluent safety.

For COD_{Mn}, all the monitored values were over the standard value. Especially, the COD_{Mn} value reached a peak in May. This may be due to the surface runoff and sewage discharge from the circumjacent factories. However, the value for NH_3-N dramatically increased in the frozen period, which was primarily due to the following reasons: 1) the low precipitation resulting in the poor dilution capability for contaminants; 2) the high evaporation loss causing the high evaporated concentration of contaminants; 3) the low water temperature and dissolved oxygen leading to poor biological activity and purification ability; and 4) organic matter in the sediment reduced to NH_3-N and released into the water [6 ,7]. The high NH_3-N content can not only affect the subsequent disinfection effect and increase chlorine consumption but also generate mutagenic materials including chloramine (NH_2Cl). These matters can lead to the production of trihalomethanes (THMs) and other DBPs in disinfected water and further reduce the drinking water safety [8, 9]. Besides, the turbidity, COD_{Mn}, and NH_3-N values in the effluent treated by the traditional water purification process were 1.25 NTU, 3.08 mg/L, and 0.82 mg/L, respectively. The effluent quality of the traditional water purification process did not meet the drinking water standard.

The UV absorbance at 254 nm (UV_{254}) is a useful indicator for the characteristics of dissolved organic matter [10]. As seen in Table 5-1, the UV_{254} value was 0.13 cm^{-1}. It indicated that the Songhuajiangjiang River possessed a high quantity of organic matter, which was similar to that of COD_{Mn}. The content of THMFP in the raw water was also large with a value of 347 μg/L, which can enhance the productivity of DBPs for the utilization of liquid chlorine disinfection in the pilot-scale plant.

According to the raw water-quality monitoring of the Songhuajiang River, the water quality problems of this water plant mainly occurred during the frozen period in winter. Moreover, the Songhuajiang River is difficult to be treated by the traditional water purification process. Thus, it is necessary to adopt an advanced treatment process to treat the Songhuajiang River and ensure drinking water quality.

Table 5-1 Raw water quality of the Songhuajiang River

Parameter	Monitoring mean value	Standard deviation	Parameter	Monitoring mean value	Standard deviation
pH	7.54	0.1	NH_3-N, mg/L	1.07	0.058
Turbidity, NTU	57	5.14	Temperature, °C	20.8	2.31
COD_{Mn}, mg/L	5.85	0.36	Alkalinity, mg/L as $CaCO_3$	65	16.7
UV_{254}, cm^{-1}	0.13	0.011	THMEP, μg/L	347	38.2

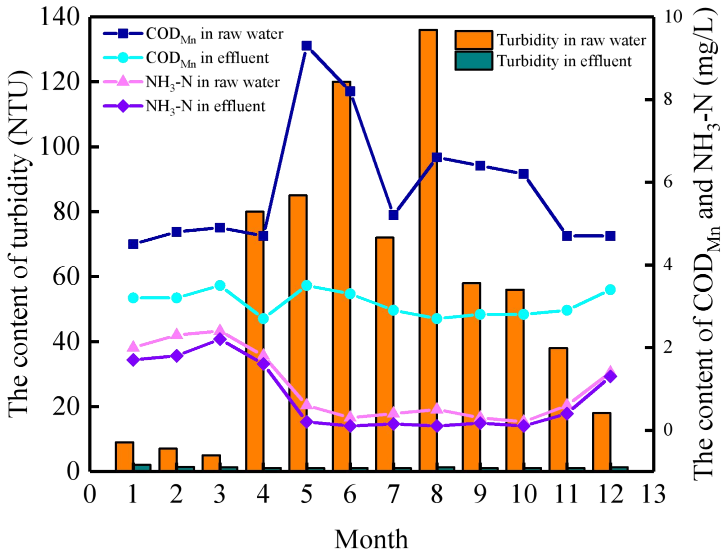


Fig. 5-1 Variation of turbidity, COD_{Mn} and NH_3-N in the raw water and effluent

5.3 Enhanced coagulation test

Enhanced coagulation technology involves the modification and strengthening of conventional coagulation technology. It not only improves the flocculation conditions but also improves the removal rate of organic matter [11]. Many water treatment workers believe that enhanced coagulation is the best way to achieve disinfection by-product compliance in the first phase of water treatment.

5.3.1 Orthogonal experiment design for the flocculation process

Orthogonal experiments are the most simple and effective method for optimizing experimental schemes. In this experiment, an eight-factor and three-level orthogonal test was used to optimize the design of the reinforced coagulation process. The turbidity of the raw water in the test sample was 105 NTU, and the chroma was 87 PCU. The dosage of the coagulant was 60 mg/L. The coagulant was made of an aluminum and iron compound. After stirring, the precipitate was left for 30 min to determine the turbidity of the supernatant solution. The results are listed in Table 5-2.

Table 5-2 Orthogonal test designs table

Test number	Factor								Turbidity (NTU)
	G_0 (s^{-1})	T_0 min	G_1 (s^{-1})	T_1 min	G_2 (s^{-1})	T_2 min	G_3 (s^{-1})	T_3 min	
1	340	1.5	199	3.5	253	4	58	8	0.88
2	340	1.5	220	3	147	5	39	9	0.87
3	340	1.5	226	2	100	6	78	10	1.00
4	340	2	199	3.5	147	4	78	8	1.98
5	340	2	220	3	100	6	58	9	1.02
6	340	2	226	2	253	5	39	10	1.01
7	340	1	199	3	147	6	39	8	1.04
8	340	1	220	2	253	5	78	9	0.95
9	340	1	226	3.5	100	4	58	10	1.19
10	441	1.5	199	2	100	5	39	8	1.20
11	441	1.5	220	3.5	147	6	78	9	0.92
12	441	1.5	226	3	253	4	58	10	0.89
13	441	2	199	2	100	5	78	8	1.31
14	441	2	220	3	147	4	39	9	0.67
15	441	2	226	3.5	253	6	58	10	0.96
16	441	1	199	2	147	6	58	8	0.98
17	441	1	220	3.5	100	5	39	9	0.94
18	441	1	226	3	253	4	78	10	1.04
K1	9.94	5.76	7.39	6.87	5.73	6.65	5.92	7.39	
K2	8.91	6.95	5.37	5.53	6.46	6.28	5.73	5.37	
K3	/	6.14	6.09	6.45	6.66	5.92	7.2	6.09	
$\overline{K1}$	3.31	1.92	2.46	2.29	1.91	2.22	1.97	2.46	/
$\overline{K2}$	2.97	2.32	1.79	1.84	2.15	2.09	1.91	1.79	
$\overline{K3}$	/	2.05	2.03	2.15	2.22	1.97	2.4	2.03	
R	2	0.4	0.67	0.45	0.31	0.25	0.49	0.67	

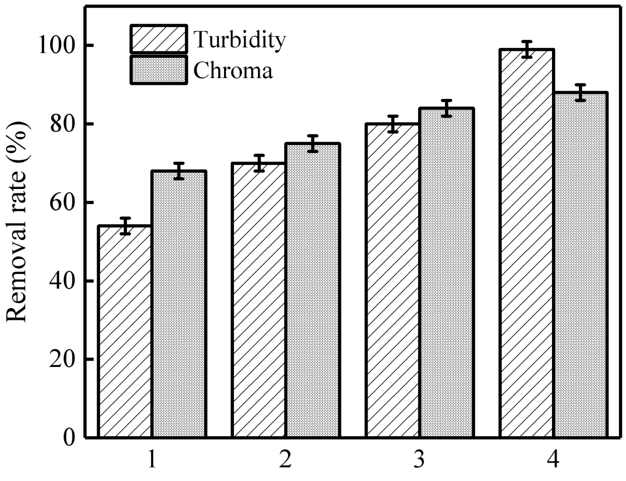
According to the progressive calculation results, fast mixing (G_0, T_0: 2, 0.4) was the main factor that affected the effectiveness of the coagulation treatment. It can be seen that fast mixing was important for the coagulation process. Meanwhile, the R-value of the first-gear velocity gradient was 0.67. The R-value of the third-gear velocity gradient was 0.49. Both of them are greater than the

R-value of the second-gear velocity gradient. Therefore, the velocity gradient of the first-gear (G_1) and the velocity gradient of the third-gear (G_3) had a strong influence on the coagulation treatment effect. During the gradual decline in velocity gradient from G_0 to G_3, the value of G_3 should be lowered to ensure that flocs are not broken up. Also, the value of G_2 should be set appropriately so that the change in G value is relatively stable.

Among the 18 tested groups, group 14 had the best water purification results. The combined mixing (G) and flocculation (T) treatments were: (G_0, T: 441， 2), (G_1, T_1: 220， 3), (G_2, T_2: 147, 5), and (G_3, T_3: 39, 10). The corresponding stirring conditions were 240 r/min (stirring for 2 min), 120 r/min (3 min), 80 r/min (5 min), and 40 r/min (10 min).

5.3.2 Choice of coagulant

The original water sample was taken from the pressure-regulated distribution well of the waterworks. In order to ensure the comparability of data in each group, the coagulation tests of the four coagulants, diatomite, polyaluminum chloride, polyaluminum chloride + diatomite, and polymeric aluminum ferric-calcium (PAFC), were carried out simultaneously. During the test, the reaction time and velocity gradient were fixed, namely 240 r/min (stirring for 2 min), 120 r/min (3 min), 80 r/min (5 min), and 40 r/min (10 min). After 30 min of precipitation of the coagulant in the water sample, the supernatant was taken for the determination of chroma and turbidity, and the treatment effects of the four coagulants were analyzed. The results are shown in Fig. 5-2. As seen in Fig. 5-2, the turbidity and chroma of the water are reduced the most by adding PAFC. The turbidity and chroma were reduced by as much as 99% and 89%, respectively, but the other coagulants had relatively poor effects on the turbidity and chroma of the water. For example, the removal rate of chroma and turbidity from the water samples was 54% and 68%, respectively, after addition of the diatomite coagulant. Compared with adding PAFC, the removal rate decreased by 39.33% and 31.31%, respectively. Therefore, the best coagulant used in this experiment was PAFC.



1.diatomite 2. polyaluminum chloride 3. polyaluminum chloride + diatomite 4. PAFC

Fig. 5-2 Effects of the different coagulants on the removal of chroma and turbidity

5.3.3 Determination of the optimum coagulant dose

To determine the optimum dose of the coagulant, 500 mL of raw water was taken. 10 mg/L, 20 mg/L, 30 mg/L, 40 mg/L, 50 mg/L, 60 mg/L, and 70 mg/L PAFC doses were added, and the turbidity and chroma of the effluent water were detected after stirring and precipitation for 30 min. The relationship of the coagulant dosage with turbidity and chroma removal rate is shown in Fig. 5-3.

It can be seen from Fig. 5-3 that the removal rate of turbidity and chroma increased with the increase of PAFC dosage. When the dose was 60 mg/L or greater, the turbidity removal rate was able to reach 99%, and the chroma removal rate reached 83%. With the addition of further coagulant, the removal rate of turbidity and chroma tended to be stable. Therefore, the optimal dose of coagulant selected in the experiment was 60 mg/L. Compared with the dosage of conventional coagulants (40 mg/L), the dosage of the enhanced coagulant is relatively high, which is mainly due to the low temperature and low turbidity of the raw water.

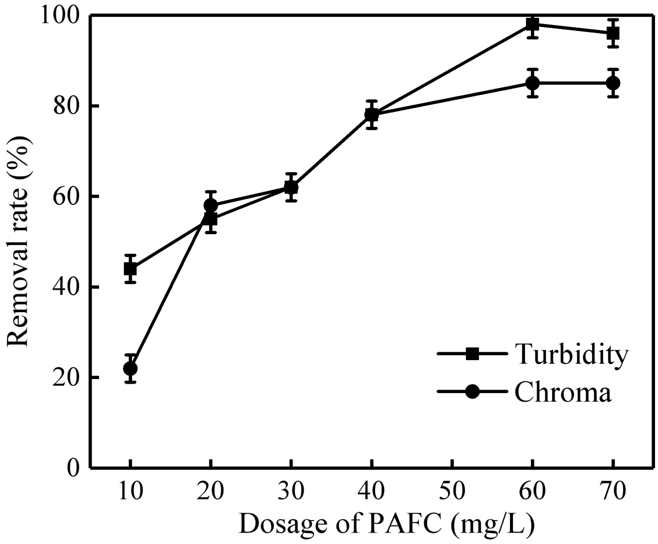


Fig. 5-3 The relationship between coagulant dosage and turbidity and chroma removal rate

5.3.4 Property comparison of the inclined-tube sedimentation tank

Inclined tube sedimentation tank is the most widely used sedimentation tank in water supply. It has the advantages of high sedimentation efficiency, low cost, small floor area and easy management. At present, the hexagonal honeycomb inclined tube sedimentation tank is widely used. The performance of inclined tube sedimentation tank is usually evaluated by six indexes, i.e. hydraulic radius R, sedimentation area per unit liquid level As, material consumption per unit volume of inclined tube MA, percentage of bonding surface P%, mud sliding performance and overall strength of inclined pipe body.

The U-shaped high-efficiency sedimentation and concentration inclined tube is a new type of high-efficiency inclined tube product which has obtained the invention patent. The seamless installation can be realized in the sedimentation tank by splicing installation mode, and it is not limited by the size of inclined pipe. Table 5-3 shows the performance comparison of U-shaped high-efficiency sedimentation inclined tube and hexagonal inclined tube.

The inclined pipe with good performance should have the characteristics of small hydraulic characteristic R, large sedimentation area per unit liquid level, small Ma consumption per unit volume of inclined pipe, small percentage of bonding area P%, good mud sliding performance and large overall strength. Among them, R and As affect the performance of the inclined tube sedimentation tank, MA and P% affect the cost of the inclined tube, the sludge performance affects the stability of the effluent quality, and the overall strength of the inclined tube affects the service life of the inclined tube sedimentation tank and greatly affects the realization of the performance of the inclined tube sedimentation tank. It can be seen from Table 5-4 that the turbidity removal rates of the two kinds of inclined tubes are 91%~98% and 93%~98%, respectively, with good sedimentation effect. However, the six performance indexes of U-shaped high-efficiency sedimentation and concentration inclined pipe are better than those of regular hexagon inclined pipe. It has not only the characteristics of convenient installation and maintenance, but also the unique anti floating design, anti-falling and anti-skid design of insert slot make it more valuable for application.

Table 5-3 Property comparison list of the U-shaped high efficiency settling inclined tube and hexagonal inclined tube

Evaluation indicator	Before renovation	After renovation
Type of inclined tube	hexagonal	U-shaped
Strength of inclined tube	high	high
Sliding mud performance	only an inclined angle of the slip plane	The slime surface is a two-dimensional inclined surface with regular shape. After the smooth surface is assembled, the upper and lower parts of the inclined pipe are flat, which is easy to slip
Hydraulic characteristic (R)	0.875	0.82
Per unit liquid level inclined tube sedimentation area (As)	16.50	18.32
Consumption of inclined pipe per unit volume (M_A)	0.76	0.67
Percentage of adhesive area (P %)	25	16.7
Removal rate of turbidity (%)	91~98	93~98

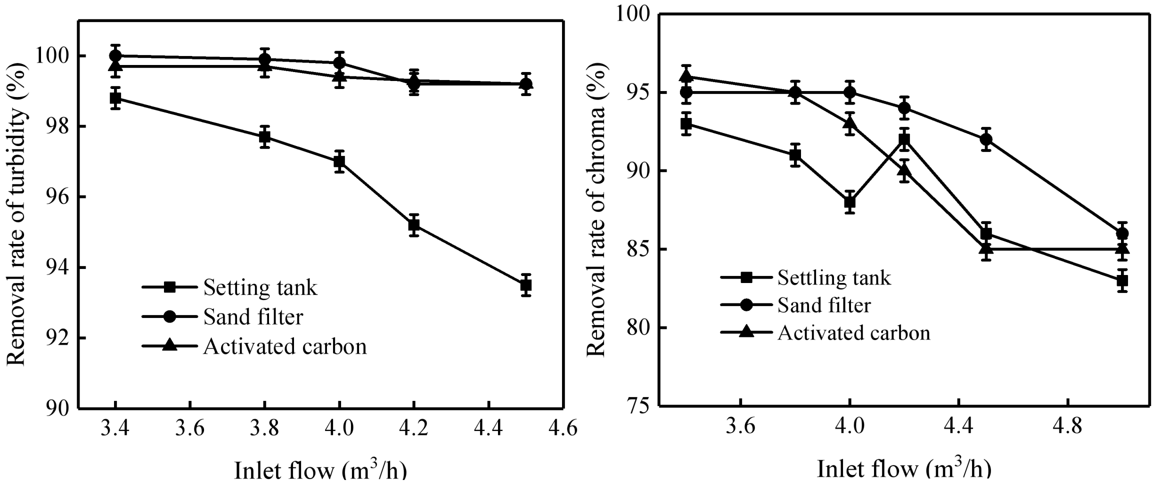
Note：The size of the two inclined tubes both are $\Phi = 3.5$ cm

5.4 Enhanced filtration test

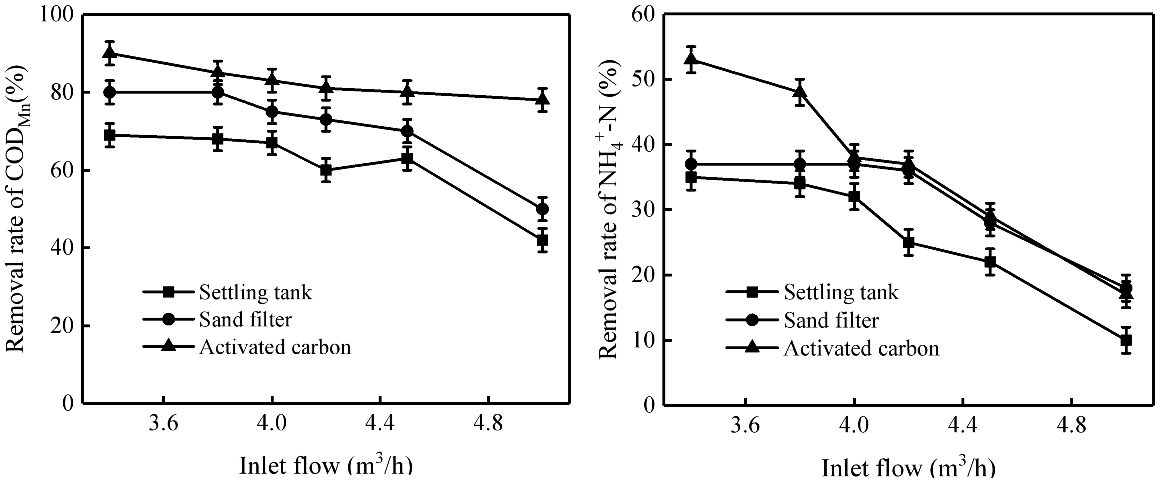
5.4.1 Load-reduction operation test

Based on operational experience at the water plant and the results of the enhanced coagulation test, the optimal dosage of the PAFC coagulant is 60 mg/L. This experiment provided the basis for further production tests to determine the optimal inlet flow operation conditions, and to also verify the feasibility of using a reduction scheme in the engineering design of the treatment plant. The raw water of the waterworks and the effluent from various processes were tested under six inlet flows. The test indices were turbidity, COD_{Mn}, chroma, and NH_4^+-N. In order to more intuitively represent the changes between the different inlet flows and the effluent quality of each process, turbidity, COD_{Mn}, chroma, and the average removal rate of NH_4^+-N under the different inlet flows were analyzed, as shown in Fig. 5-4.

As can be seen from Fig. 5-4, with the increase of inlet flow, effluent turbidity, COD_{Mn}, chroma and the removal rate of NH_4^+-N decreased in each section of the process. When the inlet flow was 3.4 m^3/h, the removal rate of turbidity and chroma during sand filtration was above 95%, the removal rate of COD_{Mn} was about 80%, and the removal rate of NH_4^+-N was about 40%. When the inlet flow increased to 5 m^3/h, the removal rate of chroma and turbidity was more than 85%, the removal rate of COD_{Mn} was about 55%, and the removal rate of NH_4^+-N was about 20%. With the increase of inlet flow, the removal rate of the various effluent indices in each section of the process showed a downward trend. The effluent removal rate in the settling tank decreased significantly, while that of the sand filter tank and the activated carbon filter tank changed little. Therefore, for the consideration of practical engineering purposes, the optimal inlet flow during load reduction operation is 3.4 m^3/h.



(a) Turbidity (b) Chroma



(c) COD_{Mn}

(d) NH_4^+-N

Fig. 5-4 Influence of different inlet flows on turbidity, chroma, COD_{Mn} and NH_4^+-N removal rate

5.4.2 Determination of the backwash cycle

In the backwashing process, the first step involves air washing for 2 min, then simultaneous air and water washing for 3 min, with a final water wash for 5 min. The washing intensity is 11.5 m^3/h. Under this condition, the inlet flow was changed to analyze the influence of different inlet flows on the backwash cycle, and the results are shown in Fig. 5-5.

When the inlet flow was 3.4 m^3/h, the backwash cycle took 20 d. With the increase of water flow, the backwash cycle decreased. When the inlet flow reached 5 m^3/h, the backwash cycle dropped to 5 d. A short backwash cycle also affects the effluent quality following filtration. According to the analyses in the previous section, increasing the inlet flow also affects the filtered water quality. Therefore, following comprehensive evaluation, the optimal inlet flow selected from this test was 3.4 m^3/h, with a backwashing cycle of 20 d.

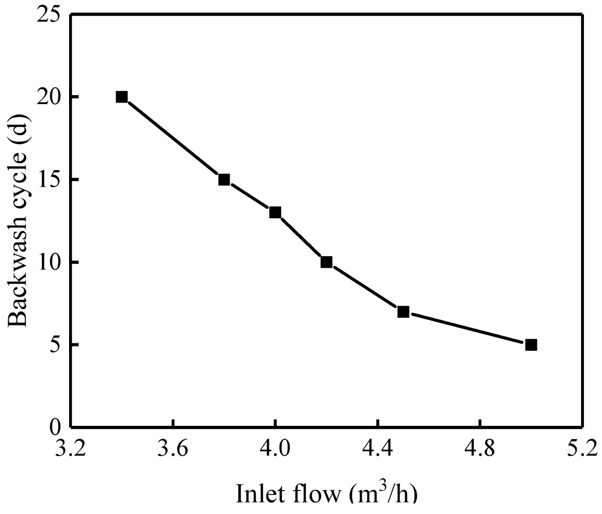


Fig. 5-5 Influence of different inlet flows on the backwash cycle

5.4.3 Determination of washing intensity

The washing intensity during sand filtration was altered and the turbidity of the effluent in the settling tank and sand filtration tank were measured once the water inlet flow had been restored for 2-3 h. The influence of washing intensities of 10.5 L/(m^2•s), 11.5 L/(m^2•s), 12.5 L/(m^2•s), and 14.5 L/(m^2•s) on the average removal rate of effluent turbidity was analyzed, as shown in Fig. 5-6.

With the increase of washing intensity, the removal rate of effluent turbidity also increased. When the washing intensity was 10.5 L/(m^2•s), the removal rate of effluent turbidity was 58.88%. When the washing intensity increased to 12.5 L/(m^2•s), the reduction in effluent turbidity reached 80.27%, and from this point, the effluent turbidity removal rate trend flattened. Therefore, it is more appropriate to limit the backwash intensity of the sand filter to about 12.5 L/(m^2•s).

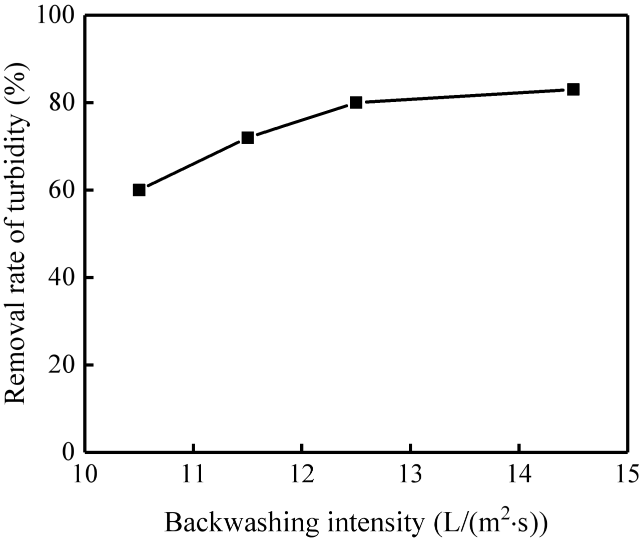


Fig. 5-6 Effect of sand filtration washing intensity on the removal rate of effluent turbidity

As can be seen from the above data, the average turbidity of the outlet water was 2.32 NTU and the chroma was 27 PCU after enhanced coagulation. After enhanced filtration, the effluent turbidity and chroma were on average 1.46 NTU and 25 PCU, while COD_{Mn} and NH_4^+-N were on average 7.83 mg/L and 2.16 mg/L. The quality of the effluent did not meet the requirements of drinking water standards, so the subsequent treatment processes described should be considered in depth.

5.5 Summary

Through the strengthening and transformation of the conventional process of a water plant in Harbin, the following results can be obtained.

(1) The conventional treatment process of a water plant in Harbin can not provide high-quality drinking water in winter. The turbidity, COD_{Mn} and ammonia nitrogen of the effluent from conventional treatment process can not meet the requirements of “Standards for drinking water quality” (GB5749-2006) in winter.

(2) The results of enhanced coagulation test show that the effect of PAFC is the best, and the optimal dosage is 60 mg/L. At this time, the removal rate of turbidity and chroma can reach 99% and 89%, respectively.

(3) The best parameters of enhanced filtration are: the inflow flow is 3.4 m^3/h, the backwash period is 20 d, the backwash strength is 12.5 $L/(m^2 \cdot s)$. At this time, the removal rate of turbidity and chroma of sand filter is over 95%, the removal rate of COD_{Mn} is 80%, and the removal rate of ammonia nitrogen is about 40%.

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Chapter 6. Pilot study on the advanced treatment in a waterworks of Harbin

6.1 Introduction

In view of the low temperature and low turbidity water, the Songhuajiang River water can not meet the increasing drinking water quality standard by using the traditional conventional process. The fifth chapter shows that the treatment efficiency is limited by enhanced coagulation and enhanced filtration. Therefore, it is necessary to upgrade the advanced treatment process of water plants in cold areas. In recent years, ozone biological activated carbon integrated process has enhanced the removal of refractory organic pollutants, which has gradually attracted the attention of researchers, and achieved good treatment effect in the field of water supply and drainage engineering [1, 2]. Li et al. [3] applied an integrated ozonation and biological activated carbon filtration (O_3-BAC) process to remove sulfonamides. A decay ranged from 45% to 92% of sulfonamides can be obtained. And results indicated that BAC filtration was capable of overcoming the problem of increased disinfection byproducts formation potential caused by ozonation. A full-scale ozonation treatment aiming at removing antibiotics, antimycotics and biocides was performed by Östman et al. [4] They found the removal efficiency of most of the studied compounds could reach more than 90%, while only 75% of benzotriazoles and fluconazole could be removed from the water. To compare the efficiency of ozone (O_3) and O_3 with granular activated carbon (GAC), a pilot-scale experiment was applied by Vatankhah et al. [5] for the productive elimination of micro-pollutants from wastewater effluent. Results revealed tris (2-carboxylethyl) phosphine (TCEP), sucralose, and meprobamate could be efficiently removed during the O_3/GAC treatment, which were superior to the sum of their removal during single ozonation and GAC adsorption experiments.

In order to ensure the safety of drinking water with Songhuajiang River water as the source, a pilot scale experiment was carried out with the advanced treatment process of ozone biological activated carbon based on the enhanced conventional treatment process of a water plant in Harbin. This paper focuses on the ozone dosage, ozone utilization rate, biological activated carbon filter process test and chlorination experiment, evaluates the feasibility of ozone biological activated carbon advanced treatment process through the stable operation of the system, and explores the joint treatment of Mopanshan Reservoir water and Songhuajiang River with this process, and preliminarily studies the impact of its combined water supply on the water quality of pipe network. It is hoped that the research results of this paper can provide technical support for the safety of drinking water in Harbin.

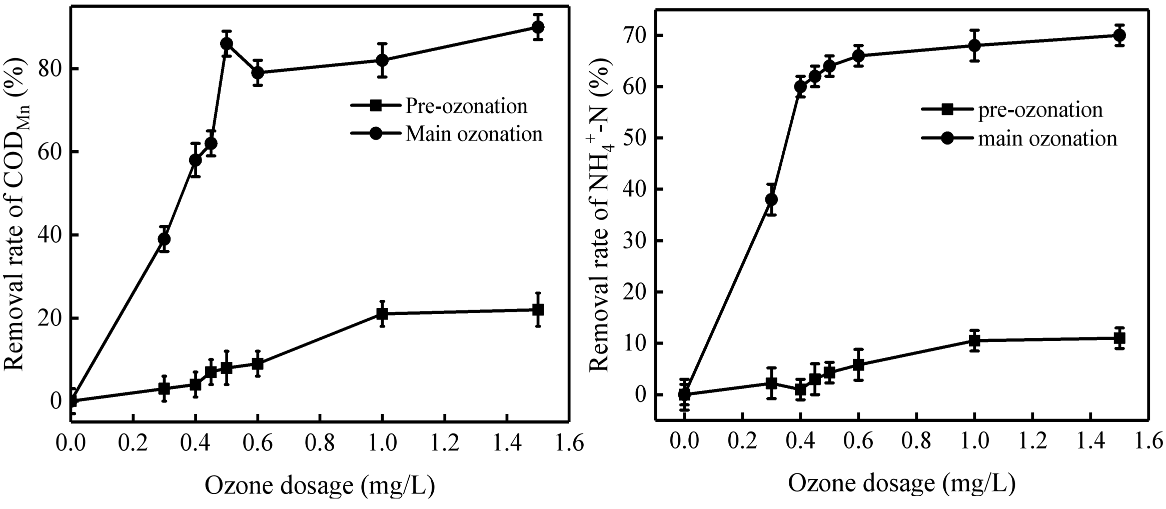
6.2 Pilot study of the O_3/BAC process

6.2.1 Determination test of ozone dosage

By changing the amount of ozone added, the changes of COD_{Mn} and NH_4^+-N concentration in the outlet water of the pre-ozonation contact pool and the main ozone contact pool were detected to determine the appropriate amount of ozone to oxidize the organic matter and NH_4^+-N in the water. In this test, the ozone doses were 0 mg/L, 0.3 mg/L, 0.4 mg/L, 0.45 mg/L, 0.5 mg/L, 0.6 mg/L, 1.0

mg/L and 1.5 mg/L. The relationship between ozone dosage and the average removal rate of organic matter is shown in Fig. 6-1.

It can be seen from Fig. 6-1 that ozone addition has a certain promoting effect on the removal of organic matter. The removal rate of COD_{Mn} and NH_4^+-N increased with the increase of ozone dosage. In general, the removal rate of organics in the main ozonation contact pool was significantly higher than that in the pre-ozonation contact pool. The removal rate of COD_{Mn} and NH_4^+-N changed little when the pre-ozonation dosage was over 1.0 mg/L. When the main ozonation dosage exceeded 0.4 mg/L, the removal rate of COD_{Mn} and NH_4^+-N reached over 60%. However, if the amount of ozone added is too large, the turbidity of the effluent from the settling tank will increase. After comprehensive consideration, it was determined that the optimum amount of ozone to add in the pre-ozonation contact pool was 1.0 mg/L and 0.4 mg/L in the main ozonation contact pool.



(a) COD_{Mn} (b) NH_4^+-N

Fig. 6-1 Effect of ozone dosage on COD_{Mn} and NH_4^+-N removal

The residual ozone was determined as 0.127 mg/L after the pre-ozonation process, reaching 87.30% of the ozonation utilizing ratio. However, the residual ozone was measured as 0.116 mg/L after the main ozonation process, which was 71.00% of the ozonation utilizing ratio. Although the excellent removal rate occurred in the main ozonation contact tank, the pre-ozonation process was more preferable to the main ozonation process for the ozonation utilizing ratio under the optimal dosage.

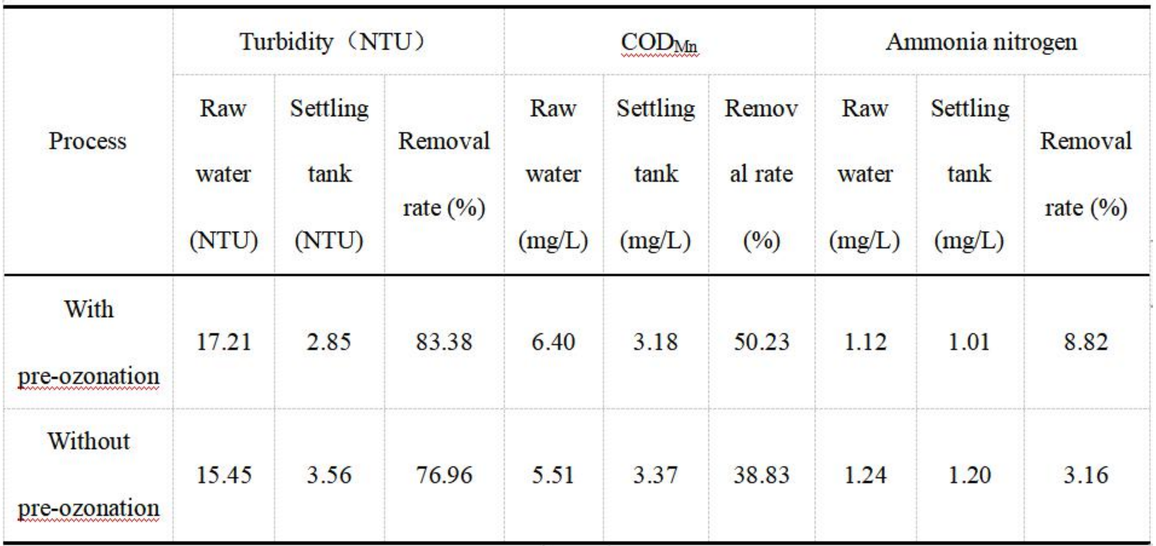
6.2.2 Influence of pre-ozonation process on conventional treatment

To understand the influence of ozone treatment on conventional treatment, a comparative analysis between the treatment effect of the precipitation tank after pre-ozonation and the treatment effect of conventional precipitation tank was carried out. The results are listed in Table 6-1.

As presented in Table 6-1, compared with the conventional treatment, the removal rate of COD_{Mn} and ammonia nitrogen increased by 22.70% and 64.17% due to the addition of pre-ozonation process.

The pre-ozonation process promoted the removal of organics in water significantly. Meanwhile, the effluent turbidity and average removal rate were 3.56 NTU and 76.96% in the precipitation tank of conventional treatment, while the effluent turbidity and average removal rate from precipitation tank were 2.85 NTU and 83.38% after pre-ozonation. Results indicated that the pre-ozonation process could effectively increase the coagulation effect and cause a micro-flocculation effect. It perhaps because the pre-ozonation process can increase the contents of organic substances with oxygen-containing functional groups (e.g. carboxylic acid) in water to form polymers with hydrolysate of metal salts and calcium salts. These polymers can lower electrostatic interaction of natural organic matter (NOM) on the inorganic particle surface and trigger polymerization of dissolved organic substances to form poly-electrolytes which can serve as adsorption bridge and make high-stability algae destabilization and produce co-precipitation. Therefore, TOC, turbidity, algae categories, and quantity in raw water, pre-ozonation and coagulation conditions are the main factors affecting the coagulation effect based on pre-ozonation.

Table 6-1 Influence of pre-ozonation process on conventional treatment



Process	Turbidity（NTU）			COD_{Mn}			Ammonia nitrogen		
	Raw water (NTU)	Settling tank (NTU)	Removal rate (%)	Raw water (mg/L)	Settling tank (mg/L)	Removal rate (%)	Raw water (mg/L)	Settling tank (mg/L)	Removal rate (%)
With pre-ozonation	17.21	2.85	83.38	6.40	3.18	50.23	1.12	1.01	8.82
Without pre-ozonation	15.45	3.56	76.96	5.51	3.37	38.83	1.24	1.20	3.16

Pre-ozonation can reduce the dosage of coagulant. And it can improve the turbidity removal rate and prolong the filtration cycle of the filter at a certain dosage of coagulation. Results proved that adding ozone separately could not eliminate the turbidity in raw water, which reflected that ozone itself had no coagulation effect. However, adding a certain amount of ozone can facilitate coagulation well. Influences of ozone dosage on coagulation performance are shown in Table 6-2.

Given the consistent removal rate of effluent turbidity from precipitation, when the ozone dosage was 0.93 mg/L, the dosage of coagulant reduced by 4%~17% compared with none ozone applied. When the dosage of ozone was greater than 1.8 mg/L, the dosage of coagulant with the same dosage would increase the precipitation effluent turbidity. It is necessary to increase the dosage of coagulant to stabilize the effluent turbidity. When the ozone dosage reached 2.50 mg/L, the dosage of coagulant increased by 6%~15%. The experimental results show that the dosage of coagulants can be reduced by adding a proper amount of pre-ozonation. Due to the presence of refractory organic compounds in the raw water, the high amount of pre-ozonation injection could not obtain a good treatment effect. Therefore, pre-ozonation is only used as pre-treatment of raw water and the dosage of pre-ozonation needs to be controlled.

Table 6-2 Effect of different dosage of ozone on dosage of coagulant

Ozone dosage (mg/L)	Turbidity of raw water (NTU)	Turbidity of settling tank (NTU)	Removal rate of turbidity (%)	Dosage of coagulant (mg/L)	Reduction rate of coagulant (%)
0	48.7	2.12	95.8	44.6	0
0.66	49.8	2.39	95.2	41.5	7.0
0.79	50.9	2.20	95.7	39.8	10.8
0.93	44.2	1.73	96.1	39.1	12.3
1.57	39.7	1.63	95.8	42.0	5.8
1.85	39.7	1.72	95.7	43.9	1.6
2.50	40.5	2.01	95.0	48.6	-9.0

6.2.3 Influence of main ozone process on carbon filter

To analyze the influence of main ozone treatment on carbon filtering tank, the effect of the carbon filtering tank after main ozone treatment was compared with the effect of carbon filtering tank without involving ozone. The results are shown in Table 6-3.

The average removal rate of effluent turbidity, COD_{Mn}, and ammonia nitrogen after coagulation, precipitation and filtering were 96.48%, 50.58%, and 12.32%, respectively. After adding the main ozone treatment, the average removal rate of effluent turbidity, COD_{Mn}, and ammonia nitrogen in the activated carbon filtering tank was increased significantly to 97.87%, 78.76%, and 28.56%, respectively. In particular, the removal rate of COD_{Mn} and ammonia nitrogen increased by nearly more than 50%. There exist a great difference in the removal rate of COD_{Mn} and ammonia nitrogen between the carbon filtering tank with and without main ozone treatment. This is mainly because the macro-molecular refractory organic substances in raw water can be oxidized into easily biodegradable macro-molecular organic substances by the main ozone tank, which enhances the biodegradability of organic substances. As a result, organic adsorption and degradation of activated carbon are promoted, and even increasing the removal rate of COD_{Mn} and ammonia nitrogen.

Table 6-3 Influence of the main ozone process on carbon filter

	Turbidity			COD_{Mn}			Ammonia nitrogen		
Process	Raw water	Carbon-sand	Removal rate (%)	Raw water	Carbon-sand	Removal rate (%)	Raw water	Carbon-sand	Removal rate (%)

	(NTU)	filtration (NTU)		(mg/L)	filtration (mg/L)		(mg/L)	filtration (mg/L)	
With main ozonation	16.63	0.35	97.87	5.69	1.20	78.76	1.21	0.91	28.56
Without main ozonation	10.28	0.36	96.48	4.37	0.97	50.58	1.41	1.08	12.32

6.2.4 Removal efficiency of UV_{254}, THMFP and TOC

For deep purification of drinking water, much attention has been given to the removal of natural organic matter such as macro-molecule humic acid and fulvic acid, which can easily react with active chlorine to generate halogenated carcinogens [6, 7]. UV_{254} can be used as an alternative parameter for some indexes, such as total organic carbon (TOC), dissolved organic carbon (DOC), and precursor of trihalomethanes (THMs) [8]. It is an important parameter to measure organic substances in water. The UV_{254} variation in each treatment unit is shown in Fig. 6-2.

As depicted in Fig. 6-2, the average UV_{254} value of raw water was 0.119 cm^{-1}. After the O_3/BAC process, the removal rate reached 87.39% with the UV_{254} value decreasing to 0.015 cm^{-1}. The removal efficiency of UV_{254} was 32.77% by the pre-ozonation process, 63.03% by the sand filtration process, and 87.39% by the O_3/BAC process. In contrast to the pre-ozonation process, the removal efficiency of the subsequent O_3/BAC process was higher than that of the pre-ozonation process with a difference of 54.62%. The UV_{254} can be drastically eliminated by the O_3/BAC process. Since UV_{254} represents organic substances with an aromatic ring structure or conjugated double bond, it can reflect the concentration of precursor of THMs. It is reported that ozone can easily react with C=C in organic substances [9]. It destroys the benzene ring and causes the aromatic property of organic matter to reduce or disappear. Therefore, the O_3/BAC process not only has high-efficiency for the removal of the trihalomethane precursor, but also significantly reduces the content of organic matters in water.

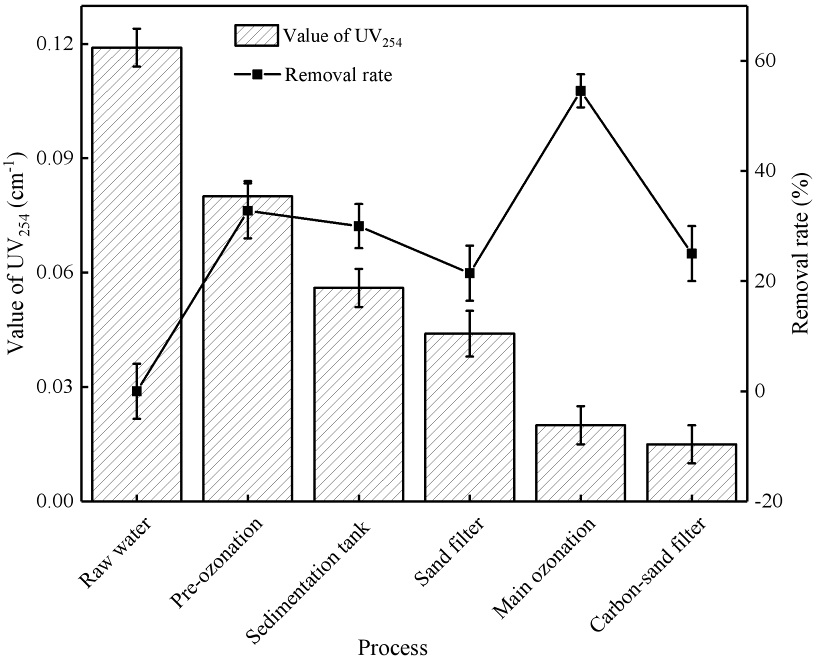


Fig. 6-2 Variation of effluent UV_{254} in each process

Disinfection by-products (DBPs) have been a concern in the water supply and processing field. Especially, there is global concern regarding trihalomethane problems [10, 11]. The components of NOM which can react with chlorine to generate THMs are identified as trihalomethane precursors. These precursors are usually determined by the trihalomethane formation potential (THMFP) to represent the content. The variation of THMFP in each treatment unit is shown in Fig. 6-3.

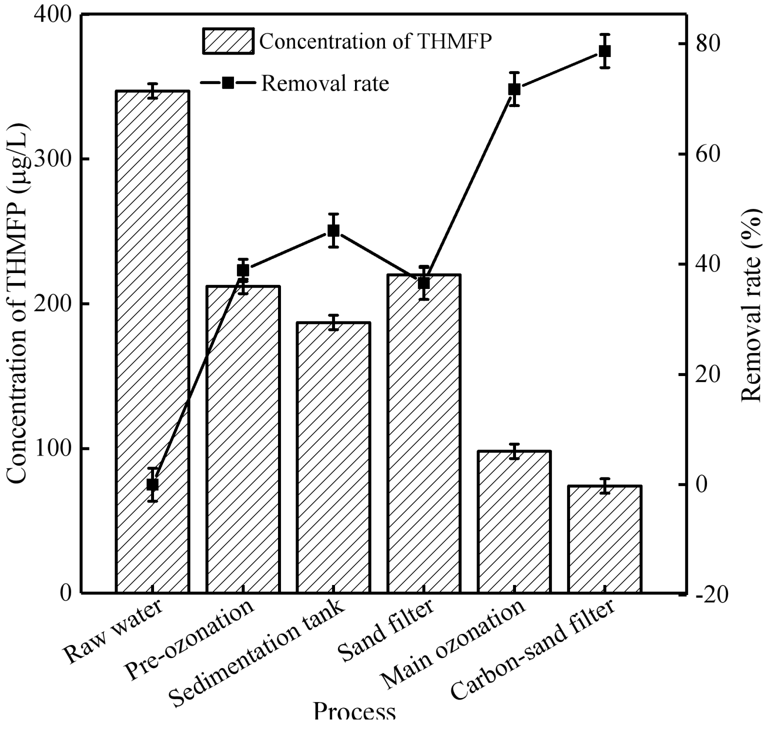


Fig. 6-3 The variation of THMFP in each treatment units

As illustrated in Fig. 6-3, the content of THMFP in raw water was 347 μg/L, which was eliminated by the pre-ozonation process with a removal rate of 38.9%. Although a part of THMFP can be removed by coagulation and precipitation, the elimination capacity is limited. For example, when the precipitation water passed through the filter tank, the concentration of THMFP increased with a removal rate of 36.6%. This may be attributed to the accumulation of algae and other organic matter in the filter material of the filter tank, since algae is also a kind of trihalomethane precursor [12, 13]. Furthermore, the main ozonation process had a dominant removal effect on the THMFP. The removal rate reached 71.76% with the value reducing from 347 μg/L to 98 μg/L. However, the removal effect of activated carbon on the THMFP was also limited, because its removal by activated carbon mainly depends on its adsorption. The adsorption capacity of activated carbon decreases with long term use, resulting in poor removal efficiency. The THMFP showed an average decrease of 78.67% from raw water to the carbon-sand filter treated water. Thus, the trihalomethane precursors in raw water can be effectively eliminated by the O_3/BAC process.

Furthermore, THMFP is also related to the variation of TOC after the ozonation oxidation. The change in TOC can reflect the state of THMFP to some extent since some dissolved organic matters are the primary components of the trihalomethane precursors. The content variation of TOC in each treatment unit is presented in Fig. 6-4. The elimination of TOC exhibited a steady increase with a removal rate of 18.6% after the pre-ozonation process and 72.09% after the O_3/BAC process. Moreover, the content of THMFP accounted for 8.07% of the TOC, while the proportion was reduced to 6.17%. This result indicated that a portion of trihalomethane precursors had indeed been eliminated from the water after the O_3/BAC process.

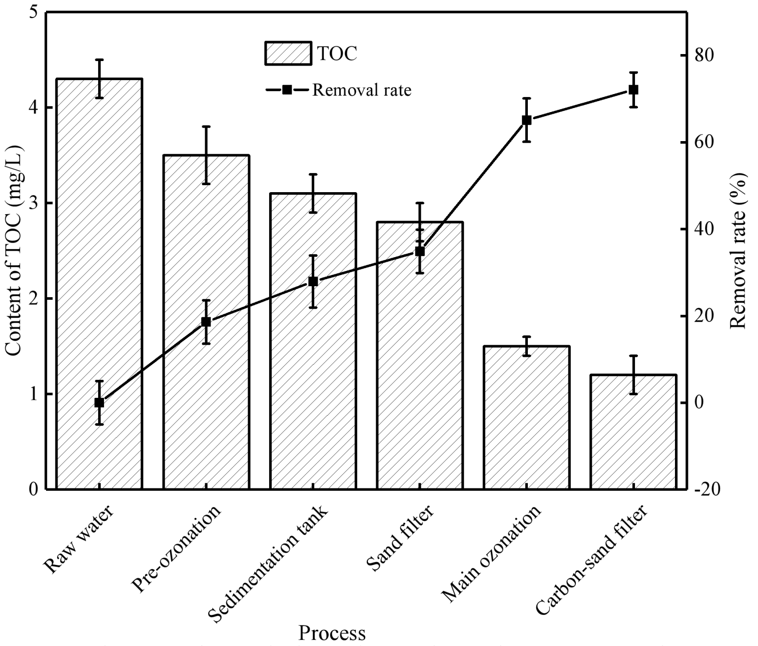
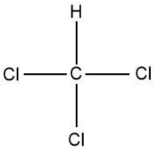
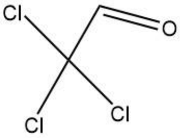
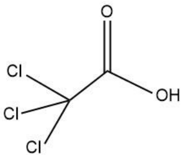
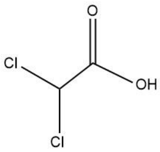
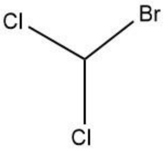
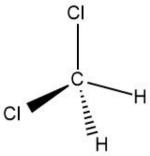
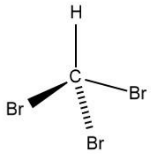
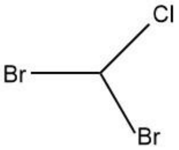
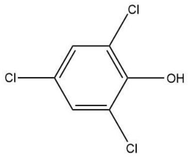


Fig. 6-4 The variation of TOC in each treatment units

The detectable DBPs in the effluent are listed in Table 6-4. These detectable DBPs all reached the requirement of "Standards for drinking water quality" (GB5749-2006). Among them, the content of the high-profile trichloroacetic aldehyde was 0.004 mg/L, which reduced by 60% in comparison with the drinking water standard (0.01 mg/L). Moreover, the contents of common trichloromethane, trichloroacetic acid, and dichloroacetic acid also decreased by 91.67%, 93%, and 74%, respectively. The other DBPs, especially those containing bromine atoms generated by the ozonation oxidation, were all below the detection limit. The production of DBPs was under good control through the treatment of the O_3/BAC process. To sum up, the precursors of DBPs can be effectively eliminated by the O_3/BAC process in the Songhuajiang River water, and also the content of the DBPs meets the national drinking water standard.

Table 6-4 The list of the detectable DBPs in the effluent

DBPs	Structural formula	Content (mg/L)
Trichloromethane		0.005
Trichloracetic aldehyde		0.004
Trichloroacetic acid		0.007
Dichloroacetic acid		0.013
Bromodichloromethane		<0.001
Dichloromethane		<0.0001

Tribromethane		<0.001
Dibromochloromethane		<0.001
Cyanochloride		<0.01
2,4,6-Trichlorophenol		<0.001

6.3 Pilot study of the BAC process

6.3.1 Activated carbon selection test

Activated carbon shows different adsorption characteristics dependent on its various pore shapes and size distribution, surface functional group distribution, ash composition, and content. Different surface chemical properties and the pore composition of the activated carbon affect the migration and diffusion rate of organic matter in the activated carbon voids, meaning that its adsorption has a certain selectivity[14, 15]. In the experiment, two different types of activated carbon were added into the system, namely crushed carbon and granular carbon. By comparing the effluent treatment effects of the two activated carbon filters, the optimal treatment was determined. The test results are shown in Table 6-5.

It can be seen from Table 6-5 that the treatment effect of crushed carbon was better than that of granular carbon. For organic compounds with small molecular weight, the adsorption and degradation effects are usually improved with the increase of hydrophobicity and the decrease of the polarity of organic compounds. Therefore, the relative molecular weight and other factors should be taken into account when choosing the type of carbon. Due to the addition of ozone in the first part of this experiment, the large molecules of organic matter were decomposed into small molecules of organic matter, so the treatment effect of the crushed carbon was better.

Table 6-5 The average removal rate of the two activated carbons

Activated carbon	Turbidity (NTU)			COD_{Mn} (mg/L)			NH_4^+-N (mg/L)		
	Main ozona	Activated carbon	Removal rate	Main ozona	Activated carbon	Removal rate	Main ozona	Activated carbon	Removal rate

	-tion		(%)	-tion		(%)	-tion		(%)
crushed carbon	1.89	0.28	84.97	2.71	1.16	57.15	0.63	0.49	21.98
granular carbon	1.98	0.62	68.52	2.72	1.57	42.18	0.62	0.49	19.28

6.3.2 Operation test of the activated carbon filter

6.3.2.1 Determination of the backwashing intensity

The air washing intensity was set at 13.5 L/(m^2•s), and the carbon filter water washing intensity was altered. After washing the water inflow was restored for 2-3 h before the turbidity of the water from the main ozone tank and the carbon filter tank was measured. The backwashing intensities considered were 8 L/(m^2•s), 10 L/(m^2•s), 11.5 L/(m^2•s), and 12.5 L/(m^2•s). The influence of the different washing intensities on the turbidity removal rate of the carbon filter is shown in Fig. 6-5.

It can be seen from Fig. 6-5 that the turbidity removal rate of the carbon filter increased with the increase of backwash intensity. When the washing intensity was 11.5 L/(m^2•s), the removal rate of turbidity was the highest, with an average removal rate of 86%. As the backwash intensity continues to increase, the removal rate of turbidity tended to flatten. Therefore, a washing intensity of 11.5 L /(m^2•s) was the most appropriate.

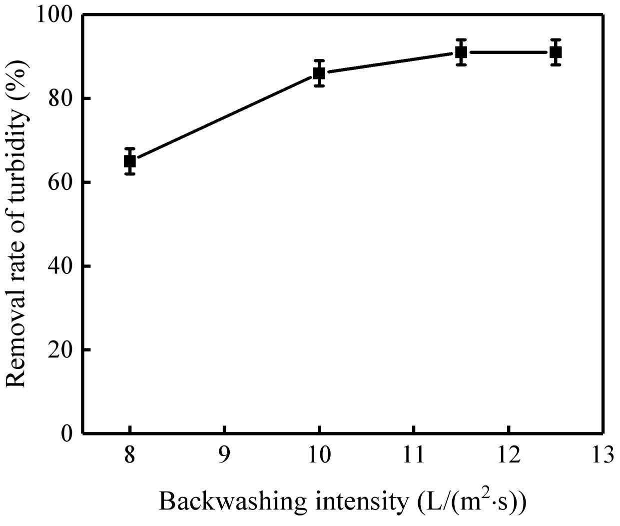
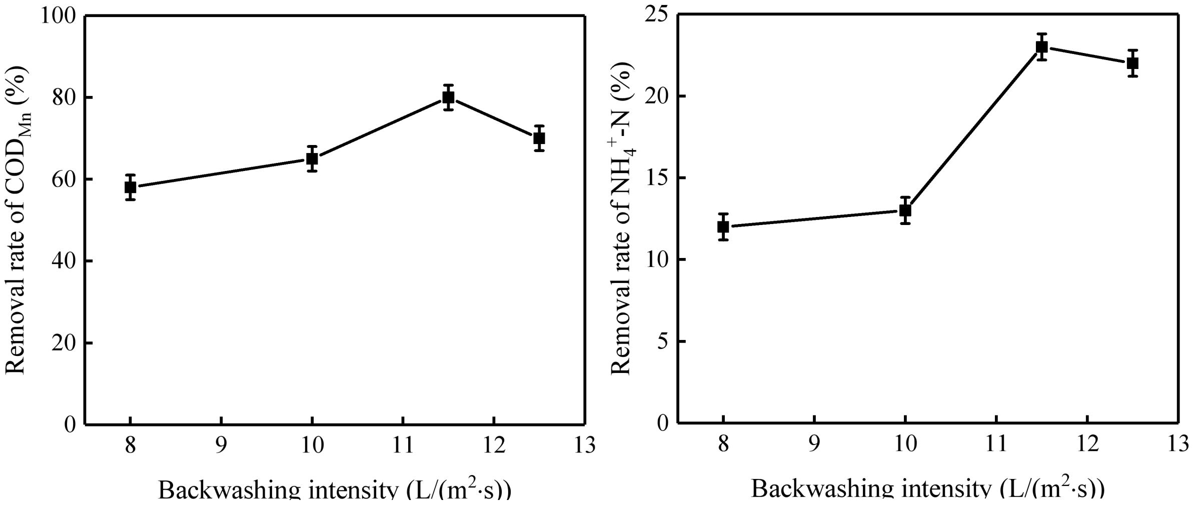


Fig. 6-5 Relationship between backwash intensity and average turbidity removal rate

The backwash intensity also has a certain influence on the removal of organic matter, so this process should be optimized. The relationship between different backwash intensities and the organic matter removal efficiency was observed, and the results are shown in Fig. 6-6.

As can be seen from Fig. 6-6, the removal rate of COD_{Mn} and NH_4^+-N from the carbon filter rose with the increase of backwash intensity. When the backwash intensity reached 11.5 L/(m^2•s), the removal rate of COD_{Mn} and NH_4^+-N also reached their highest values, which were 80% and 23%, respectively. It can be seen from the above that when the backwash intensity is 11.5 L/(m^2•s), both turbidity and organic matter are removed efficiently.



(a) COD$_{Mn}$ (b) NH$_4^+$-N

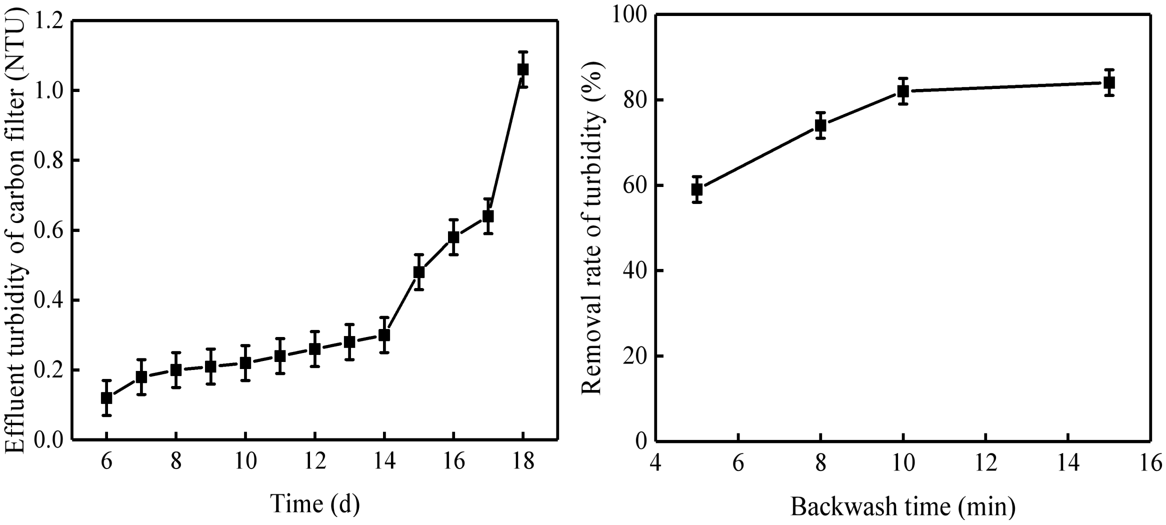
Fig. 6-6 Relationship between backwash intensity and COD$_{Mn}$ and NH$_4^+$-N

6.3.2.2 Determination of backwash cycle and backwash time

During operation, with relatively stable turbidity in the inlet water of the carbon filter tank and a backwash intensity of 11.5 L/(m^2•s), the changes in the daily turbidity of the outlet water after backwashing were observed to determine the optimal backwash duration. When the backwash time was altered, the turbidity removal rate was then measured once the inlet water had been restored for 2-3 h, as shown in Fig. 6-7.

As can be seen from Fig. 6-7 (a), the effluent turbidity of the carbon filter was stable between 0.15 NTU and 0.3 NTU between 6-14 days. After that, the turbidity of the effluent increased slightly. At 18 d, the water quality began to deteriorate, and the turbidity of the effluent reached more than 1 NTU. At this time, the carbon filter should be backwashed, which indicates that the backwashing cycle is generally about two weeks. In actual operation, it is difficult for the backwash cycle to be too long, as extended time intervals not only affect the water output but are also not conducive to flushing. In addition, the backwash cycle should not be too short, frequent washing of the filter will affect the growth of microorganisms on the activated carbon, so in actual operation, the backwash cycle should be appropriately adjusted according to the actual changes in turbidity.

As can be seen from Fig. 6-7 (b), the turbidity removal rate of the activated carbon filter increased with the increase of backwashing time. When the backwash time was 10 min, the turbidity removal rate was 81%. When the backwash time increased, the turbidity removal rate remained basically stable. Therefore, the optimal time for backwashing was determined to be 10 min.



(a) Backwash cycle (b) Backwash time

Fig. 6-7 Turbidity changes with backwash cycle and backwash time

6.3.2.3 Determination of the running limit during backwash

If the filter tank is seriously "run away", the filter material thickness will decrease, which will affect the filtering effect. In order to adjust the backwash intensity better, the influence of backwash intensity on the swelling capacity of the filter material was analyzed, and the optimum backwashing intensity was determined. The relationship between different backwash intensities and swelling percentages is shown in Fig. 6-8.

It can be seen from Fig. 6-8 that the swelling capacity of the filter material increased with the increase of backwash intensity. When the backwash intensity reached 14.5 L/(m^2•s), the filter material swelling capacity was 56%, and it was observed that the filter began to run. Therefore, the optimum backwash intensity for the filter running limit was determined to be 14.5 L/(m^2•s).

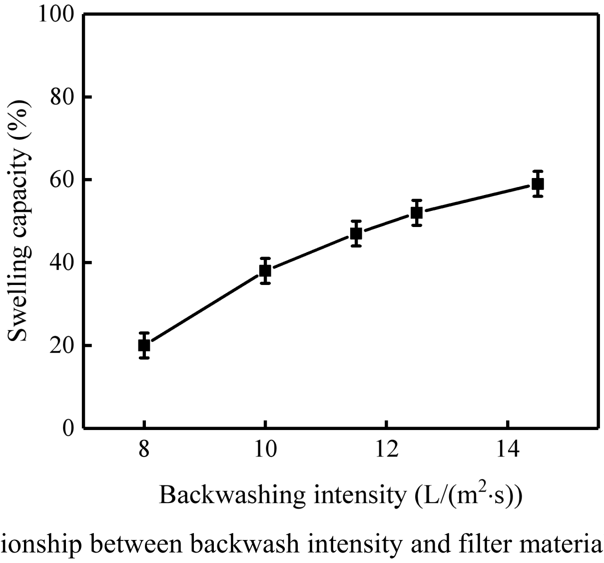
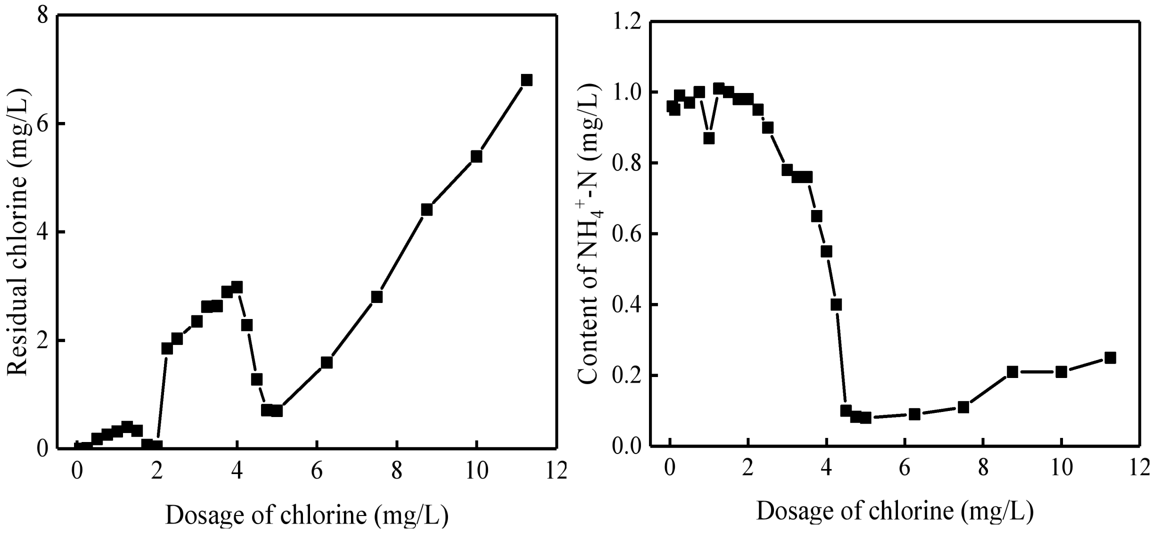


Fig. 6-8 Relationship between backwash intensity and filter material swelling capacity

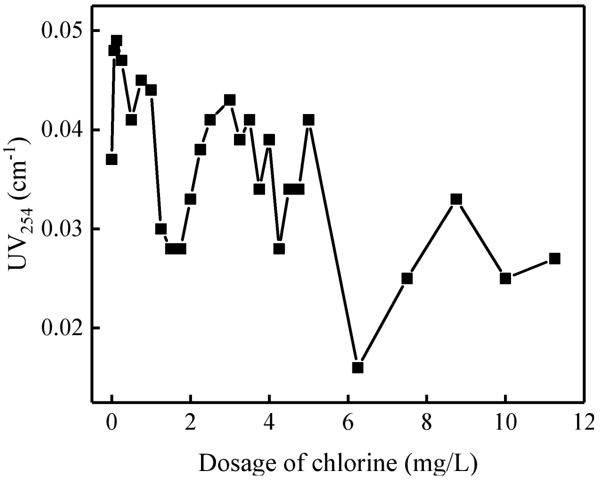
6.4 Liquid chlorine disinfection

After the raw water has been treated by coagulation, sedimentation and filtration, most of the suspended substances in the water have been removed, but there are still organic matters and a considerable number of ammonia nitrogen compounds in the water. Due to the unstable nature, chemical reactions often occur and gradually change into ammonia, which exists in the form of free state or ammonium salt. However, ammonia nitrogen is difficult to remove under low temperature and low turbidity conditions. The break point chlorination test table is shown in Table 6-6, and the relationship curve between chlorine dosage and residual chlorine, effluent ammonia nitrogen and UV_{254} is shown in Fig. 6-9 (a) (b) (c).

It can be seen from Fig. 6-9 (a) and Table 6-6 that a small amount of residual chlorine begins to appear when the chlorine dosage is 0.063 mg/L, and the free residual chlorine is zero. The residual chlorine began to increase slowly after adding chlorine, and the residual chlorine was compound chlorine. When the chlorine dosage reaches 4.0 mg/L, the residual chlorine reaches the highest point, and the residual chlorine amount is 2.98 mg/L. After continuous chlorination, the residual chlorine was still produced. At the same time, chloramines were oxidized into compounds that did not have disinfection effect, and the residual chlorine began to decrease. When the dosage of chlorine reached 5 mg/L, the residual chlorine decreased to the minimum. After that, free residual chlorine appeared in water, and then the residual chlorine increased with the increase of dosage. It can be seen from Fig. 6-9 (b) and Table 6-6 that when the chlorine dosage is between 0~1.25 mg/L, the ammonia nitrogen content in effluent fluctuates little. When the chlorine dosage increased from 1.25 mg/L to 5 mg/L, the ammonia nitrogen content in effluent decreased with the increase of chlorine dosage. Then, with the increase of chlorine dosage, the ammonia nitrogen content in effluent began to increase gradually. UV_{254} is closely related to the precursors of trihalomethanes (THMs). It can be seen from Fig. 6-9 (c) and Table 6-6 that the UV_{254} value fluctuates greatly with the increase of chlorine dosage. However, when the chlorine dosage was 6.25 mg/L, the UV_{254} value reached the lowest value of 0.016 cm^{-1}. In general, when the chlorine dosage is between 0~6.25 mg/L, UV_{254} has a gradually decreasing trend. When the chlorine dosage continued to increase, the UV_{254} value began to increase, which increased the risk of disinfection by-product precursors in water. To sum up, adding appropriate chlorine dosage can not only ensure a certain amount of residual chlorine, but also control the ammonia nitrogen content and UV_{254} value of the effluent of the system, so as to ensure that the ammonia nitrogen and disinfection by-product precursors can reach the standard in the low temperature and low turbidity period.



(a) Residual chlorine (b) NH$_4^+$-N



(c) UV$_{254}$

Fig. 6-9 Relationship between dosage of chlorine and residual chlorine, NH$_4^+$-N, and UV$_{254}$

Table 6-6 Test of breakpoint chloranation

Dosage of available chlorine (mg/L)	Total residual chlorine (mg/L)	Free chlorine residual (mg/L)	Combined chlorine residual (mg/L)	NH$_4^+$-N (mg/L)	UV$_{254}$ (cm^{-1})	Trichloromethane (mg/L)
Raw water	0	0	0	1.02	0.037	<0.01
0.063	0.06	0	0.06	0.96	0.048	<0.01
0.125	0.10	0	0.10	0.95	0.049	<0.01
0.25	0.24	0.01	0.23	0.99	0.047	<0.01
0.5	0.46	0.18	0.28	0.97	0.041	<0.01
0.75	0.80	0.26	0.54	1.00	0.045	<0.01

1	1.07	0.32	0.75	0.87	0.044	<0.01
1.25	1.26	0.40	0.86	1.01	0.030	<0.01
1.5	1.37	0.33	1.04	1.00	0.028	<0.01
1.75	1.46	0.07	1.39	0.98	0.028	<0.01
2	1.56	0.04	1.52	0.98	0.033	<0.01
2.25	1.85	1.85	1.68	0.95	0.038	<0.01
2.5	2.03	2.03	1.79	0.90	0.041	<0.01
3.0	2.35	2.35	2.18	0.78	0.043	<0.01
3.25	2.62	2.62	2.48	0.76	0.039	<0.01
3.5	2.63	2.63	2.52	0.76	0.041	<0.01
3.75	2.89	2.89	2.77	0.65	0.034	<0.01
4.0	2.98	2.98	2.01	0.55	0.039	<0.01
4.25	2.28	2.28	1.45	0.40	0.028	<0.01
4.5	1.28	1.28	0.94	0.1	0.034	<0.01
4.75	0.71	0.71	0.30	0.083	0.034	<0.01
5.0	0.70	0.70	0.17	0.08	0.041	<0.01
6.25	1.81	1.59	0.22	0.09	0.016	<0.01
7.5	3.03	2.80	0.23	0.11	0.025	<0.01
8.75	4.55	4.41	0.41	0.21	0.033	<0.01
10	5.84	5.39	0.45	0.21	0.025	<0.01
11.25	7.31	6.80	0.5	0.25	0.027	<0.01

The standard of drinking water requires that the free residual chlorine in the effluent is more than 0.5 mg/L, and the content of ammonia nitrogen is below 0.5 mg/L. It can be seen from Table 6-6 that when the chlorine dosage is increased to 4.25 mg/L, the free residual chlorine is 0.8 mg/L, and the ammonia nitrogen value of effluent is 0.4 mg/L, both of which meet the above standards. Therefore, it is determined that the optimal chlorine dosage is 4.25 mg/L. According to the above analysis, the curve of chlorination at break point and the relationship between chlorine dosage and ammonia nitrogen in effluent are obtained, as shown in Fig. 6-10 and Fig. 6-11.

It can be seen from Fig. 6-10 that 5 mg/L chlorine dosage is the break point. However, in Fig. 6-11, when the chlorine dosage is 4.25 mg/L, the ammonia nitrogen is 0.4 mg/L, which has met the requirements, so the break point is not the optimal chlorine dosage. In the actual production, it can be adjusted according to the water quality and the chlorine dosage.

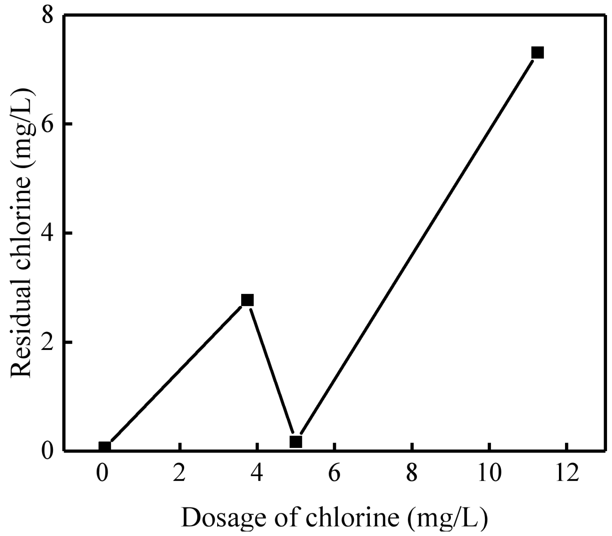


Fig. 6-10 Breakpoint chloranation

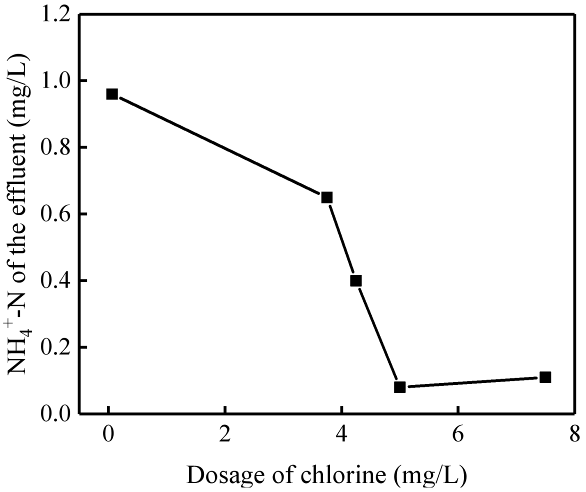


Fig. 6-11 Relationship between dosage of chlorine and NH_4^+-N of the effluent

The ammonia nitrogen concentration of raw water is about 1 mg/L. if the ammonia nitrogen concentration of water body rises suddenly, the amount of chlorine added will be affected. Therefore, ammonia water is added to raw water to make ammonia nitrogen reach 2.5 mg/L. The influence of chlorine addition on ammonia nitrogen and residual chlorine is analyzed. The test results are shown in Table 6-7.

It can be seen from Table 6-7 that when the ammonia nitrogen reaches 2.7 mg/L and the effective chlorine is 8.25 mg/L, the residual chlorine in the effluent is 0.83 mg/L, and the ammonia nitrogen content is 0.338 mg/L, which can meet the drinking water quality standard. Therefore, when the concentration of ammonia nitrogen is high, the amount of chlorine should be determined according to the actual situation. In general, due to the biological activated carbon process has a good removal of ammonia nitrogen, the ammonia nitrogen in the effluent of the carbon filter is generally maintained at about 1 mg/L during stable operation, and the dosage of available chlorine will not change much.

Table 6-7 Test of adding ammonia and chloride

Dosage of available chlorine (mg/L)	Total residual chlorine (mg/L)	Free chlorine residual (mg/L)	Combined chlorine residual (mg/L)	NH_4^+-N (mg/L)	Trichloromethane (mg/L)
Raw water	0	0	0	2.739	<0.01
2.5	3.28	1.47	1.81	1.698	<0.01
5.0	6.52	2.32	4.2	1.601	<0.01
6.25	6.51	2.37	4.14	1.390	<0.01
7.5	4.17	1.22	2.95	0.902	<0.01
7.5	4.29	1.64	2.65	0.831	<0.01
7.75	3.68	1.16	2.04	0.612	<0.01
8.0	3.21	0.97	2.24	0.552	<0.01
8.25	2.78	0.83	1.95	0.338	<0.01
8.50	2.34	0.66	1.68	0.260	<0.01
8.75	1.99	0.55	1.44	0.163	<0.01
8.75	1.69	0.53	1.16	0.109	<0.01
10.0	0.64	0.59	0.05	0.057	<0.01

According to China's drinking water standard, the free residual chlorine in the treated water should not be less than 0.3 mg/L after 30 min contact, and should not be lower than 0.05 mg/L at the end of the pipe network. In order to ensure that the residual chlorine can meet the standard after chlorination at the break point, continuous monitoring of chlorine content in the effluent after 10 hours was carried out on site. The results are shown in Fig. 6-12. The dosage of available chlorine is 4.25 mg/L, and the ammonia nitrogen content in carbon filter water is 1.031 mg/L.

It can be seen from Fig. 6-12 that the residual chlorine in the effluent is mainly composed of the combined residual chlorine. When the chlorine dosage is 4.25 mg/L, the free residual chlorine content in the effluent is 0.36 mg/L and the ammonia nitrogen content is 0.19 mg/L. The effluent can meet the national drinking water standard. But on the whole, with the increase of contact time, the contents of ammonia nitrogen, total residual chlorine, combined residual chlorine and free residual chlorine in effluent showed a gradual decline trend. It can be seen that under the optimal dosage of available chlorine, all the indexes in the effluent quality can meet the requirements of the “Standards for drinking water quality” (GB5749-2006).

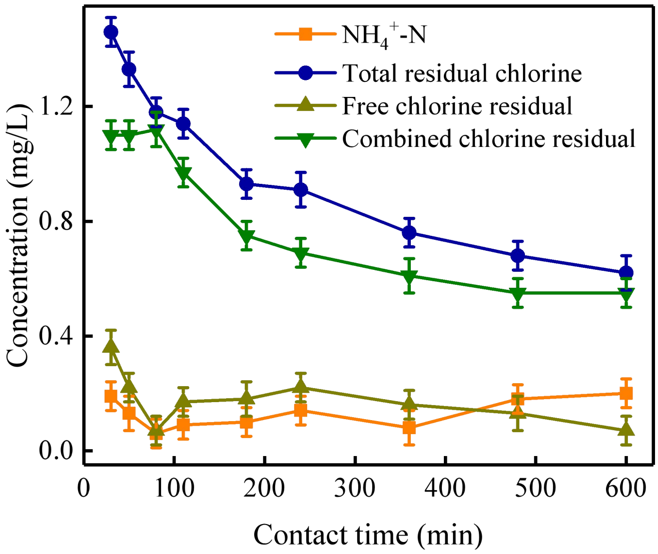


Fig. 6-12 Variation of chlorine with the change of contact time

6.5 Stable operation of the O_3/BAC process and biological stability

6.5.1 Stable operation of the O_3/BAC process

As mentioned above, the water quality deterioration of the Songhuajiang River usually occurred in the frozen period, increasing the treatment difficulty. The upgraded O_3/BAC process can significantly alleviate this problem. The turbidity, variation of the organic matters, and even the content of trihalomethane precursors in the cold period can all be effectively removed through the upgraded O_3/BAC process, and the effluent quality can meet the domestic drinking water standard. To evaluate the stable operation effect of the O_3/BAC process, stable running of the pilot-scale test for about three months (October 2018 - March 2019) was investigated during the frozen period of the water plant (Fig. 6-13~Fig. 6-16). In this section, the parameters of turbidity, chroma, COD_{Mn}, and NH_4^+-N were selected to appraise the water quality.

The turbidity variation during the stable operation is illustrated in Fig. 6-13. It can be seen from Fig. 6-13 that the turbidity of raw water and pre-ozonation effluent both fluctuated in waveform during the frozen period, while the effluent turbidity was stable after the subsequent treatments. In particular, the turbidity value remained unchanged for the carbon filter effluent. The removal rate of turbidity after the upgraded O_3/BAC process was more than 95%. The effluent turbidity was about 0.2 NTU, indicating that the effluent met the threshold limit value (1 NTU) of “Standards for drinking water quality” (GB5749-2006).

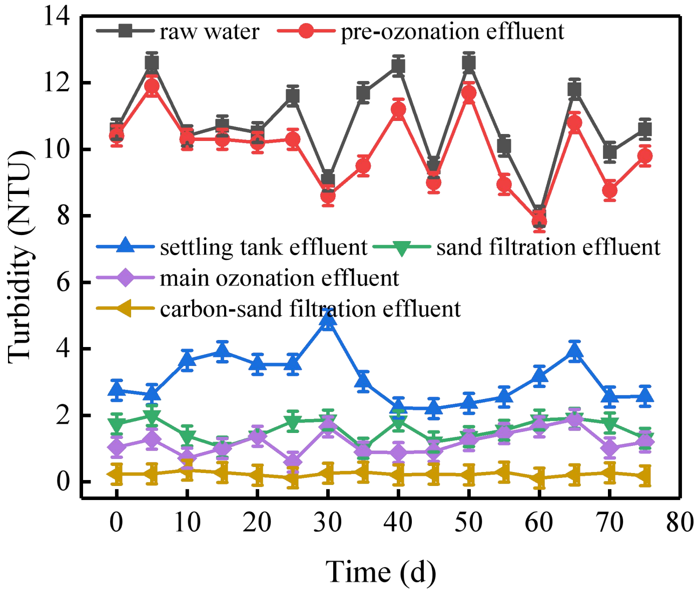


Fig. 6-13 Turbidity variation during stable operation

Chroma is caused by the water-soluble humus, organic or inorganic substances, which reflects the apparent pollution status of water. The chroma variation during the stable operation is depicted in Fig. 6-14, which was evidently similar to the turbidity variation. The chroma was mainly removed in the sand filtration process and the O_3/BAC process with a decrease of 71.05% and 93.16%, while the treatment efficiency of the pre-ozonation process was poor with a removal rate of only 7.89%. Chroma was primarily eliminated in the O_3/BAC process. Moreover, the effluent chromaticity was stable, with an average value of 3 PCU during the operation of the system. This satisfactorily meets the threshold limit value (15) of “Standards for drinking water quality” (GB5749-2006).

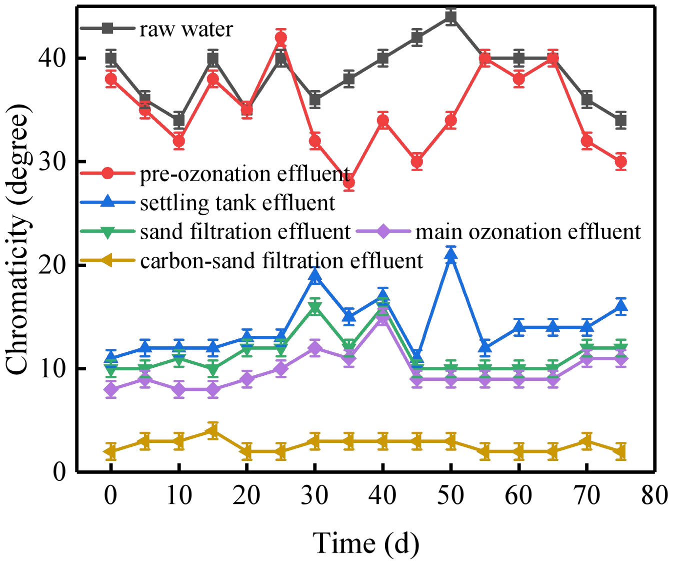


Fig. 6-14 Chroma variation during stable operation

The COD_{Mn} variation during stable operation is shown in Fig. 6-15. The change in COD_{Mn} was relatively stable during the frozen period. The average concentration of COD_{Mn} in raw water was 5.71 mg/L, while the removal efficiency reached 4.03% after the pre-ozonation, 50.09% after the main ozonation, and 88.27% after the O_3/BAC process. Although the COD_{Mn} exhibited a large fluctuation at some point, the COD_{Mn} of the effluent remained stable. The average COD_{Mn} value was 0.67 mg/L in the effluent, which meets the threshold limit value (3 mg/L) of "Standards for drinking water quality" (GB5749-2006). In other words, the modified process has a good removal effect on the organic matter in water.

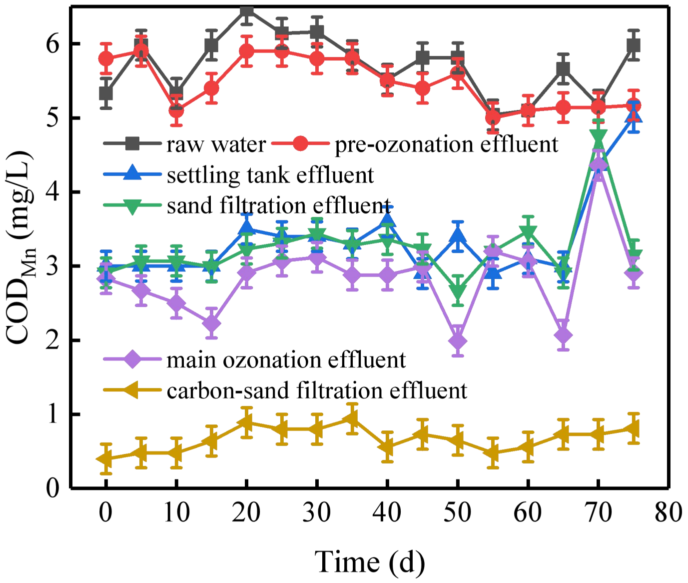


Fig. 6-15 COD_{Mn} variation during stable operation

The NH_4^+-N variation during the stable operation is presented in Fig. 6-16. As seen from Fig. 6-16, the fluctuation of NH_4^+-N in each treatment unit was severe, especially in the initial stage of the system. The average concentration of NH_4^+-N was 1.58 mg/L in raw water. However, the value increased by 13.29% after the pre-ozonation process. This is because the organic nitrogen was oxidized into NH_4^+-N via O_3, which further caused the increase in NH_4^+-N content after treatment by the pre-ozonation process. Through the subsequent O_3/BAC process, the NH_4^+-N content was drastically reduced by an average of 72.78%, especially by activated carbon filtration. This was mainly due to the combination of activated carbon adsorption and microbial degradation. Furthermore, the biological activated carbon column also had a strong impact load resistance for the NH_4^+-N removal, which was similar to the previous report [16]. As seen from Fig. 5-1, the variation of NH_4^+-N in the effluent was gentle with an average value of 0.43 mg/L, indicating that NH_4^+-N content was also in accordance with the threshold limit value (0.5 mg/L) "Standards for drinking water quality" (GB5749-2006).

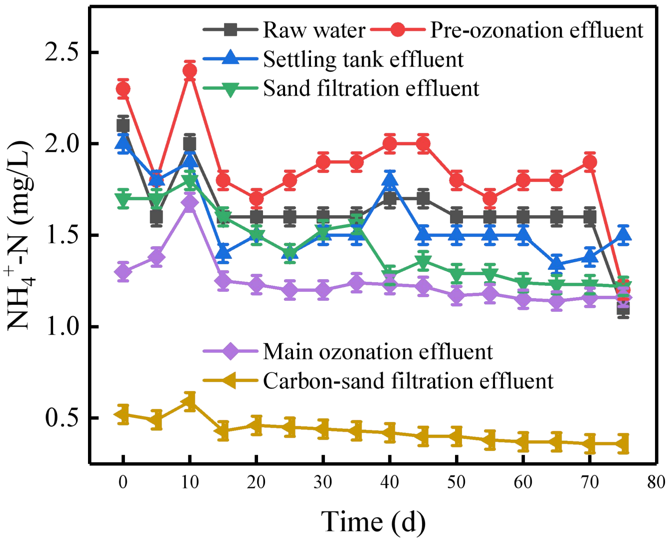


Fig. 6-16 NH_4^+-N variation during stable operation

In summary, the water quality of the Songhuajiang River can meet the current drinking water standard through the upgraded O_3/BAC treatment. The major water quality indexes also showed no great fluctuations after the modified system ran stably for about three months.

6.5.2 Biostability analysis

The biological stability of drinking water refers to the potential of organic nutrient matrix in drinking water to support the growth of heterotrophic bacteria, that is, the maximum possibility of bacterial growth. The main factor limiting the growth of heterotrophic bacteria in water supply network is organic matter. However, due to the low concentration of many biodegradable substances in water, it is difficult to determine the specific concentration by chemical methods. Therefore, the concept of assimilable organic carbon (AOC) was proposed by foreign researchers, and a biological method was proposed to determine the concentration of AOC by the growth of Pseudomonas fluorescens.

Because AOC includes many biodegradable compounds (such as ethanol, amino acids, carboxylic acids, etc.), it provides the substrate and metabolic energy for microorganisms, so its concentration has a great impact on the growth of microorganisms in water. Since AOC was proposed, people have noticed the effect of ozone on it. After more than ten years of efforts of many researchers, it has been concluded that ozonation can increase the concentration of AOC in water. It has been proved that the increase of AOC in the influent after ozonation will lead to the reproduction of bacteria in the pipe network, which will lead to the overproduction of Escherichia coli and other pathogenic bacteria in the water. This may also be due to the fact that the molecular weight of ozonation products is smaller and easier for bacteria to degrade. The change of AOC in the treatment process is shown in Fig. 6-17.

It can be seen from Fig. 6-17 that the AOC content of raw water increased by 52.83% after pre ozonation. After coagulation, sedimentation and filtration, AOC was only slightly reduced, and the removal rate was 11.11%. After ozonation, AOC content in water increased by 35.16%. In addition, biological activated carbon also showed a good removal of AOC, the removal rate reached 43.35%. It can be seen that the ozonation process can significantly increase the AOC content in water, while the precipitation filtration process will reduce the AOC content, so that the water quality can achieve biological stability. After the biological activated carbon treatment of water and chlorine disinfection, AOC did not increase, but also decreased to less than 100 μg/L, it can be considered that the effluent quality has reached biological stability.

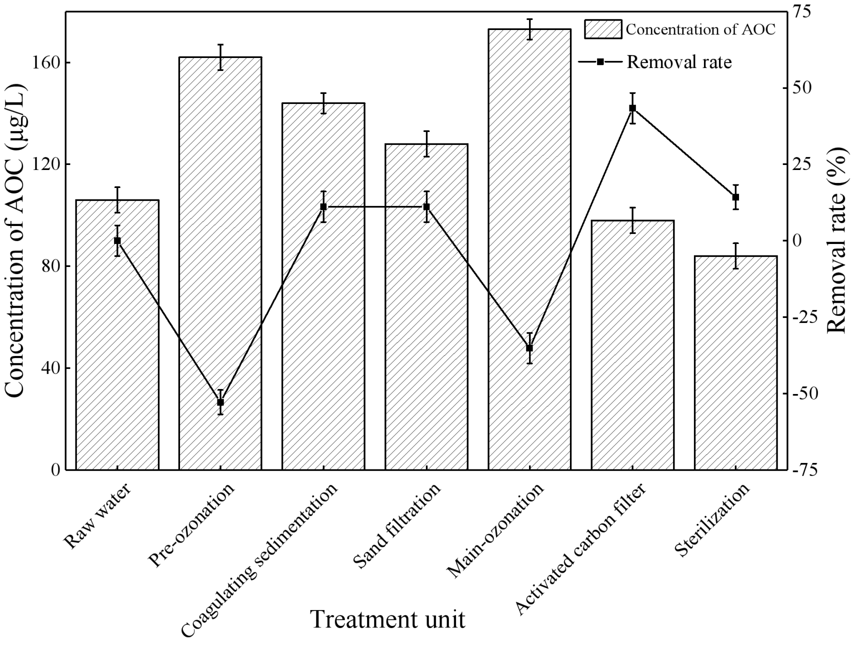


Fig. 6-17 Variation of AOC in each treatment unit

To sum up, after stable operation of the system, for the low temperature and low turbidity water in cold areas, the effluent quality of the water plant can not only stably meet the standard of “Standards for drinking water quality” (GB5749-2006), but also achieve biological stability, reducing the risk of microbial reproduction.

6.6 Water quality analysis of effluent

Through the detailed study of O_3/BAC treatment process, the results show that the process has good treatment effect on Songhuajiang River water. In this section, Songhuajiang River water and Mopanshan Reservoir water are taken as raw water. After stable operation of the system in winter, water is taken from the ozone activated carbon filter to analyze the water treatment standards of the two water sources.

6.6.1 Routine water quality test index

6.6.1.1 Microbiological index

The standard limits of total coliform, heat-resistant coliform and total bacterial count were not detectable, not detectable and 100 respectively. The detection results of total coliform group, heat-resistant coliform group and total bacterial count in the effluent of Songhuajiang River water and Mopanshan Reservoir water were all 0, indicating that the effluent microbial indexes of the two water sources could reach the standard after being treated by O_3/BAC process.

6.6.1.2 Toxicological index

The toxicological indexes of the effluent from Songhuajiang River and Mopanshan Reservoir were lower than 0.1 times of the limit value or not detected. Among them, the standard limit of bromate is 0.01 mg/L, and the effluent detection index of ozone carbon filter in two water sources is less than 0.005 mg/L.The standard limit of chloroform is 0.06 mg/L, and the detection index of Songhuajiang River effluent is 0.0031 mg/L, which is 0.05 times of the limit value. The effluent of Mopanshan Reservoir is 0.0062 mg/L, which is 0.1 times of the limit value, which is lower than the standard limit. For the phenomenon that the monitoring index of Mopanshan Reservoir effluent is higher than that of Songhuajiang River effluent, we think that the detection index is trace, which is more likely caused by detection error, which needs further observation in the follow-up detection.

6.6.1.3 Sensory traits and general chemical index

The test results of Mopanshan Reservoir effluent meet the standard requirements. The effluent of Songhuajiang River reaches the standard except for some indexes. Among them, odor and taste, the standard requires no abnormal odor, odor, Songhuajiang River water for soil flavor grade III. The standard requirement is none, and the effluent of Songhuajiang River is slightly yellow. The standard limit of oxygen consumption (COD_{Mn}) is 3 mg/L, the detection index of Mopanshan Reservoir effluent is 1.5 mg/L, and that of Songhuajiang River is 3 mg/L.

The standard limit value of turbidity (NTU) is 1 NTU, the detection index of Mopanshan Reservoir effluent is 0.78 NTU, and that of Songhuajiang River is 0.46 NTU. The turbidity detection index of Mopanshan Reservoir water is higher than the control index of platform operation 0.3 NTU and the detection result of detection center is 0.1 NTU. There are two possible reasons. One is the pollution of the sampling bottle; the other is that after 20 hours of water sample, turbidity phenomenon occurs due to some reason, which needs further observation in the follow-up test.

The standard limit value of ammonia nitrogen is 0.5 mg/L, the detection index of Mopanshan Reservoir effluent is less than 0.02 mg/L, and the detection index of Songhuajiang River effluent is 0.02 mg/L. The results are lower than that of the detection center and the field test, and further observation is needed in the follow-up test. Other indexes were up to standard.

6.6.2 Unconventional water quality test index

Under the detection conditions mentioned in Chapter 2, 35 kinds of organic compounds were detected in the source water. Among them, 28 kinds of organic compounds were eliminated from the effluent of Songhuajiang River and Mopanshan Reservoir, and three kinds of short chain organic compounds were added, namely, diethyloxyethane, ethyldimethylpentane and chamomile ring, which were the decomposition products of 35 kinds of organic matters by oxidation. Among the 35 kinds of organic matter detected in the source water, there are three kinds of unconventional detection items required by the new national standard, namely toluene, dichlorobenzene and diethyl phthalate. The prescribed limits for toluene, 1,2-dichlorobenzene, 1,4-dichlorobenzene and diethyl phthalate were 0.7 mg/L, 1 mg/L, 0.3 mg/L and 0.008 mg/L, respectively. The total analysis showed that the four indexes of the two water sources were all less than 0.001 mg/L.

To sum up, the water quality of Mopanshan Reservoir and Songhuajiang River can reach the national drinking water quality standard after being treated by O_3/BAC process.

6.7 Water quality of the combined water supply

In order to verify whether the water from Mopanshan Reservoir and Songhuajiang River will affect the official website after treatment and mixing, in February 2018, the water from the two sources was taken as the raw water, and after independent water treatment, the water was jointly supplied to the urban area through the water supply network. The water quality analysis is as follows.

6.7.1 Water quality of the urban water supply network

In this experiment, the chemical stability and biological stability of water quality in the water supply network were focused. Turbidity, iron, manganese and hardness are used for chemical stability, and total coliform group and total bacteria count are used for biological stability. The specific results are shown in Table 6-8, 6-9 and 6-10. It can be seen from the table that the turbidity, hardness, iron, manganese and other indicators in the water supply network are lower than the standard limits, and there is no obvious fluctuation, indicating that the chemical stability of water quality in the water supply network has not been damaged. Similarly, the total number of bacteria and the total coliform group representing the biological stability were not detected, indicating that the biological stability was not damaged. It shows that the water quality of water supply network has not changed significantly in the process of joint water supply of Mopanshan Reservoir and Songhuajiang River.

Table 6-8 Variation of turbidity and hardness in the pipe network

Monitoring site	Water quality index					
	Turbidity (NTU)	Hardness (mg/L)	Turbidity (NTU)	Hardness (mg/L)	Turbidity(NTU)	Hardness (mg/L)
Xinyang road of the Daoli district	0.508	68	0.371	64	0.369	40
Hongzhuan road of the Daoli district	0.345	100	0.315	92	0.365	48
Fushun road of the Daoli district	0.474	80	0.371	72	0.475	48

Qinghua road of the Nangang district	0.293	76	0.338	72	0.286	40
Harbin road of the Nangang district	0.425	74	0.333	56	0.474	44
Hexing road of the Nangang district	0.239	52	0.515	100	0.269	36
Qiaobei road of the Nangang district	0.339	52	0.310	52	0.276	40
Beixin road of the Daowai district	0.229	104	0.480	76	0.665	32
South 14th road of the Daowai district	0.334	58	0.356	80	0.370	52
Minsheng road of the Xiangfang district	0.382	62	0.249	48	0.372	40
Xusheng road of the Xiangfang district	0.324	48	0.171	70	0.363	44
Rongjiang road of the Qunli district	0.312	56	0.495	106	0.390	72

Table 6-9 Variation of Fe and Mn in the pipe network

Monitoring site	Water quality index					
	Fe (mg/L)	Mn (mg/L)	Fe (mg/L)	Mn (mg/L)	Fe (mg/L)	Mn (mg/L)
Xinyang road of the Daoli district	<0.002	0.015	<0.002	0.009	<0.002	0.004
Hongzhuan road of the Daoli district	<0.002	0.023	<0.002	0.021	<0.002	0.009
Fushun road of the Daoli district	<0.002	0.017	<0.002	0.011	<0.002	0.013
Qinghua road of the Nangang district	<0.002	0.032	<0.002	0.013	<0.002	0.005
Harbin road of the Nangang district	<0.002	0.026	<0.002	0.013	<0.002	0.004
Hexing road of the Nangang district	<0.002	0.041	<0.002	0.012	<0.002	0.005
Qiaobei road of the Nangang district	<0.002	0.018	<0.002	0.011	<0.002	0.004
Beixin road of the Daowai district	<0.002	0.032	<0.002	0.021	<0.002	0.021
South 14th road of the Daowai district	<0.002	0.025	<0.002	0.020	<0.002	0.005

Minsheng road of the Xiangfang district	<0.002	0.014	<0.002	0.008	<0.002	<0.002
Xusheng road of the Xiangfang district	<0.002	0.023	<0.002	0.010	<0.002	<0.002
Rongjiang road of the Qunli district	<0.002	0.020	<0.002	0.025	<0.002	0.020

Table 6-10 Variation of total coliform and total plate count in the pipe network

Monitoring site	Water quality index					
	total coliform (A/L)	total plate count (A/L)	total coliform (A/L)	total plate count (A/L)	total coliform (A/L)	total plate count (A/L)
Xinyang road of the Daoli district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Hongzhuan road of the Daoli district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Fushun road of the Daoli district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Qinghua road of the Nangang district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Harbin road of the Nangang district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Hexing road of the Nangang district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Qiaobei road of the Nangang district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Beixin road of the Daowai district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
South 14th road of the Daowai district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Minsheng road of the Xiangfang	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected

district						
Xusheng road of the Xiangfang district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Rongjiang road of the Qunli district	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected

6.7.2 Study on the chemical stability of pipe network

Larson ratio (LR) and water quality causticity ratio (WQCR) were used to evaluate the chemical stability of the pipeline network. Table 6-11 shows the comparison of LR of effluent water after different raw water treatment. The higher the LR of water quality is, the stronger the corrosiveness of water quality is. It can be seen from the data in the table that the effluent water after treatment of Mopanshan Reservoir raw water is more corrosive to the pipe network than the treated water from Songhuajiang River. However, when the water supplied by Mopanshan Reservoir is mixed with Songhuajiang River water, the stability of the pipe network will not be damaged after mixing.

Table 6-11 Water quality index and LR of the effluent

Drinking water source	Water quality index					LR
	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^- (mg/L)	HCO_3^- (mg/L)	pH	
Mopanshan Reservoir	8.84	9.51	1.24	34	6.8	0.80
Songhuajiang River	8.77	15.6	1.06	90	7.0	0.44

The higher the WQCR is, the stronger the corrosivity of water quality is. Table 6-12 shows the WQCR of treated water quality of Mopanshan Reservoir and Songhuajiang River. It can be seen from the table that after the raw water of Songhuajiang River passes through the pipe network, its WQCR is less than 1, which indicates that the risk of yellow water after water source switching is small, that is, it has no impact on the chemical stability of the pipe network.

Table 6-12 Water quality index and WQCR of the effluent

Drinking water source	Water quality index (mg/L)						WQCR
	Cl^-	SO_4^{2-}	NO_3^-	Alkalinity	Dissolved oxygen	Residual chlorine	
Mopanshan Reservoir	0.25	0.1	0.09	0.34	0.32	0.9	1.06
Songhuajiang River	0.25	0.16	0.08	0.9	0.32	0.9	0.45

6.8 Summary

In this chapter, a pilot test of ozone biological activated carbon advanced treatment process was carried out in a water plant in Harbin, and the water quality of Mopanshan Reservoir water and Songhuajiang River water supply system was preliminarily studied. The main research results are as follows.

(1) The average removal rates of turbidity, COD_{Mn}, NH_3-N, UV_{254}, TOC and THMFP in the effluent after the O_3/BAC process were 97.97%, 84.84%, 64.29%, 87.39%, 72.09% and 78.67%, respectively. Importantly, the deuterogenic DBPs in the effluent were all under good control after treatment by the O_3/BAC process. These typical indexes in the effluent all reached the requirement of "Standards for drinking water quality" (GB5749-2006).

(2) The average utilization rate of ozone is 87.30%, and it has good coagulation aid effect. The optimum dosage of ozone is 1.0 mg/L, which can save about 12% coagulant. Main ozone biological activated carbon is the main process of the scheme. The average utilization rate of ozone in the main ozone process was 71%, which was lower than that of pre-ozonation, and the optimal dosage was 0.4 mg/L. After six months of stable operation, the average removal rates of turbidity, COD_{Mn}, ammonia and UV_{254} were 97.87%, 78.76%, 28.56% and 88.4%, respectively. Except for ammonia nitrogen, other indexes of the effluent meet the drinking water standard. Ammonia nitrogen can be reduced to less than 0.2 mg/L after chlorination at break point, which can meet the standard of drinking water. The treatment effect of the whole treatment process is still good, and there is no big fluctuation during the stable operation of the system.

(3) The optimal chlorine dosage was 4.25 mg/L, the free residual chlorine and ammonia nitrogen met the requirements, and the detection of chloroform was less than 0.01 mg/L. According to the safety analysis, the AOC removal rate of activated carbon filter reached 43.4%, and the concentration of AOC in the effluent water was 86 μg/L, which reached the biological stability. The combination of ozonation and BAC can effectively remove the precursors of chlorination disinfection by-products in water.

(4) A total of 104 indexes except for two pests were detected in the source water, the effluent of carbon filter and the effluent of the second pumping station of the water plant. The qualitative analysis of three groups of water samples was carried out according to the national drinking water standard. The results showed that all the indexes met the drinking water standard. According to Larson ratio and water quality causticity ratio, it can be preliminarily judged that the combined supply of two water sources will not cause damage to the chemical stability of the pipe network, and no obvious fluctuation of water quality is found.

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Chapter 7. Engineering economic analysis

7.1 Introduction

Through the analysis of the first three chapters, it is found that the water quality of the water plant is good after upgrading. This chapter takes a water plant in the northeast cold region as an example to carry out the advanced treatment process transformation with ozone biological activated carbon as the main raw water, and evaluates the environmental benefits and economic feasibility of the project.

7.2 Introduction to the transformation of advanced treatment process

The new advanced treatment process treatment structures include: pre-ozonation contact tank, intermediate lifting pump station, main ozonation contact tank, ozone generator room and biological activated carbon filter.

7.2.1 Pre-ozonation contact tank

The design scale of pre ozone contact tank is 41×10^4 m^3/d, and one pre-ozonation contact tank is divided into two grids. The contact tank is a fully enclosed rectangular reinforced concrete structure, with a plane size of 20.0 m, a width of 18.0 m, a depth of 6.6 m, an effective water depth of 6.0 m and a total effective volume of 1700 m^3.

The designed pre-ozonation dosage is 0.5~1.5 mg/L, and the residence time of contact tank is 5 min. Each contact tank is divided into two compartments. Ozone is added by water jet.

7.2.2 Intermediate lifting pump station

After the conventional treatment filter, a lifting pump station is set to lift the effluent from the filter to the newly-built main ozone contact tank, which is adsorbed by the activated carbon filter, and then gravity flows back to the clean water tank after treatment.

The well is 24.0 m long, 10.0 m wide and 4.0 m deep. It is an underground cast-in-place reinforced concrete structure. Among them are 6 submersible mixed flow pumps, 4 for use and 2 for preparation. The single pump performance is Q=4300 m^3/h，H=6 m，N=90 kW。

7.2.3 Main ozonation contact tank

The design scale of the main ozonation contact tank is 41×10^4 m^3/d. There is one main ozone contact tank, which is divided into two compartments. It is 56 m in length, 15 m in width and 6.6 m in depth. It adopts semi underground cast-in-place reinforced concrete structure. The main ozone contact tank is located after the conventional treatment filter and before the new activated carbon filter. The total effective volume of contact tank is 5000 m^3.

The designed main ozonation dosage is 1~3 mg/L, and the residence time of contact tank is 15.0 min. Each contact tank is divided into two grids. Among them, microporous disc diffuser is used for ozone distribution. The top of the contact tank is equipped with two ozone tail gas destructors.

7.2.4 Ozone generator

The ozone generator system shall include ozone generator, air source, power supply and control equipment, instruments, ozone and oxygen leakage detection and alarm equipment.

Three ozone generators were selected in the design, and the preparation capacity of each ozone generator was 40 kg/h (ozone concentration was 10%). The generator is a horizontal tube ozone generator.

7.2.5 Biological activated carbon filter

The activated carbon filter in the project is the last process of advanced treatment process and the final control of the water quality. The activated carbon filter tank type of the project is air-water backwashing activated carbon filter (equivalent to V-type filter).

A total of 32 filters are divided into two series, and each series is arranged in two rows. The pipe gallery is located in the middle of two rows of filters. The design filtration rate is 5.46 m/h and the forced filtration rate is 5.6 m/h. The filter is washed with air and water, the intensity of air washing is 50 $m^3/h \cdot m^2$, and the washing time is 3 min. The washing intensity was 20 $m^3/h \cdot m^2$ and the washing time was 8 min. The design flushing cycle is 96 hours.

The effective area of single filter is 100 m^2, the plane size is 9.4×12.5 m, and the height of filter is 5.80 m. The filter material is activated carbon with a thickness of 2.0 m. The pebble bearing layer (2 ~ 4, 4 ~ 8, 8 ~ 16, 16 ~ 25 mm) is 200 mm at the bottom of the activated carbon layer, and the water depth above the filter material is 1.5 m. The filter is washed by backwash water pump and air washed by blower. The filter time and head loss are used to control the backwash period, and pneumatic valves are selected for all filters.

A wastewater recovery pool is set on one side of the backwash drainage channel of each series of filters to accommodate the backwash drainage of the activated carbon filter. The wastewater recovery tank is considered to meet the capacity of primary backwash drainage. There are 4 submersible pumps in the wastewater recovery tank, 2 for use and 2 for standby, to return the backwash water to the surge tank and discharge the sediment to the sludge discharge regulating tank. The single pump performance is $Q=300\ m^3/h$，$H=15\ m$，$N=15\ kW$。

The filter room adopts truss structure, size 84×96 m, height 11 m.

The comprehensive room includes blower room and backwash pump, which is built together with the activated carbon filter room to provide air source and water source for backwashing of activated carbon filter tank and air source for pneumatic valve in water purification room.

There are three blowers, roots blower, for filter backwashing, two for use and one for standby. The process parameters are: $Q=50\ m^3/min$，$\triangle P=6000\ mmH_2O$，$N=110\ kW$。

Two backwash water pumps are used and one is standby, which pumps water from the main outlet channel of the filter tank, with single pump performance $Q=1000\ m^3/h$，$H=10\ m$，$N=55\ kW$。

7.3 Environmental and social benefit analysis

The water quality effect of the water treatment plant after the transformation meets the requirements of the “Standards for drinking water quality” (GB5749-2006), and the water quality is stable. The specific situation is analyzed in Chapter 5 of this paper. After the increase of the advanced treatment unit, the diversity of the operation adjustment of the water treatment plant is increased, which provides a safer guarantee for the effluent to meet the standard. After commissioning and operation, the equipment and facilities are stable. Due to the further improvement of water quality, the content of organic matter, ammonia nitrogen, and precursor of disinfection by-product can be reduced, so that Songhuajiang water in the cold northeast area has a more favorable guarantee as drinking water source, and alleviates the disadvantages of single drinking water supply in Harbin City, and contributes to the responsibility of the enterprise.

7.4 Total project cost

After the reconstruction, the design scale of the water plant is 410000 m^3/d. The project mainly includes adding advanced treatment process to the existing water treatment plant. Table 7-1 shows the investment estimate of the upgrading process of the water treatment plant. The total direct cost of the project is 158.9947 million yuan, and the increased cost per ton of water is 387.8 yuan/ton based on the design scale of 410000 m^3/d.

Table 7-1 Estimate sheet of the fixed investments

Project name: Advanced treatment technical renovation project of a purification plant

Order	Name of the work process or cost	Value (ten thousand yuan)			
		Construction works	Equipment	Installation project	Total
1	Ozone system	426.15	4800.00	281.95	5508.10
2	Ozone generator room	133.65	4800.00	240.00	5173.65
3	Pre-ozonation contact tank	45.00	/	12.65	57.65
4	Main ozonation contact tank	247.50	/	29.30	276.80
5	lift pumping station	66.00	215.00	32.25	313.25
6	Activated carbon filter room	3272.16	4861.68	270.85	8404.69
7	Pure water room	1128.96	188.40	15.07	1332.43
8	bacterial activated carbon filtration	2143.20	4673.28	255.77	7072.25
9	electric engineering	/	428.05	107.01	535.06
10	Automation and instrument	/	405.90	32.47	438.37
11	Factory renovation (including demolition)	550.00	/	150.00	700.00
	Direct project cost	4314.31	10710.63	874.53	15899.47

7.5 Operating cost estimation of the advanced processing

7.5.1 Conditions and basic data for the financial evaluation

The economic evaluation of the reconstruction project is carried out in accordance with the principles and requirements specified in the economic evaluation methods and parameters of construction projects issued by the state (Development) Planning Commission [1, 2].

1. Project design life

According to the characteristics of the reconstruction project, the design life of the project is calculated as 22 years. The reconstruction period of the project is 2 years and the operation period is 20 years.

2. Total project investment and financing

The total investment in fixed assets of the project is 158.9947 million yuan, with a loan of 100 million yuan for 5 years, and the rest will be solved by self-financing.

3. Staffing and wages

The staff quota is 100: the factory is divided into water intake post (3 shifts and 4 turns, 2 persons in each shift, 8 persons in total), water purification agent (3 shifts and 4 turns, 2 persons in each shift, 8 persons in total), disinfectant putting post (3 shifts and 4 turns, 2 persons in each shift, 8 persons in total), carbon filter post (3 shifts and 4 turns, 2 persons in each shift, 8 persons in total), ozone preparation workshop（3 shifts and four reverses, 2 persons in each shift, 8 persons in total), water distribution pump room (3 shifts and 4 reverses, 2 persons in each shift, 8 persons in total), machine repair workshop (8 persons for mechanical maintenance, 6 persons for electrical maintenance, 6 persons for automatic control, 6 persons for statistics and management, 6 persons for canteen warehouse management, 8 persons for routine work and 4 persons for laboratory test. The average annual salary is calculated at 48000 yuan per person (including social security, provident fund and other expenses). The principle of post staffing is one operation and one supervision to ensure production safety.

4. Depreciation of fixed assets

The depreciation of fixed assets is calculated by the average life method, and the net salvage value rate is 5 %.

5. Repair charge

The annual repair fee is calculated at 2% of the fixed assets.

6. Water charges

The State shall, in accordance with the law, implement a system of license for drawing water and a system for paid use of water resources. According to the relevant regulations of Heilongjiang Provincial Water Resources Department, the water resources fee is 0.20 yuan per cubic meter when the water plant takes water from the river.

7. Cost of power and drugs

The power cost is calculated according to the design index and the current electricity price, and the pharmaceutical cost is determined by referring to the production data.

The cost is as follows: the electricity charge is 0.60 yuan/kWh for bulk industrial power consumption, 85% for power facility efficiency (94% for motor efficiency and 90% for water pump efficiency), and 12.63% for advanced treatment power consumption. In addition, the dosage of coagulant composite aluminum iron is calculated as 60 mg/L, the dosage of activated carbon is calculated as 20 mg/L, and the dosage of chlorine is calculated as 4.25 mg/L. The price of coagulant composite aluminum iron is about 1500 yuan/ton, activated carbon is about 1000 yuan/ton, and disinfectant (liquid chlorine) is about 800 yuan/ton.

8. Carry out of the water price

Harbin water supply adopts the principle of centralized water supply and unified charging, and the price of clear water per cubic meter is 2.40 yuan.

9. Taxes

The value-added tax is calculated at 6% of the sales revenue, the urban maintenance and construction tax and the education surcharge are calculated at 7% and 3% of the value-added tax respectively, and the income tax is calculated at 25%.

10. Benchmark yield

In the financial evaluation, the benchmark rate of return is 7%.

11. Bank lending benchmark annual interest rate

The benchmark annual interest rate for bank loans is 4.9%.

7.5.2 Estimate of the total cost

The total cost of the project includes: water resources cost, fuel and power cost, salary and welfare expense, repair cost, depreciation cost, amortization fee, interest expense and other expenses. The estimated values are as follows.

Water charges: 0.20 yuan/m^3×41 ten thousand m^3/d = 82000 yuan/d。

Power costs: (1) Power costs of taking water: (90 kW × 90% × 24 h × 4 + 15 kW × 94% × 24 h × 2 × 2 + 110 kW × 94% × 24 h × 2 + 55 kW × 90% × 24 h × 2) × 0.6 yuan= (7776 + 1353.6 + 4963.2 + 2376) kW·h × 0.6 元/kW·h = 9881.28 yuan/d

(2) Power costs of the advanced treatment: 9881.28 yuan/d × 12.63% = 1248.01 yuan/d

Conventional coagulant cost: 60 mg/L × 41 ten thousand m^3/d × 1500 yuan/ton/ 365 d = 101095.89 yuan/d

New coagulant cost: 20 mg/L × 41 ten thousand m^3/d × 1000 yuan/ton/ 365 d = 22465.75 yuan/d

Cost of liquid chlorine: 4.25 mg/L × 41 ten thousand m^3/d × 800 yuan/ton/ 365 d = 3819.18 yuan/d

Wages and benefits: 48000 yuan/person/year × 100 / 365 d = 13150.68 yuan/d

Repair charge : 15899.47 ten thousand yuan × 2% / 20 / 365 d = 435.6 yuan

Depreciation and amortization charges: (1-5%)/10 year×100%×15899.47 ten thousand yuan/20/365d=2069.11 yuan

Bank loan interest:10000 ten thousand yuan × 4.9% / 365 d = 13425 yuan/d

The total daily cost is RMB 249590.5.

Unilateral water production cost: According to the design scale of the project, the daily water supply is 410000 m^3, and the daily total cost is 249590.5 yuan. The water supply cost per cubic meter is determined to be 0.609 yuan/m^3.

Sales revenue estimation:The sales revenue of the project is mainly the water fee intervention, and the water price is calculated as 1.50 yuan/m^3. The total daily water fee income is 615000 yuan.

Sales taxes and surcharges: Calculate according to formulary pay tax standard, the cost of value added tax is 1.50 yuan/m^3 × 41 ten thousand m^3/d × 6% = 36900 yuan/d. The urban maintenance and construction tax and education surcharge are (7% + 3%) × 36900 yuan/d = 3690 yuan/d. A total of 40590 yuan of value-added tax, urban maintenance and construction tax and education surcharge should be paid every day.

Total profit: The annual sales revenue of the project minus the annual total cost, sales tax and surcharges, bank loan interest, is the total daily profit. The total daily profit of the project is 311394.5 yuan. The daily net profit of the project is 157644.5 yuan and the annual net profit is 57540243 yuan.

7.6 Summary

In this chapter, the economic evaluation of a water plant upgrading project in Harbin can draw the following conclusions.

(1) The total investment in fixed assets of the project is 158994700 yuan, the total daily cost is 249590.5 yuan, and the water supply cost per cubic meter is 0.609 yuan/m^3.

(2) The daily net profit of the project is 157644.5 yuan and the annual net profit is 57540243 yuan.

It can be seen that the upgrading of water purification process of a water plant in Harbin can not only improve the quality of water supply, but also achieve certain benefits in long-term operation.

Reference

[1] Otter P., Sattler W., Grischek T., Jaskolski M., Mey E., Ulmer N., Grossmann P., Matthias F., Malakar P., Goldmaier A., Benz F., Ndumwa C. Economic evaluation of water supply systems operated with solar-driven electro-chlorination in rural regions in Nepal, Egypt and Tanzania. Water Research. 187 (2020) 116384-116397.

[2] Walker N. L., Norton A., Harris I., Williams A. P., Styles D. Economic and environmental efficiency of UK and Ireland water companies: Influence of exogenous factors and rurality. Journal of Environmental Management. 241 (2019) 363-373.

Chapter 8. Conclusions

With the continuous progress of economy and society, the single water supply mode has seriously hindered the development of Harbin City and the health of citizens. Therefore, this study studied the water quality differences, characteristic pollutants and sources of Mopanshan Reservoir and Songhuajiang River, two major water sources in Harbin. In order to deal with the current problems of water sources in Harbin, this paper takes a water treatment plant in Harbin as an example to upgrade the water purification process, and puts forward an effective measure to alleviate the risk of water supply in Harbin from the process transformation and the preliminary test of water quality of dual source water supply mode. The main experiments involved in this study include the water quality monitoring of Mopanshan Reservoir and Songhuajiang River, the enhanced treatment experiment of conventional water purification process, the ozone activated carbon experiment and the preliminary test of joint water supply of two water sources. The main conclusions are as follows.

In the chapter 1, background, previous research, objectives, and organization of the thesis are described.

In the chapter 2, an overview of the theory of urban safe water supply, the major reagents and experimental apparatus, methods of water quality assessment, and location map of the two drinking water sources.

In the chapter 3, we compared and analyzed the source water quality of Mopanshan Reservoir and Songhuajiang River in Harbin. The results show that most of the Mopanshan Reservoir basically meet the water quality standard above Case III, but some indicators exceed the Case III water quality standard, and the water quality has the trend of eutrophication. With the continuous deepening of Songhuajiang River treatment, the water quality of Songhuajiang River has been basically maintained at Case III water quality standard, reaching the water quality target requirements of drinking water functional zone, and the water quality has been improving year by year. The pH value of Mopanshan Reservoir raw water is less than 7.0, and that of Songhuajiang River is more than 7.0. The total hardness of Mopanshan Reservoir raw water is lower than that of Songhuajiang River water, but the total phosphorus of Mopanshan Reservoir water exceeds the standard. The contents of dissolved oxygen, ammonia nitrogen, fluoride, sulfate, chloride, nitrate, iron and fecal coliform in raw water of Songhuajiang River were higher than those in Mopanshan Reservoir raw water. The potassium permanganate index and chemical oxygen demand of the raw water of Mopanshan Reservoir and Songhuajiang River decreased year by year, but the organic matter comprehensive index of Songhuajiang River was still higher than that of Mopanshan Reservoir raw water. In addition, the CCME WQI scores of Mopanshan Reservoir from 2016 to 2018 were 76, 68 and 64, respectively, indicating that the pollution situation has a rising trend year by year. After years of treatment, the water quality of Songhuajiang River has been improved. The CCME WQI score increased from 54 to 65, indicating that the water quality of Songhuajiang River has been significantly improved after years of treatment by the government.

In the chapter 4, based on the experimental data, we analyzed the main pollutants and the distribution of pollution sources in the two water sources in Harbin. At the same time, we compared and analyzed the effluent quality of the two water sources after regular water purification process. The results showed that the characteristic pollutants of Mopanshan Reservoir water were permanganate index, total nitrogen and total phosphorus. Among them, the permanganate index showed the characteristics of seasonal over standard, the total nitrogen increased year by year, the water was slightly polluted, and there was a trend of eutrophication. The pollutants mainly come from agricultural non-point source pollution such as pesticides and chemical fertilizers, domestic sewage and surface runoff. The characteristic pollutants of Songhuajiang River raw water are permanganate index, chemical oxygen demand and ammonia nitrogen. Among them, permanganate index exceeded the standard in summer and ammonia nitrogen exceeded the standard in winter. The pollutants in Songhuajiang River Basin mainly come from the discharge of industrial wastewater and surface runoff. After the conventional treatment of raw water from the Mopanshan Reservoir, only the chloral could not meet the national standard, while all other water quality indices could reach the requirements of "Standards for drinking water quality" (GB5749-2006). For the Songhuajiang River, all the water quality indices and DBPs could meet the national standard after the conventional treatment, apart from the NH_4^+-N in the icebound season. Through contrast and analysis, the Songhuajiang River is more suitable for the drinking water at present.

In the chapter 5, taking Songhuajiang River water as raw water, the operating parameters of enhanced conventional water purification process were determined through experiments. The results of enhanced coagulation test show that the effect of composite Al Fe is the best, and the optimal dosage is 60 mg/L. At this time, the removal rate of turbidity and chroma can reach 99% and 89%, respectively. The optimal parameters of enhanced filtration are as follows: influent flow rate 3.4 m^3/h, backwash cycle 20 d, backwash intensity 12.5 $L/(m^2\cdot s)$. Under these conditions, the removal rate of turbidity and chroma of sand filter is above 95%, the removal rate of COD_{Mn} is 80%, and the removal rate of ammonia nitrogen is about 40%.

In the chapter 6, we still take Songhuajiang River water as raw water, and determine the operation parameters of ozone activated carbon process through experiments. The water quality of the two water sources was studied. The results show that the average utilization rate of ozone is 87.30%, and it has a good coagulation aid effect. The optimum dosage of ozone is 1.0 mg/L, which can save about 12% coagulant. Main ozone biological activated carbon is the main process of the scheme. The average utilization rate of ozone in the main ozonation process was 71%, which was lower than that of pre-ozonation, and the optimal dosage was 0.4 mg/L. Ammonia nitrogen can be reduced to less than 0.2 mg/L after chlorination at break point, which can meet the standard of drinking water. And there is no big fluctuation during the stable operation of the system. The optimal chlorine dosage was 4.25 mg/L, and the free residual chlorine and ammonia nitrogen met the requirements, and the detection of chloroform was less than 0.01 mg/L. According to the safety analysis, the AOC removal rate of activated carbon filter reached 43.4%, and the concentration of AOC in the effluent water was 86 μg/L, which reached the biological stability. The combination of ozonation and BAC can effectively remove the precursors of chlorination disinfection by-products in water. After six months of stable operation, the average removal rate of turbidity can reach 97.87%, the average removal rate of COD_{Mn} is 78.76%, the average removal rate of ammonia nitrogen is 28.56%, the total removal rate of UV_{254} is 88.4%, and all the indexes of effluent quality can meet the requirements of “Standards for drinking water quality” (GB5749-2006). The treatment effect of the whole treatment process on raw water is still very good, except for ammonia nitrogen, other indicators of the effluent meet the drinking water standard. According to Larson ratio and water quality causticity ratio, it can be preliminarily judged that the combined supply of two water sources will not cause damage to the chemical stability of the pipe network, and no obvious fluctuation of water quality is found.

In the chapter 7, on the basis of conventional water purification process, a water treatment plant in Harbin was transformed into an ozone activated carbon process, and the engineering economic analysis was carried out. The analysis results show that the total investment in fixed assets of the project is 158.9947 million yuan, the total daily cost is 249590.5 yuan, the water supply cost per cubic meter is 0.609 yuan/m^3, and the total daily net profit is 157644.5 yuan. It can be seen that the upgrading of water purification process of a water plant in Harbin can not only improve the quality of water supply, but also achieve certain benefits in long-term operation.