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Study on health risk assessment of reuse of reclaimed water in Tianjin urban water system

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ABSTRACT

Healthy operation of urban water system contributes to urban sustainable development. The study on the healthy operation of reuse of reclaimed water in this system is the current priority. Tianjin is located in the eastern part of North China. Lack of fresh water resources has been a hindrance to its economic and social development. To remove this bottleneck, Tianjin initiated a number of projects to reuse reclaimed water for agricultural irrigation, groundwater recharge, industry, landscapes and recreation areas. If handled improperly, the reuse would pose a threat to human health. In this study, health risk assessment (HRA) model is adopted to monitor the reclaimed water quality at three observation stations in Tianjin, risk factors are obtained by horizontal and vertical contrast, and rectification measures are proposed.

Key words: Urban Water System, Reclaimed Water, HRA(Health Risk Assessment), Assessment Model, Renewable water

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INTRODUCTION

An urban water system includes natural water cycle, artificial water cycle, economic water cycle and social water cycle, as shown in Diagram 1. Artificial water cycle is comprised of water supply, water use, water drainage and treatment. Water cycle operates by the consumption of part of water as well as treatment of the sewage generated. Part of urban water evaporates and becomes atmospheric water while part of it becomes sewage. Part of the sewage will become new reuse water resources after environmental and ecological treatment while part of the treated sewage will percolate through slowly and become groundwater resources or become urban water resources in the process of evaporation and precipitation with the rest draining into water bodies, which is how urban artificial water cycle repeats. Water environment recovery in artificial water cycle focuses on sewage treatment and water reuse. The urban water cycle refers to artificial water cycle in this study, that is, water circulates among the three processes of access, use and drainage and relative water bodies. This is social reinforcement on water cycle in nature.

2.Water Supply and Demand and Reuse of Reclaimed Water in Tianjin

2.1.Water Supply and Demand in Tianjin

With the rapid economic development of Tianjin, development and utilization of water resources are faced with new problems concerning water quality and water quantity. According to the paper Tianjin Water, the total amount of water available in Tianjin was 10.11, 11.31 and 18.30 billion cubic meters in 2006, 2007 and 2008 respectively, the total amount of surface water being 6.62, 7.50 and 13.61 billion cubic meters respectively and the total amount of groundwater being 4.43, 4.76 and 5.91 billion cubic meters respectively. The total supply in Tianjin was 22.96, 23.37 and 22.33 billion cubic meters in 2006, 2007 and 2008 respectively, surface water supply being 16.10, 16.46 and 15.96 billion cubic meters among which 5.81, 6.05 and 6.14 billion cubic meter were from Luanhe River, groundwater supply being 6.76, 6.81 and 6.25 billion cubic meters, supply by reclaimed water after advanced treatment being 0.08 billion cubic meters on average, and desalinated seawater supply being 0.02, 0.02 and 0.04 billion cubic meters respectively. When classified according to use, water includes industrial water, residential water and ecological water, industrial water consumption being 19.35, 19.70 and 18.57 billion cubic meters respectively, residential water consumption being 3.12, 3.16 and 3.11billion cubic meters, and ecological water consumption being 0.49, 0.51 and 0.65 billion cubic meters respectively. Water consumption rates were 68%, 69% and 69%.

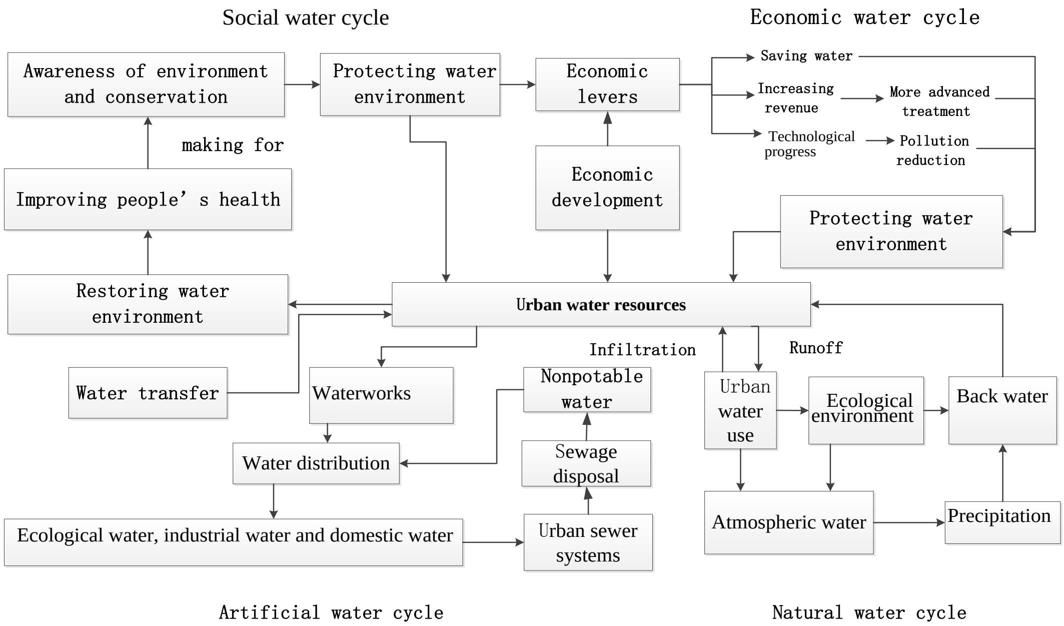


Fig. 1. Water Cycles in an Urban Water System

Tianjin, known as "Downstream Nine Rivers", is a downstream city of Haihe River where the nine rivers meet, these rivers being Nanyun River, Beiyun River, Ziya River, Daqing River, Yongding River, Chaobai River, Jiyun River, Yongdingxin River and Duliujian River. Haihe River system was the natural water source of Tianjin before 1970s. However, the building of reservoirs upstream reduced the discharge of Haihe River into the sea. With less water flowing downstream into the sea, salt-laden seawater began to push upstream, which led to increasingly high salt content in rivers. Besides, regional economy developed rapidly and population increased fast. Therefore, Tianjin is faced with a severe water crisis, which poses a hazard not only to industrial and agricultural production but also to drinking water of urban residents. The State Council launched the emergency project of water diversion from the Yellow River to Tianjin for the sixth time in recent years, transferring a hundred billion cubic meters of water to Tianjin. Nevertheless, Tianjin still suffers from severe fresh water shortage. South-to-North Water Transfer Project completed in 2010, rainfall, reuse of reclaimed water and popularization and application of seawater desalination technology will help to ease the water shortage in Tianjin.

2.2 Reuse of Reclaimed Water in Tianjin

Tianjin, located in the eastern part of North China, has been suffering from severe water scarcity. The new water scarcity crisis forces us to take countermeasures. There are three approaches to water scarcity besides saving water: interbasin water transfer; rational exploitation of groundwater; urban wastewater reclamation and reuse. At present, Tianjin has built Ji Zhuangzi Water Reclamation Plant, whose water production capacity has reached 5 tons/day, providing reclaimed water for some residential areas and enterprises in Nankai District and Hexi District. The plan for production expansion to 9 tons/day will be implemented soon. Five more reclaimed water supply systems are to be built in five years. The five plants in Xianyang Road, Beicang, Eastern Suburbs, Shuanglin and Zhangguizhuang will provide reclaimed water for the city proper and some areas outside the outer ring. A small-scale water circulatory system will be built downtown.

Research on wastewater reuse has been conducted at research institutes during the period of the seventh Five-Year Plan of China. In 2000 Tianjin municipal government began to prepare Jizhuangzi wastewater reuse project in which water recycled by Jizhuangzi Sewage Treatment Plant served as water source. This project was launched at the end of 2002. The treated water is mainly used for flushing in and around Tianjin Meijiang ecological residential quarter, landscapes in ecological quarters, landscaping, street sprinkling, water-cooling systems and other industries. 3600 families had used nonpotable water for flushing in Meijiang ecological residential quarter by 2005, which proved popular[1]. Tianjin has built 7 water reclamation plants with total supply of 211,500 m^3/d, among which 4 plants with total supply of 170,000 m^3/d are in the central city and 3 plants with total supply of 41,500 m^3/d in Binhai New Area. Ji Zhuangzi Water Reclamation Plant in downtown Tianjin and New Water Source No. 1 Plant in TEDA had supplied water while the other five plants had been qualified but had not supplied water yet by the end of 2008. The former supplied water for industrial users, urban uses, landscapes and city greening in Hexi District and Nankai District. The latter supplied water for industries, landscapes and city greening in TEDA. As water resources for industries, residential quarters and green belts of industrial zones, the two plants saved a large quantity of clean water. The former sold as much as 3.53 million cubic meters of water and the latter sold as much as 4 million cubic meters of water in 2008.

3.Health Risks of Urban Use of Reclaimed Water

3.1.The Main Urban Uses of Reclaimed Water

Reclaimed water or recycled water is former wastewater that is treated to meet water quality requirements so as to be of beneficial use. Reclaimed water has obvious advantages compared with desalinated seawater and water transferred from other river basins. From an economic point of view, the obtaining of reclaimed water has the lowest cost of about 1-3 yuan/ton while the cost of desalination of sea water is about 5-7 yuan/ton and the cost of inter-basin water transfer is about 5-20 yuan/ton. From an environmental point of view, reclamation and reuse of wastewater help to improve the ecological environment and make for a virtuous cycle of aquatic ecosystems. The main urban uses of reclaimed water are summarized in **Table 1**.

3.2 The Hazards to Human Environment and Health and Exposure Routes

The most important issue in wastewater reuse for agricultural irrigation is the risk to human health. Intestinal viruses and pathogens in sewage may pose a hazard to human health. When reclaimed water is used for irrigation, we hold consider not only the effects of pathogens on health but the impaction agricultural production as well Too much nitrogen, for example, may lead to the lengthening of crop growing season, non-plump fruits, late maturing of plants, loss of original flavor (fruit or vegetables), sugar reduction (sugar beet or vine) and starch reduction in potatoes[2].Reclaimed water quality criteria for groundwater recharge should consider such factors as pathogens, total mineral content, heavy metals and stable organic compounds to ensure the safety of environment and human health. Pathogen content in water is closely related to human health. If we do not assess the quality of reclaimed water used for recharge, groundwater may be polluted by low concentrations of chemicals for a long period of time, which may have an impact on human health. It was found that the test animals were liable to suffer from carcinogenesis or flare-up safter drinking contaminated water.

Table 1.The Main Urban Uses of Reclaimed Water

Categories	Uses	Categories	Uses
Agricultural water	Irrigation	Urban water	Green belt irrigation, landscaping
	Afforestation and seedling		Flushing, street sweeping
	Farms, pastures		Vehicle washing
	Aquaculture		Building construction, fire control
Industrial water	Cooling water	Landscaping water	Ornamental landscapes
	Cleaning water		Entertainment landscapes
	Boiler water		Restoring natural wetlands or creating artificial wetlands
	Process water		Surface water replenishment (rivers, lakes)
	Water flooding		Groundwater replenishment(replenishment of drinking water, prevention of seawater intrusion or land subsidence)

Water quality criteria for industrial use are usually lower than that for drinking water. There is great potential for reuse of reclaimed water for industrial production and industrial cooling systems. Water quality criteria differ among various industries. Water used in the food processing industry must meet the criteria for drinking water. Water used in electronic industry must meet the criteria for high purity. The criteria for water used in leather manufacture are less demanding [3].The reuse of reclaimed water for landscapes includes reuse for water features (such as fountains, waterfalls and ponds) and recreational reuse. The former involves no physical contact such as boating and fishing, while the latter involves physical contact, such as swimming and ice skating. The reuse for landscapes helps to protect the ecological balance of aquatic life and maintain the ornamental water landscapes of urban lakes, rivers and parks. Urban domestic water consumption is much smaller than that of industrial water consumption, accounting for only about 20% of the total consumption. Municipal water use includes landscaping, vehicle washing, street sprinkling, and toilet flushing and so on. As people have frequent contact with urban sewage, water for municipal use should be strictly sterilized before use.

When recycled water is used in the areas where people have frequent contact with it, such as sprinkling of crops eaten raw, open spaces and parks, sports grounds, and recreational landscapes (such as swimming, surfing),bacteria, viruses and other pathogenic microorganisms may pose a great threat to human health[4]. When urban wastewater is used for groundwater recharge, its heavy metals, pathogens and non biodegradable organisms may pollute groundwater and may endanger human health via drinking water[5]. When wastewater is reused for landscapes and recreation areas, its high nitrogen and phosphorus content may make water environment eutrophicated and toxic chemical substances will destroy the biodiversity of water environment. In addition, when recycled water is used for irrigation of crops, urban green belts and other public places, the aerosol by spraying may also put people at risk.

4.Health Risk Assessment

Risk Assessment began in a few industrialized countries in the 70s, among which the United States has conducted the most extensive research in this area. In the last two decades risk assessment technology went through roughly three periods[6]. During the early 70sand early 80s, risk assessment was in its infancy. In 1976, U.S. Environmental Protection Agency(USEPA) issued "Guidelines for Carcinogen Risk Assessment" for the first time. But risk assessment was not clearly defined then, toxicity identification being the only approach. The mid-80s was the period of technology readiness for risk assessment system when risk assessment was greatly improved. In 1983, United States National Academy of Sciences (NAS) published its report entitled *Risk Assessment in the Federal Government: Managing the Process*[7].According to this report, risk assessment involves four stages, known as "four-step approach": hazard identification, dose-response assessment, exposure assessment and risk characterization. Each stage is explicitly defined. This approach serves as the basic framework of risk assessment. USEPA then issued a series of risk assessment technical documents, principles or guidelines for risk assessment, mostly in terms of human health. For example, guidelines for carcinogen risk assessment, guidelines for teratogenic risk assessment, guidelines for the health risk assessment of chemical mixtures, guidelines for development toxicity risk assessment, and guidelines for exposure assessment were released in 1986 [8-12]. In 1989, USEPA revised the 1986 guidelines. Thus, a scientific system of risk assessment was built and has been evolving and improving since 1989. The present risk assessment study involves two basic aspects: human health and ecological risk assessments.

Health risk assessment (HRA), a new technical approach, was created and developed in the past few years. It is the process to estimate the probability of adverse health effects in humans who may be exposed to risk factors and to assess health status [13] [14]. HRA complies with the general principles of risk assessment while following its own procedures and methods. At present, HRA adopted the "four-step approach" published in the report by NAS in 1983: hazard identification, dose-reflected assessment, exposure assessment, and risk characterization. HRA includes qualitative HRA and quantitative HRA. Hazard identification itself is a process of qualitative HRA and the first step of quantitative HRA as well, that is, the premise for the subsequent three steps.

4.1 Hazard Identification

Hazard identification is the process of determining whether exposure to a risk factor can cause an increase in the probability of adverse health effects, that is, conducting a qualitative HRA of the potential to cause harm. Hazard identification is also referred to as hazard evaluation, which can be directly used for registers of hazardous chemicals. The first step is to collect data regarding the substance that is to be assessed, including its physical and chemical properties, exposure routes, structure-activity relationship, characterization of toxicokinetics, toxicological effects, short-term biological experiments, long-term animal carcinogenicity experiments and epidemiological research in certain populations. The collected data should be analyzed, processed and visualized. The main task is to evaluate the quality, applicability and reliability of data, namely the weight of evidence for toxicity. The authorities concerned are responsible for setting uniform and comparative evaluation standards

A judgment should be made as to the toxicity of the tested substance to humans after the collected data is analyzed, audited and evaluated. In this process, the chemicals are classified according to their evidence for toxicity. The authorities concerned are also responsible for classification standards.

Hazard identification process has two uses. First, it can be used to decide whether to make further quantitative risk assessment of the tested substance. Second, it can be used to rank chemicals for human hazard according to its toxicity and the amount of exposure in populations. Hazard ranking is usually based on weight of evidence for collected data. Weight-of-evidence ranking methods can be variable between different risk factors.

4.2 Dose - Response Assessment

A dose-response relationship describes how the probability of adverse health effects (the responses) is related to the amount and condition of exposure to an agent (a risk factor). It is a quantitative basis for risk assessment.

Dose-response assessment is to identify the lowest dose of a risk factor where the adverse effect is observed in the human population exposed and the excess risk caused by the amount of exposure to such a dose. The former (D_L) refers to the lowest dose for exposure to a certain risk factor over a period where the adverse effect is observed. The unit of dose is usually mg. The latter (Pe) refers to the difference between the probability of adverse health effects in an exposed group (P_t) and that in a non-exposed comparison group (P_c). Maximum observed effect level (NOEL), the maximum No-Observed-Adverse-Effect Level (NOAEL), lowest-observed-adverse-effect level (LOAEL) can be directly used to estimate D_L. Thus,

$$D_L = (NOEL, NOAEL, LOAEL) / \prod_{i=1}^{n} F_i \bullet 365 \bullet T \tag{1}$$

Hallenbeck proposed that safety factor be selected in the following ways. There are two formulae for Pe [15]:

$$P_e = P_t - P_c \tag{2}$$

$$P_e = (P_t - P_c)/(1 - P_c) \tag{3}$$

4.3 Exposure Assessment

Exposure assessment is the process of measuring, estimating or predicting the magnitude, frequency and duration of exposure to a risk factor in environmental media. It is a quantitative basis for risk assessment.

Exposure assessment process is to identify the greatest average amount of exposure of individuals to a risk factor over a period of time, which is expressed as D_H:

$$D_H = C \bullet I \bullet T \tag{4}$$

C——Average weight (measured in mg) of risk factors in pollutants (air, aquatic foods)
I——Average daily pollutant intake of individuals exposed
T——Average days of exposure of individuals exposed

***4*.4 Risk Characterization**

Risk characterization is the process of estimating the probability of adverse health effect in populations exposed to risk factors under various conditions.

Risk characterization has two major components. First, quantitative estimation and interpretation of health risk; second, explanation of assessment results and discussion of assessment process, particularly analysis of the uncertainties through the process, namely, risk evaluation of the results of risk assessment. The first step of health risk estimation is to identify risk factor or unit risk (R), which refers to excess heath risk caused by risk factors per density when individuals or populations are exposed to the risk factors in question. The second step is to calculate R by the lowest dose of a risk factor where the adverse effect is observed (D_L) and the excess risk caused by the exposure to such a dose(P_e), as identified in dose-response assessment. The formula is as follows:

$$R = P_e / D_L \tag{5}$$

R is the basis of health risk estimation, which can be expressed in various ways. Common expressions of health risk include maximum excess risk of individuals, EC(the number of excess cases of crowds over a year), acceptable exposure limits and so on.

5.Health Risk Assessment of Reclaimed Water in Tianjin

There are two main risk assessment models for water circulation:⑴Carcinogen Risk Assessment Model. It is generally believed that trace amounts of carcinogens may be a health hazard. Carcinogenic risk, usually expressed as RISK, is defined as the product of average long-term daily intake and carcinogenic potency factor. It refers to cancer incidence (above normal levels) caused by exposure to a carcinogen. This model is formulated as follows:

$$R^c = \sum_{i=1}^{k} R_i^c \tag{6}$$

$$R_i^c = [1 - esp(D_i q_i)]/70 \tag{7}$$

R^c in the formula stands for average individual annual cancer risk caused by chemical carcinogen i via drinking water; Di stands for average daily exposure per unit body mass to chemical carcinogen i via drinking water, mg / (kg.d).⑵Non-carcinogen Risk Assessment model. It is generally believed that non-carcinogen will not be a health hazard until it exceeds a certain threshold.

$$R^n = \sum_{i=1}^{n} R_{ip}^c \tag{8}$$

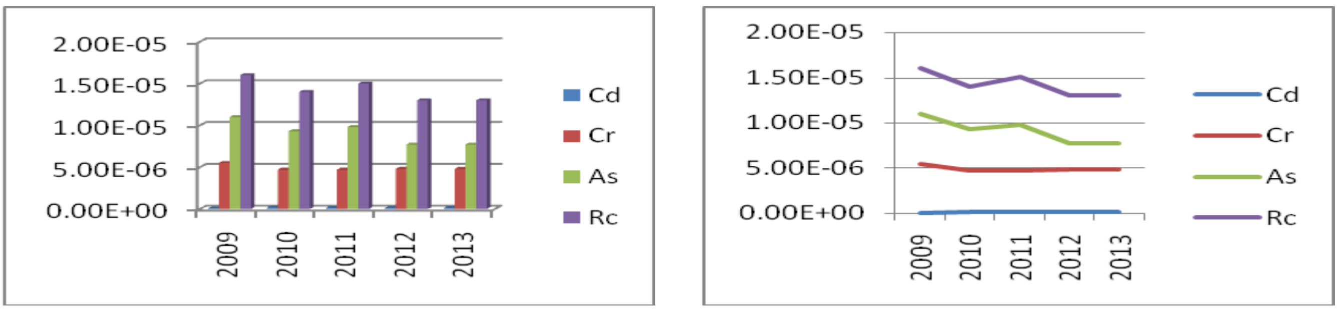
$$R_{ip}^c = (D_{ip} \times 10^{-6} / RfD_{ip})/70 \tag{9}$$

R^n in the formula stands for average individual annual health risk caused by non-carcinogen i; Dip stands for average daily exposure per unit body mass to non-carcinogen i, mg / (kg.d).

The assessment in question used the monitoring results at the three observation stations from 2003 to 2007. The average of monitoring data about the surface and bottom of water is taken as the final monitoring data of one observation station. The average of data within one year is taken as the annual average of this observation station. The average of the annual averages of three observation stations is the annual average of this reservoir. The average individual annual risk of health hazard caused by chemical carcinogens and non-carcinogens (non-gene toxic substances) is shown in Table 3 and Table 4.

Table 3 Risk Caused by Chemical Carcinogens （R^c） From 2009 to 2013

YEAR	Cd	Cr	As	Rc
2009	6.8E-08	5.5E-06	1.1E-05	1.6E-05
2010	1.6E-07	4.7E-06	9.3E-06	1.4E-05
2011	1.4E-07	4.7E-06	9.8E-06	1.5E-05
2012	1.4E-07	4.8E-06	7.7E-06	1.3E-05
2013	**1.4E-07**	**4.8E-06**	**7.7E-06**	**1.3E-05**



（a）bar chart about Chemical Carcinogen **(b)line chart about Chemical Carcinogens**

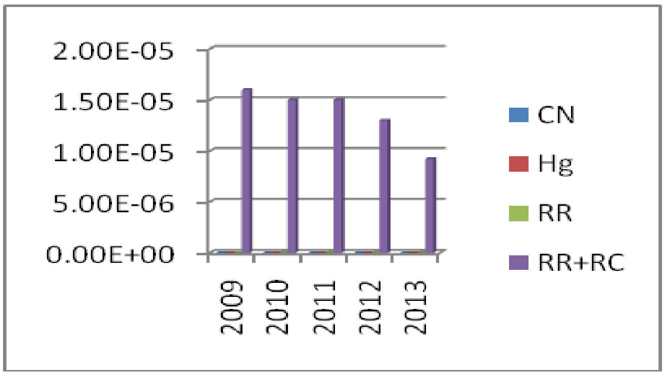
Fig1：Risk Caused byChemical Carcinogens

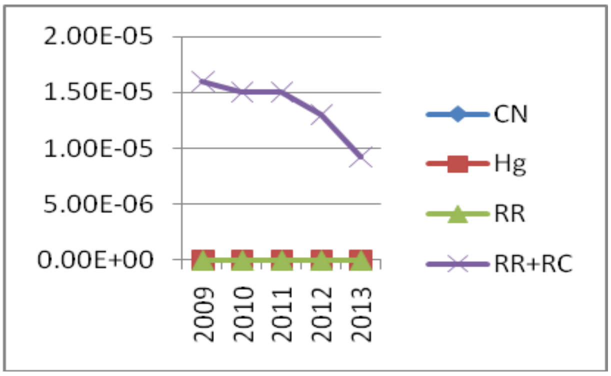
Table 4 Risk Caused by Non-carcinogens（R^n）and Total Risk of Yuqiao Reservoir From 2009 to 2013

YEAR	CN	Hg	RR	RR+RC
2009	2.4E-11	4.3E-11	5.2E-10	1.6E-05
2010	2.4E-11	1.2E-11	5.5E-09	1.5E-05
2011	2.4E-11	1.1E-11	5.5E-09	1.5E-05
2012	2.4E-11	8.7E-12	5.9E-09	1.3E-05
2013	2.4E-11	9.6E-12	6.1E-09	9.2E-06

As shown in the tables, the current individual annual risk of health hazard caused by all pollutants is 9.2E-06 (see Table 4). That is, the probability of illness or death caused by pollutants in drinking water per year is nine in a million. This risk is lower than 1.0E-04, the individual annual risk of health hazard caused by all pollutants in drinking water recommended by US Environmental Protection Agency, and 5.0E-05, the largest acceptable value recommended by ICRP, but it is nearly ten times the value recommended by Sweden and the Netherlands.

Among all pollutants, the risk of chemical carcinogens is much higher than that of non-carcinogens, the former being 1508 times the latter. The individual annual risk is between 1.4E-07 and 5.0E-06, that is, the probability of one's health being impacted by chemical carcinogens in water in one year is 1 to 5 in ten million. Individual annual health risk caused by chemical carcinogens was being reduced year by year in the past five years.





(a)bar chart about factor of risk **(b)line chart about factor of risk**

Fig2: Risk Caused byNon-carcinogens（R^n）and Total Risk of Yuqiao Reservoir From 2009 to 201

CONCLUSION

Water resources are the indispensable material base of life and the important safeguard for socio-economic development. Strategies for water recycling and reuse promote circular economy and at the same time offer solutions to water pollution. Circular economy is centered on the relationship between pollution treatment and reuse of reclaimed water. The notions of waste reduction, even no waste, reuse and turning waste into resources in circular economy are consistent with those of economics. These methods not only reduce costs but also increase capital. Strategies for water recycling and reuse offer solutions to water scarcity and glaring contradiction between supply and demand in Tianjin. Such strategies are also positive approaches to the serious water pollution in Tianjin.

Health risk assessment of urban reclaimed water is aimed at assessing water quality as various pollutants may generate harmful effects in humans in the process of water reuse. The reclaimed water is primarily reused in agricultural irrigation, industry, groundwater recharge, landscapes and recreation areas. As our reclaimed water management strategy depends primarily on the comparison of conventional water quality indexes and standard ones, the current assessment method, to some extent, weakened the potential impact of toxic and harmful factors stipulated by national water quality standards. If health risk assessment of reclaimed water becomes a part of routine environmental assessment, it will be easier to have a more scientific, objective, comprehensive and immediate understanding of reclaimed water quality and safety so as to implement necessary pollutant priority control strategy and environmental protection strategy.

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