Comprehensive Evaluation of Effectively Utilizing Reclaimed Water to Accomplish Sustainable Development in Tianjin, China

Graduate School of Life and Environmental Sciences, University of Tsukuba  Nan XIANG
Graduate School of Life and Environmental Sciences, University of Tsukuba  Feng XU
Graduate School of Life and Environmental Sciences, University of Tsukuba  Yoshiro HIGANO

1. Introduction

Water resources are one of the most important things for human existence and social development. Also, with the increase of economic and population in developing countries, water scarcity and pollution problems are becoming more and more prominent recently. Wastewater reuse has drawn increasing attention worldwide as an integral part of water resources management. Such a move is driven by two major forces: scarcity of clean water resources and heightened environmental concerns [1-3]. Reclaimed water reuse has been used in large municipalities in many parts of the world, especially in areas where the water resources are scarce and population and economic growth is rapid [4]. Tianjin is one of the typical areas in point. In 2009, only 2.01% of total water supply in Tianjin comes from reclaimed water reuse, the reclaimed water projects have just started.

Reclaimed water reuse practice can be traced back to several centuries ago. And there are a large number of studies on waste water treatment from technological and engineering aspects. However, there is rather rare research on reclaimed water utilization modeling and prediction. In most of these studies, conclusions are derived from simple data analysis and foreign experiences [5-8]. Research on construction and analysis of a comprehensive simulation policy that includes the introduction of current treatment technologies to control water pollutant emissions without deteriorating the socio-economic activities level are badly needed.

In the study, we selected Tianjin city as an objective region, and utilized linear modeling as research method, constructed comprehensive evaluation model to prove the feasibility and possibility on using reclaimed water promotion and water quality control policy to improve economic and social development.

2. Current situation of the catchment area

Tianjin, one of four biggest municipalities in China, is located in northern China, near Beijing, capital of China, and the downstream of Haihe River basin.

2-1 Local situation

There are 13 districts and 3 counties in Tianjin, the land area is 1,191,970 hectares. About the land usage, agriculture land accounts for the biggest part, 60.87%; construction land accounts for 32.13%; and unused land is 829.85ha, accounts for 7%. The total population in Tianjin in 2009 is 122.816 million, and with the urbanization process, the urban population increasing rate is much higher than rural population.

From the following figures, we can see that Tianjin’s GDP keeps a steady increasing trend; the increase rate is above 10% per year. Also, the three industries composition demonstrates that Secondary Industry is the monopoly industry while its composition steady rises; primary industry only contributes a little to Tianjin’s economic, and its composition is low; tertiary industry’s GDP contribution declines year by year[9].

2-2 Water supply situation

Water shortage is a serious problem in Tianjin. Total water resource amount in 2009 is 2337 million m³. The per capita water resources in Tianjin is 190 m³ in 2009, it is only 1/13 of China average, and only 1/52 of world average.

And the water supply structure is not stable for future development. Water supply is largely depending on surface water which is highly pullulated. And over 25% of water supply comes from water transferred from the other area, such as Luan River in Hebei province. Reclaimed water only contributes to 0.51% of total water supply. Large transferred water supply dependence is not only leading to resource waste, but also causing water supply unstable [10]. Reclaimed water can be a potential supply resource in saving water shortage problems.
2-3 Water quality situation

Surface water quality in Tianjin is not enlightened; over 70% of surface water in Tianjin is in inferior V level. Also, from figure 4, rivers with red line are over qualified, and large amount of waste water is directly discharged to the ocean, Bohai Bay, without treatment. This will cause hidden danger for local area.

![Surface water classification in 2009](image3.png)
![COD emission amount in Tianjin](image4.png)

Figure 4 shows the COD emission amount from 2002 to 2009. Limited to data availability, Tianjin only use COD in water pollution monitoring, this paper uses COD as the water pollutant control index in simulation. From 2001, Tianjin government has put proposals to improve water quality, therefore, with the economic rapid development, COD amount has been controlled stably, and the trend is declining. However, the total COD amount and water quality still need to be improved badly. Tianjin government has proposed to reduce and control COD amount in development plant until 2020.

2-4 Reclaimed water utilization situation

Furthermore, waste water reuse situation has just started in this area; the reclaimed water reuse rate is really low, only 2.01% of reclaimed water is used in Tianjin. While the waste water disposal rate is 72.40%, a large amount of treated waste water has not been used. Compared with Beijing, the reclaimed water reuse rate is 57.55%, there is a large gap of reclaimed water utilization between these 2 Adjacent areas. It also demonstrates that there is large potential to use reclaimed water in Tianjin.

Tianjin government also realized the importance to use recycle water in improving water quality and saving water. Local government established a 10 years target to increase reclaimed water recycle rate to 50-60% in 2020.

<table>
<thead>
<tr>
<th>Table1. Reclaimed water utilization (2009) units:( 10,000ton)</th>
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<tbody>
<tr>
<td>Total amount of water resource</td>
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<tr>
<td>Tianjin</td>
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<td>Beijing</td>
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</tbody>
</table>

Source: Tianjin Water Bureau Statistical Year Book 2010, Beijing Water Bureau statistical Year Book 2009

From the current situation analysis, we can see that Tianjin water supply structure need to be perfected; over 70% of surface water in Tianjin is in inferior V level, water quality is not well; and waste water treatment coverage
proportion still needs to be improved, reclaimed water utilization rate is low, 2.01%.

With the rapidly regional development, water scarcity is intensifying and water pollution is deteriorating. Thus, it is important to research on waste water utilization in order to solve water shortage and water pollution problems.

3. Research model construction

3-1 Case setting

In order to achieve sustainable development in catchment area, water quality should be improved along with water resources saving. Since Tianjin government use COD as the major water quality control index, we adopted COD to control the water environment from 2010 to 2020, 25% decrease in 2020 compared with that in 2010.

Aims to find out the contribution of reclaimed water to economic development, we set case 50, case 60, case 70 and case 80 to observe the total GDP amount and developing trend. Case 50 means 50% of sewage is reused as reclaimed water in 2020. Furthermore, we find out the maximize reclaimed water rate can be achieved is 75%, therefore, we added 2 cases, Case 65 and case 75 in analysis. There are 5 different cases in evaluated in this paper.

3-2 Region Classification

Regards to the simulation framework, the catchment area is divided into 11 areas based on these administration division and regional plan.

<table>
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<tr>
<th>Index</th>
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<th>Index</th>
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<tbody>
<tr>
<td>1</td>
<td>Central Urban</td>
<td>Heping District</td>
<td>3</td>
<td>Dongli District</td>
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<td></td>
<td>Area</td>
<td>Hedong District</td>
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<td>Xiqing District</td>
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<td>Jinnan District</td>
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<td>Nankai District</td>
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<td>Beichen District</td>
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<td>Hebei District</td>
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<td>Wuqing District</td>
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<td>Hongqiao District</td>
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<td>Baodi District</td>
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<td>2</td>
<td>Binhai New Area</td>
<td>Tanggu District</td>
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<td>Ninghe County</td>
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<td>Han’gu District</td>
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<td>Jinghai County</td>
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<td>Dagang District</td>
<td>11</td>
<td>Jixian County</td>
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</table>

3-3 Water supply and demand classification

And the water supply is divided into two types, clean water and reclaimed water. Water demand resource is separated into 2 groups: household living water and industry water, and industry are divided into Primary industry, secondary Industry and Tertiary Industry.

3-4 Reclaimed water treatment technology choice

(1) Technology A

Technology A is Double membrane technology which is used in Beijing development area in China. This technology uses skill “MF(Micro Filtration) +RO(Reverse Osmosis)” in waste water treatment. This technology’s merits including large sewage treatment capacity, high water disposal rate (≥75%), and low operation cost. Compare to technology B, its treatment capacity is larger, but the reclaimed water recycle rate and quality is lower.

(2) Technology B

Technology B is Ceramic membrane water treatment system. Japan has advanced waste water treatment technology, especially in reclaimed water utilization area. Ceramic membrane water treatment which is developed by Metawater.co.ltd, has high water quality treatment ability. The advantages including stable operation with inferior input water; high water resource recycle rate which is over 90%; low operation cost; and easy to be cleaned. However, the treatment capacity of waste water is small. Unit disposal cost is higher than Double membrane technology in producing reclaimed water.
4. Model structure

4-1 Objective function

The objective function was constructed to maximize the total GDP over the target term (t=11) in order to determine an optimal policy.

\[
\text{MAX} \sum_t \text{GDP}(t)
\]  
(1)

4-2 Reclaimed water cycle balance model

Total water supply amount is:

\[\text{WS}(t) = \sum_j \sum_m \text{WSP}_j^m (t) + \sum_j \sum_m \text{WSR}_j^m (t) + \sum_j \text{WS}_j^I (t)\]  
(2)

\text{WS}(t): \text{water supply in time t; } \text{WSP}_j^m (t): \text{water supply from clean water; } \text{WSR}_j^m (t): \text{water supply from reclaimed water.}\]

The water demand amount is:

\[\text{WD}(t) = \sum_j \sum_m \text{Ewj}_j^m \cdot X_j^m (t) + \sum_j \text{Ewj}_j^I \cdot z_j\]  
(3)

\text{WD}(t): \text{Water demand in time t; } \text{Ewj}_j^m: \text{Coefficient of water demand of industry m in region j; } \text{X}_j^m (t): \text{Production of industry m in the area of region j; } \text{WS}(t) \geq \text{WD}(t)\]

We assumed that the total sewage amounts except Primary industry have been disposed in sewage plant, including existing sewage plant and new established sewage plant. Therefore, the reclaimed water amount is decided by new established sewage plant, it has new technology to provide reusable water for Primary and Secondary industry.

\[\text{RW}(t) = \sum_j (\alpha \cdot \text{SPW}_j^A (j, t) + \beta \cdot \text{SPW}_j^B (j, t))\]  
(4)

\text{RW}(t): \text{Reclaimed water amount provided by sewage plant; } \alpha: \text{Reclaimed water recycle rate of technology A; } \beta: \text{Reclaimed water recycle rate of technology B; } \text{SPW}_j^A (j, t): \text{Water amount treated by new sewage plant A in region j; } \text{SPW}_j^B (j, t): \text{Water amount treated by new sewage plant B in region j; }\]

4-3 Water Pollutant Flow Balance Model

The total water pollutant amount of COD is discharged by economic and social activities:

\[\text{TP}_p^d (t) = \sum_j \sum_m \text{Ep}_j^m \cdot X_j^m (t)\]  
(5)

\text{TP}_p^d (t): \text{The total net load of water pollutant COD at time t; } \text{Ep}_j^m: \text{Coefficient of water pollution of industry m in region j; } \text{X}_j^m (t): \text{Production of industry m in the area of region j; }\]

4-4 Social-Economic model

In assumption, the new established sewage plant can provide reclaimed water. The sewage plant investment is proved by financial support and other social sources. The following is flow balance in the commodity market:

\[\text{X}(t) \geq A \cdot \text{X}(t) + \text{C}(t) + \text{I}(t) + \text{B}^p \cdot \text{I}^p + \text{I}^S \cdot \text{I}^S + \text{e}(t) + \text{T}(t)\]  
(6)

\text{X}(t): \text{Total product of industry in the study area; } \text{A}: \text{Input-output coefficient matrix (ex.;) } \text{C}(t): \text{Total consumption at time t(en;)} \text{I}(t): \text{Total investment at time t(en;)} \text{B}^p: \text{Column vector of m-th coefficient that induced production by construction of sewage plant (ex;)} \text{I}^p: \text{Total investment for construction of sewage plant (en;)} \text{I}^S: \text{Total investment for construction of sewage plant (en;)} \text{e}(t): \text{Column vector of net export(en;)} \text{T}(t): \text{Column vector of transfer product between provinces in China(en;)}\]

5. Simulation Results Analysis

In this study, 5 scenarios are established to evaluate the contribution of reclaimed water to economic development.
under COD constraint. The following results can be achieved:

5-1 Objective function

Under the water pollutant constraint, as well as the new sewage plant construction encouragement policy each year, GDP in Tianjin can get steady improvement since 2010. Between cases 50 to 75, there is a quick increase from case 50 to 60; the contribution of reclaimed water to economic is significant. The maximize total GDP can be got is 11679.87 billion Yuan, 368.65 billion more than case 50. Although the top recycle rate of reclaimed water is 75%, total GDP is declined. Therefore, we chose case 65 as the optimal plan for sustainable development in the target area.

From the GDP increasing trend of case 50 to 75, when we introduced new technology, the GDP increasing rate in the former 5 years is higher than latter. Especially, in case 50, GDP decreases since 2015. This demonstrates that the current technology and sewage plant cannot provide enough incentive power for both economic and environmental improvement.

5-2 Reclaimed water utilization trend

Through simulation, we get the reclaimed water utilization potential in Tianjin from 2010 to 2020. With the economic development and financial support in research area, reclaimed water facilities are established and the total reclaimed water usage amount is growing significantly.

The total reclaimed water amount is increased from case 50 to case 75. In case 65, the total amount of reclaimed water can be provided from 2010 to 2020 is 29838.62 million tons.

Figure 7 shows the recycle rate of sewage water from 2010 to 2020 in case 65. Since the reclaimed water is produced by new sewage plant in assumption (which is almost the reality in Tianjin city, in 2009 only 2.01% of reclaimed water is used), waste water recycle rate is increasing continuously in the 11 years, and the waste water treated by new sewage plant can substitute the existing old sewage plant step by step. In 2010, only 1.54% water supply comes from reclaimed wastewater, and in 2020, its percentage rises to 17.46% while economic development and environmental protection. In 2020, total water demand is 27854.57 million tons, and reclaimed water can save 4689.20 million tons clean water for Tianjin city.

From the above figure, we can see the reclaimed water recycle can get continue development if we construct the
new sewage plant with technology A and B, for their high waste pollution disposal ability and financial support. In 2020, total sewage amount is 7214.15 million tons, and 65% waste water can be recycled by new sewage plant, also this can contribute a lot to water pollutant declination. There is a large potential to utilize and adopt new technologies in Tianjin city to achieve sustainable development.

5-3 New sewage plant construction and distribution

Also, from scenarios, we can get the distribution of new sewage plant in 11 regions of Tianjin. From 2010 to 2020, there will be 42 plants being built. Regions with high population aggregation and economic development will construct more sewage plant in the long run, such as the central urban area and Binhai New Area. Also, regions that are short of wastewater disposal capacity will introduce new sewage plant at first, such as Beichen and Jinghai.

The current sewage disposal capacity in Tianjin is the basis for constructing new sewage plant in simulation. The simulation chooses to build new sewage plant in these areas lack of sewage disposal ability. Also, the new sewage plant construction is constrained by local government financial capacity and industry’s development.

The total budget is 4.29 billion Yuan from 2010 to 2020, only 0.39 billion Yuan’s investment each year. And in the former years, sewage plant with technology B is constructed more than that with technology A. In the latter 5 years, the investments between 2 technologies are almost even, they have their own advantages in providing reclaimed water.

From this simulation results, we can also give specific policy proposals in constructing new sewage plant and adopt which kind of technology, in order to prompt reclaimed waste water reuse and achieve economic optimal development.

6. Conclusion

When we adopted a policy that introduces new technology to increase reclaimed water recycle in order to save water resource and improve the water quality, the policy was proven to be an effective tool to achieve the sustainable development target in the catchment area.

In short, this paper holds on that:

(1) Reclaimed water recycle can be an effective method to save water resource, reduce water pollutant and improve economic development in the catchment area;

(2) New technologies adopted from China and Japan can provide sufficient reclaimed water production capacity to achieve the local government reclaimed water utilization plan (50-60% reclaimed water recycle rate). Moreover, the recycle rate can achieve 75%, while 65% recycle is considered to be the optimal choice for sustainable development.

(3) Specific sewage plant construction plan is provided for local government policy references, including the technology choice and financial budget input etc.

In spite of these implications, this research has some limitations which call for follow-up research. First, this research needs to put water price of difference water supply sources in consideration; furthermore, specify water supply sources, such as water transferred from other provinces, rain water and sea water; classify the water demand of reclaimed water, etc.